The statistical applications on the galaxies and AGNs in SDSS

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Outline

- Introduction
  - The Sloan Digital Sky Survey
  - The large galaxy and QSO samples in SDSS legacy
  - The classical statistical studies in SDSS

- Our statistical applications
  - The statistical nature of the brightest group galaxies;
  - The tile between accretion disk and stellar disk;
  - The redshift dependence of the composite quasar spectra: implications on the cosmic dust extinction.

Why statistical studies?

- Common properties
  - Constraints to physical models
  - Physical implications
- Astronomical units: no experiment
  - Observe a galaxy from different direction ☹
  - Observe many galaxies from the same direction ☺
- Cosmological principle

Shortcomings of statistical studies

- Correlation ≠ causality

- A city with more bars also with more book stores (Antonucci)
  - Doesn't mean people like reading also like drinking

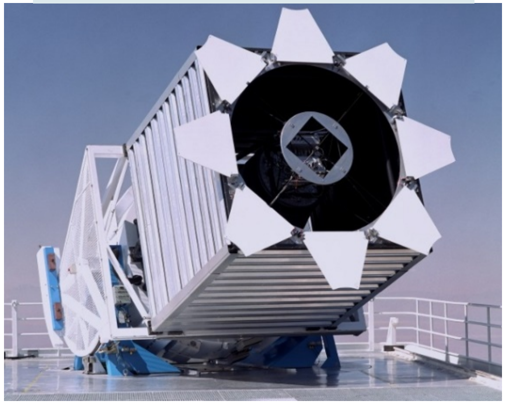
Modern galaxy survey

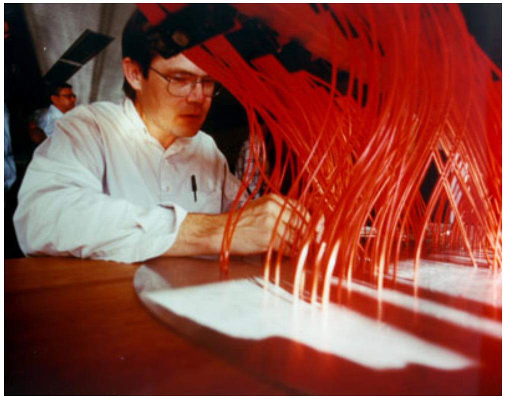
- Developed together with the increasing of computational power and storage capability.

- Sloan Digital Sky Survey (SDSS, Since 2000)
  - 2.5 m special designed survey telescope
  - (u,g,r,i,z) five bands photometry
  - Multi-fiber spectroscopy
    - 640 fibers in SDSS I,II
    - 1000 fibers in SDSS III
  - ~50 TB data (DR8)

- Next generation
  - LSST: 1PB raw data per year

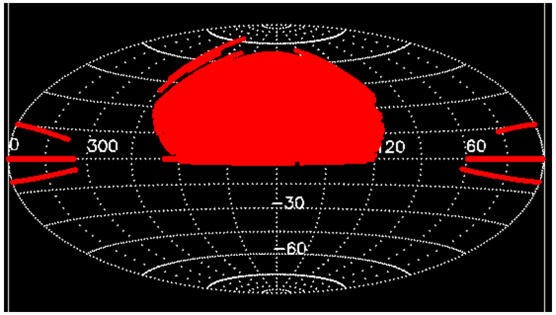
http://www.sdss.org/



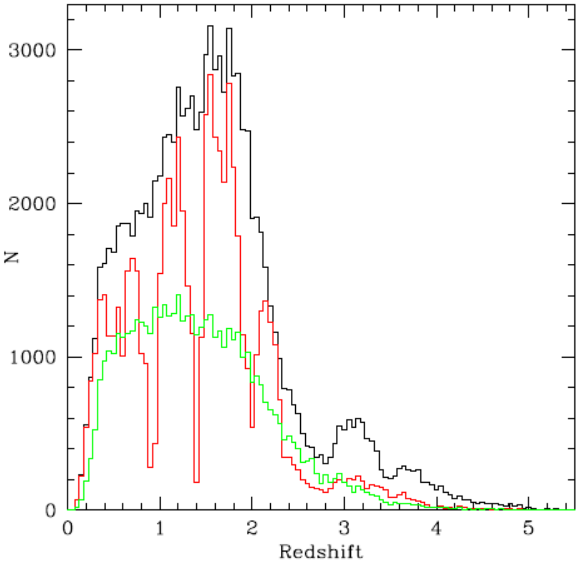


SDSS –I/II Legacy (2000-2008)

- Photometry
  - ~8400 sq deg
  - u,g,r,i,z to (22.0, 22.2,22.2,21.3,20.5) mag

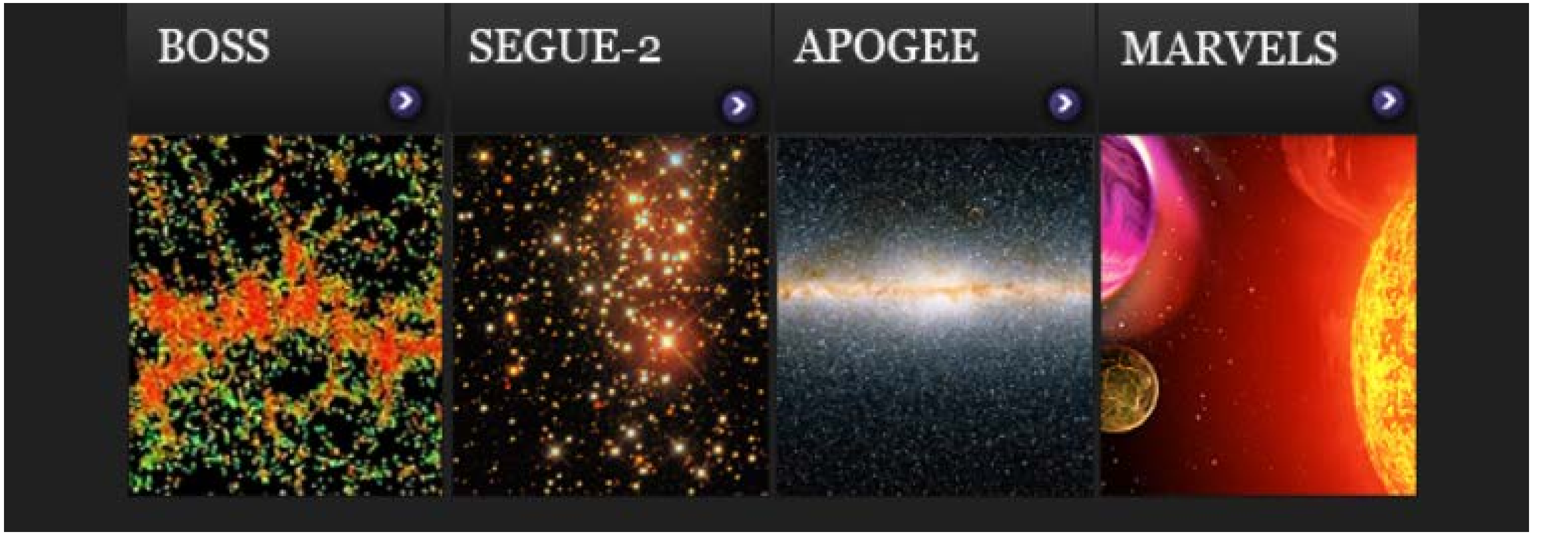


- Spectroscopy
  - Main galaxy sample (r<17.77)
    - ~700k, z~0.1
    - completeness ~90% (another 10% LAMOST)
  - Luminous red galaxies
    - ~300k, Volume-limited to z~0.38 and up to z~0.55
  - QSO sample
    - >100k QSOs with z up to ~5
    - $M_i < -22$



SDSS III and IV

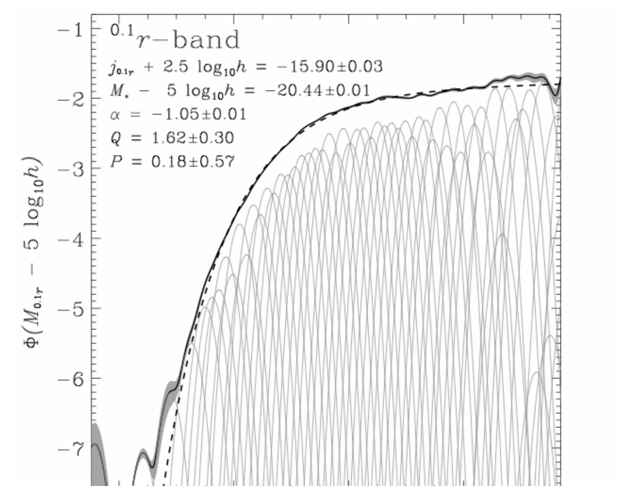
- SDSS III (2009-2014)



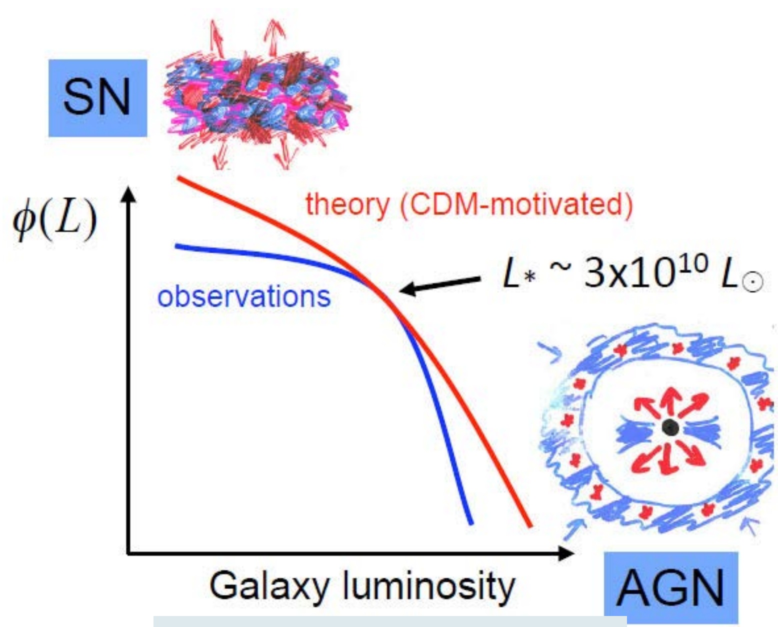
- SDSS IV (2014-2019)
  - APOGEE, MaNGA, eBOSS
  - We are members! (SHAO, NAO, SJTU, NJU)

Classical statistical studies in SDSS (I) Basic distributions

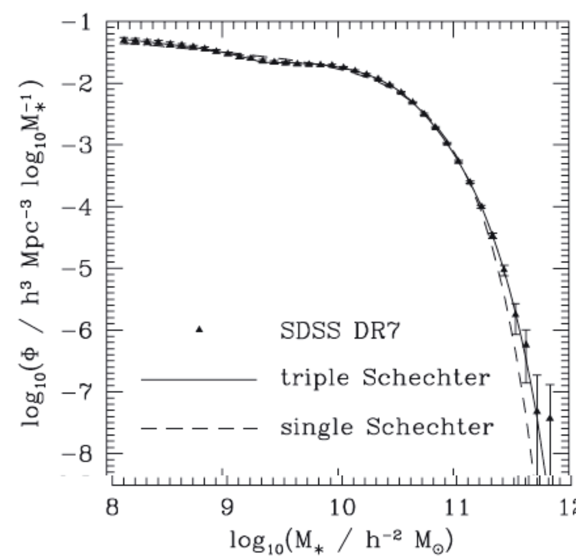
Blanton et al 2003



- Luminosity function
- Stellar mass function



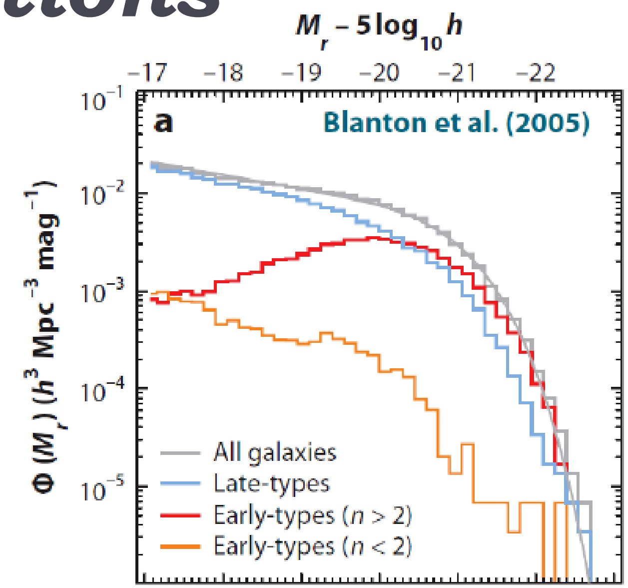
e.g. Croton et al. 2006



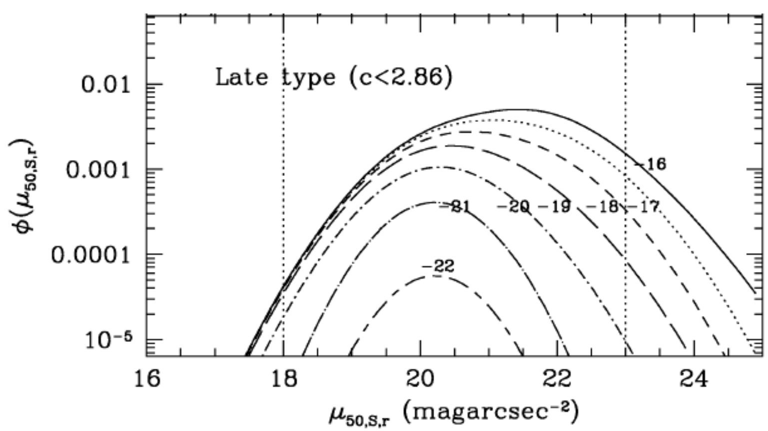
Li & White 2007

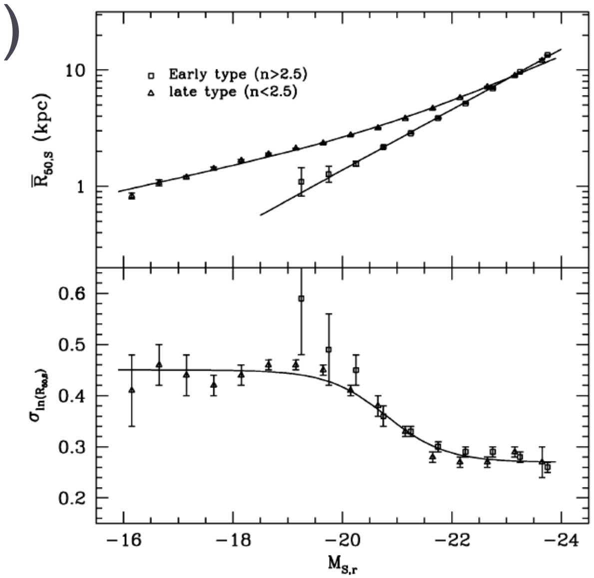
(II) Conditional distributions

- Conditional luminosity function
  - Halo mass $P(L|M_h)$ (Yang et al. 2005)
  - Morphology(Nakamura et al. 2003)
  - Inclination (Shao, Xiao & Shen 2007)
  - Environment (Tempel et al. 2010)
  - See Blanton & Moustakas (ARA&A,2009)



- Size distribution f(R|M) (Shen et al. 2003)
  - Surface brightness distribution

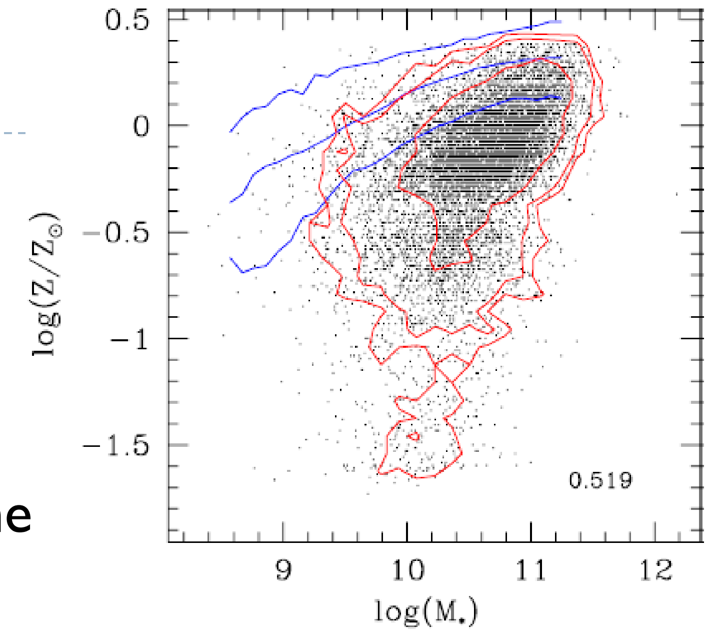


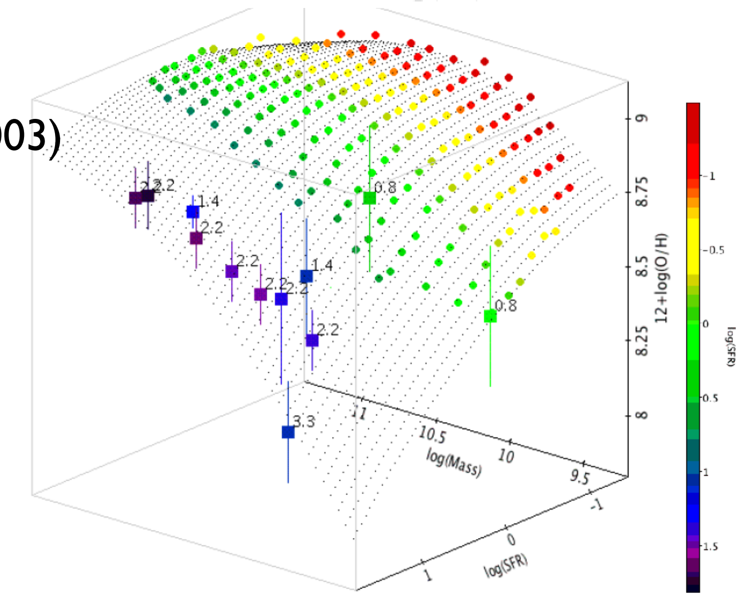


(III) Scaling relations

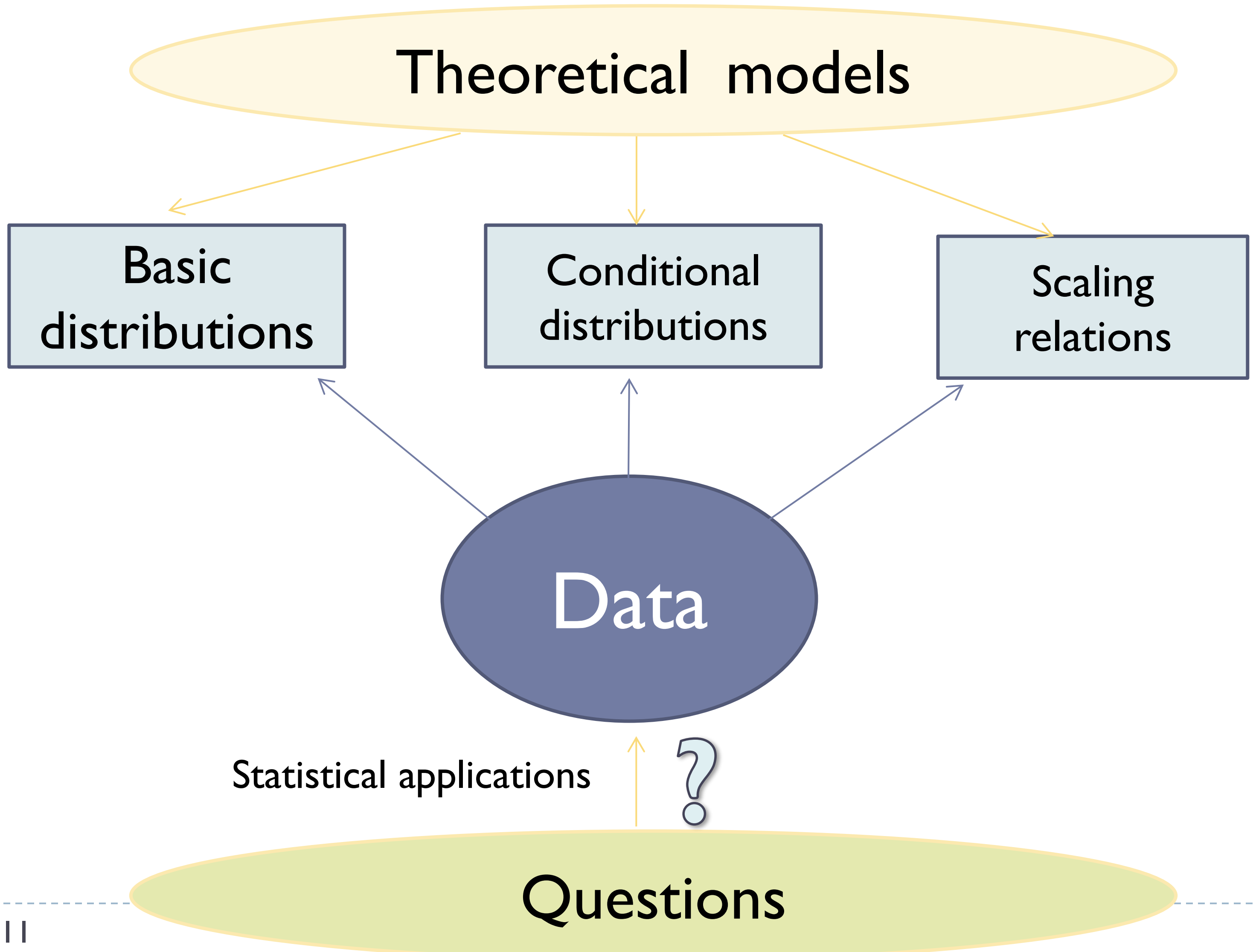
- Mass – metallicity relation
  - Fundamental Metallicity Relation
    - SFR-Mass-Metallicity (Mannuci et al. 2010)
  - The star formation history of galaxies
- Tully-Fisher relation and Fundamental Plane
  - TF: spiral galaxies
    - $L = A V_{rot}^{a}$ (Shen et al. 2002,2009)
  - FP: elliptical galaxies
    - $\text{Log } R_e = a \text{ Log } \sigma + b \text{ Log } I_e + c$ (e.g. Bernardi 2003)
  - Dark matter halo VS stellar mass
- M-sigma relation (e.g. Gu 2009)
  - The co-evolution between the galaxy and black hole

Chang & Shen (2006)





Can statistical studies tell us more?

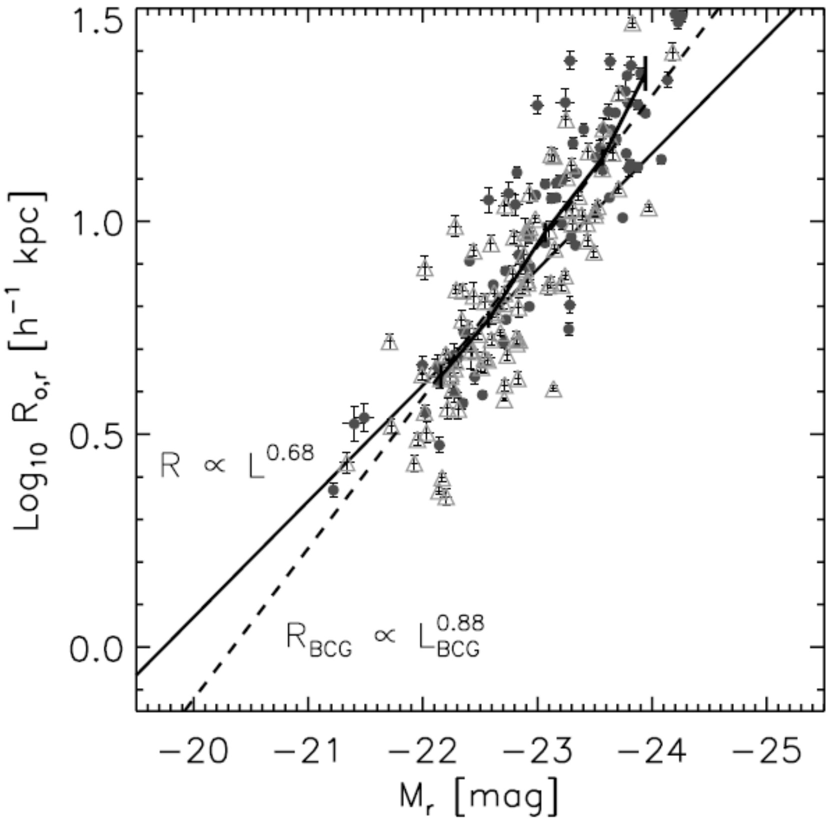


Key ingredients of statistical applications

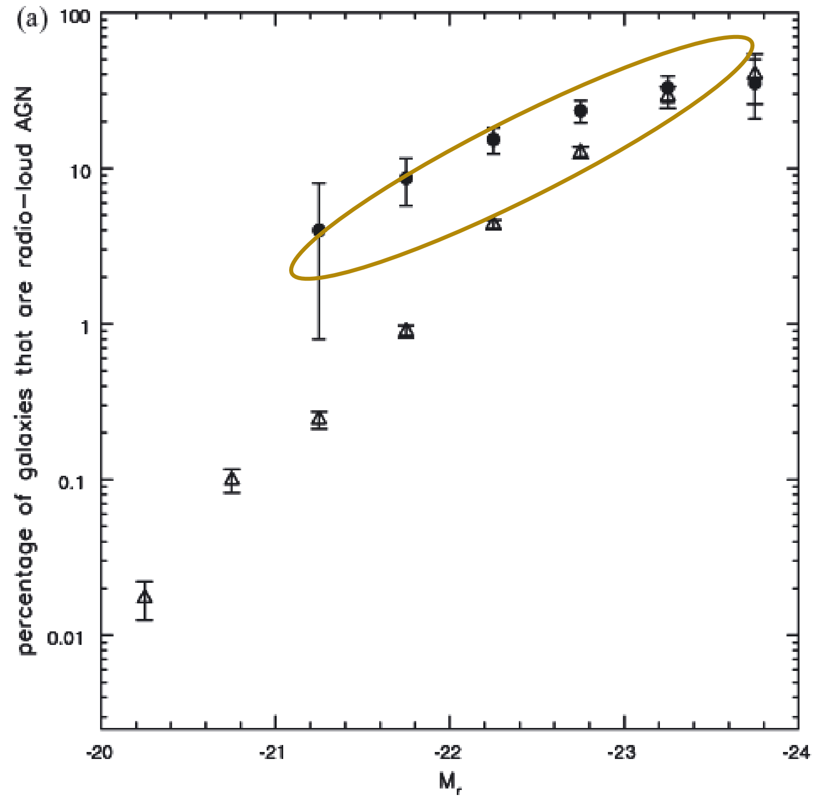
- Large sample
  - Case I: the statistical nature of the brightest group galaxies
- Selection effects: control sample
  - Case II: the tilt between the accretion disk and stellar disk
- Statistical hypothesis
  - Case III: the cosmic dust extinction: implications from quasar composite spectrum

(I) the statistical nature of the brightest group galaxies (Shen et al. ApJ, 2014)

- Brightest group/cluster galaxies(BGGs)
  - Center of group/cluster scale haloes
    - Extreme brightness in rich cluster, small scatter(0.3mag)
  - Red ellipticals
    - Old and passively evolved stellar population
  - Formation
    - subsequent merge of small systems, assemble most of their mass at early time
- BGGs show specialties in observations
  - More extended surface brightness profile than $r^{1/4}$ law
    - (Bernardi et al. 2007)
  - On fundamental plane, different from the normal ellipticals
    - (Von der Linden 2007)
  - More likely to be radio-loud AGN (Von der Linden 2007)



Bernardi et al. 2007



Von der Linden 2007

Physical view of BGGs

- BGGs are the central galaxies of a halo, the other galaxies are satellites.
- The centrals are distinct from satellites

We split the CLF in a central and a satellite term:

$$\Phi(L|M) = \Phi_c(L|M) + \Phi_s(L|M)$$

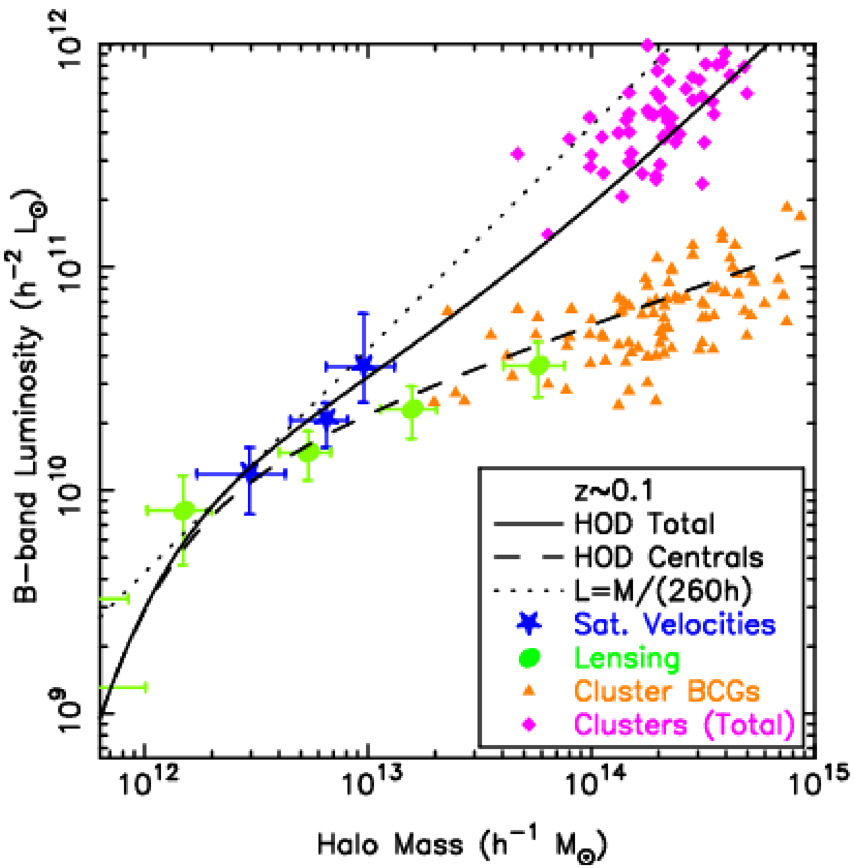
For centrals we adopt a log-normal distribution:

$$\Phi_c(L|M)\mathrm{d}L = \frac{1}{\sqrt{2\pi}\sigma_c} \exp\left[-\left(\frac{\ln(L/L_c)}{\sqrt{2}\sigma_c}\right)^2\right] \frac{\mathrm{d}L}{L}$$

For satellites we adopt a modified Schechter function:

$$\Phi_s(L|M)\mathrm{d}L = \frac{\phi_s}{L_s}\left(\frac{L}{L_s}\right)^{\alpha_s} \exp\left[-(L/L_s)^2\right]\mathrm{d}L$$

M_h- M_1 relation



The BGGs are brighter in higher mass halos.

$$\bar{L}_1 = L_0 \frac{(M_{\rm h}/M_1)^{\gamma_1}}{[1 + (M_{\rm h}/M_1)]^{\gamma_1 - \gamma_2}} ,$$

e.g. Zheng et al. 2007

Statistical View of BGGs

- BGGs may be special only because of their definition.

- Order statistics (OS): statistics on the *j-th* largest members of groups with *N* members
  - Extreme value statistics (EVS) correspond to OS of $j=1$
  - Basic assumption: all group members are drawn from the same population
  - *N*: sample size

- Basic conclusion of the OS/EVS
  - For the same population, if the sample size *N* is larger, the extreme value is larger
    - The BGGs are brighter in higher mass(richer) halos!

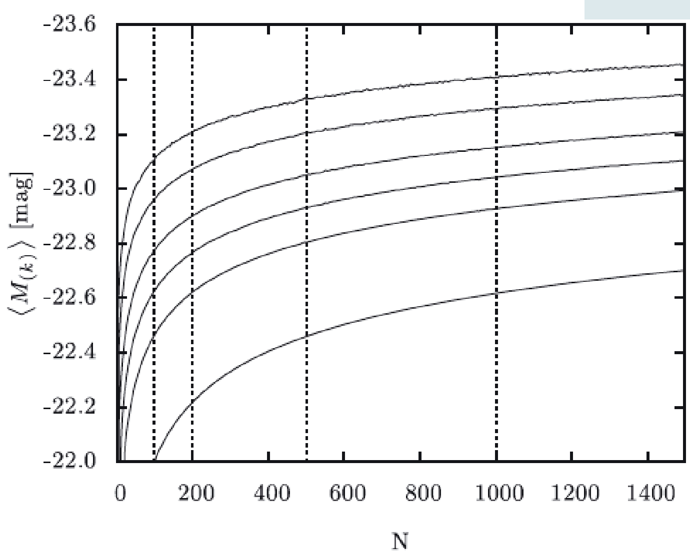
Chinese basketball team
Average height 2.0m
Population: 1.3 billion

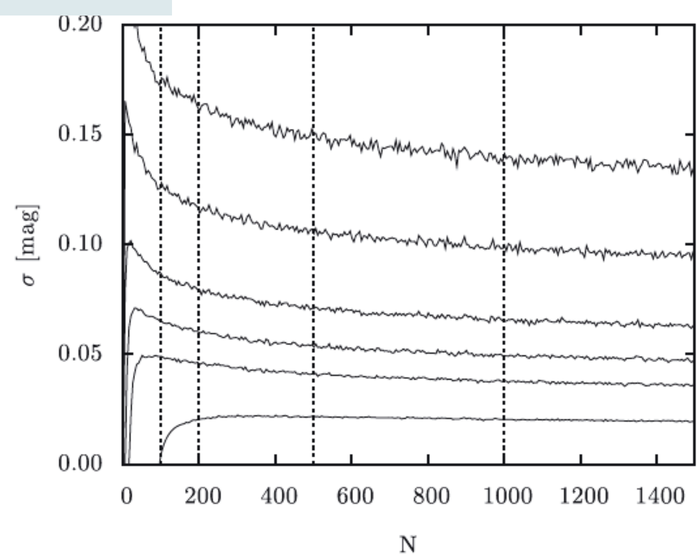
Japanese basket ball team
average height: 1.95m
Population: 0.13 billion

Other conclusions of EVS/OS

- The scatter of the extreme values
  - decrease with the increasing of the sample size *N*
    - the brightest members of rich clusters: standard candle(0.3 mag, Postman 1995)
  - decrease with the increasing of the order *j*
    - The scatter of the Second brightest member galaxies is smaller than BGGs

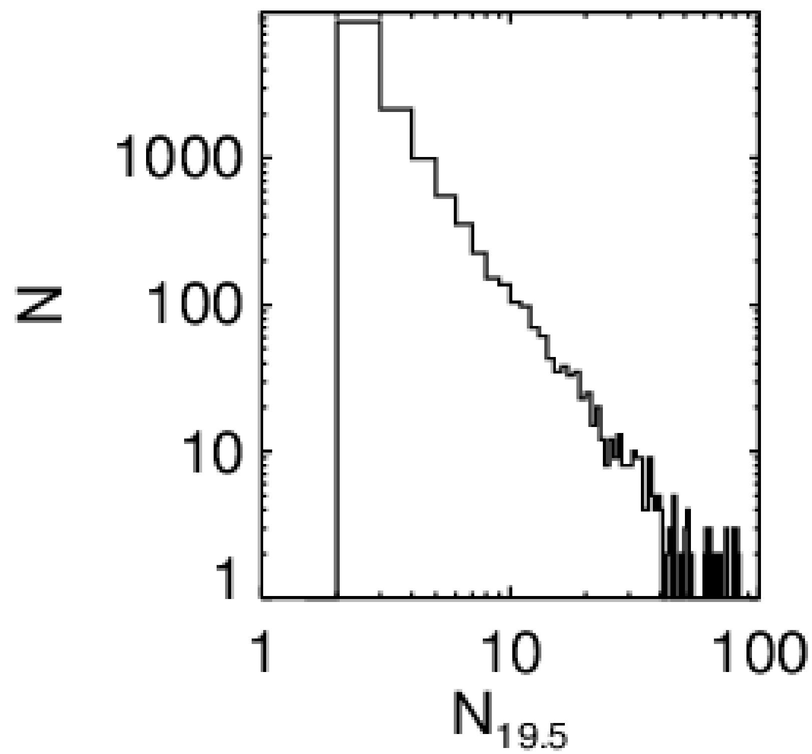
Dobos & Csabai 2010





SDSS DR7 group catalog (Yang et al.)

- Richness $N_{19.5}$
  - Number of galaxies M_r<-19.5
- complete to z<0.09
  - M_r=-19.5 (r=17.77 at z=0.09)
- Number of groups $N_{19.5}$> 1
  - 16,014
- Number of group members
  - 62,081



OS prediction: statistical sample

Real groups

Mr=-20.1
Mr=-20.2

Mr=-20.1
Mr=-20.2
Mr=-20.6

Mr=-19.8
Mr=-20.0
Mr=-20.1
Mr=-21.0

…….

Mr=-20.1
Mr=-20.2
Mr=-20.1
Mr=-20.2
Mr=-20.6
Mr=-19.8
Mr=-20.0
Mr=-20.1
Mr=-21.0

……

Mr=-20.0
Mr=-20.2
Mr=-20.6
Mr=-21.0
Mr=-20.1
Mr=-20.1
Mr=-20.2
Mr=-19.8
Mr=-20.1

……

statistical groups

Mr=-20.0
Mr=-20.2

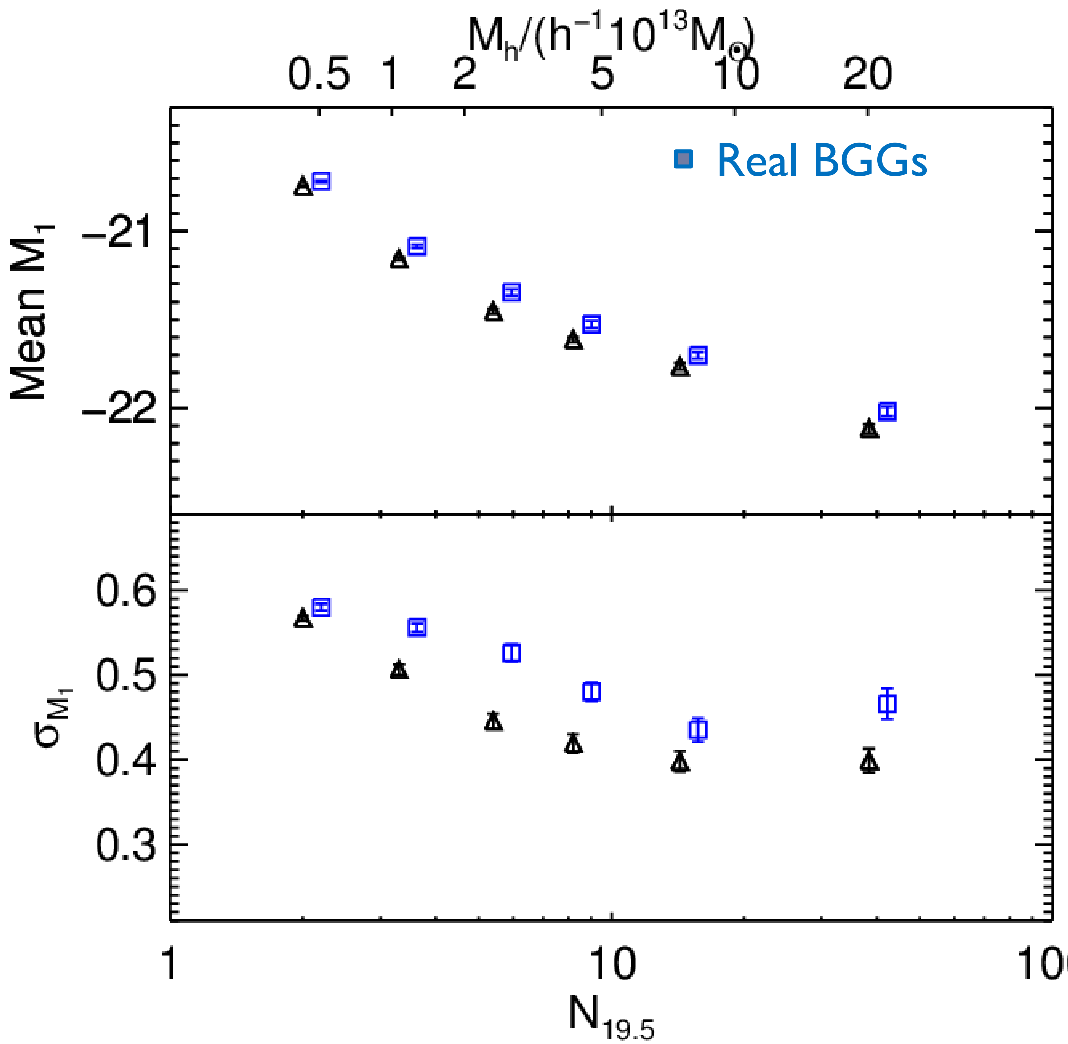
Mr=-20.6
Mr=-21.0
Mr=-20.1

Mr=-20.1
Mr=-20.2
Mr=-19.8
Mr=-20.1

…….

The statistical groups have the same richness and underlying distribution as the real groups

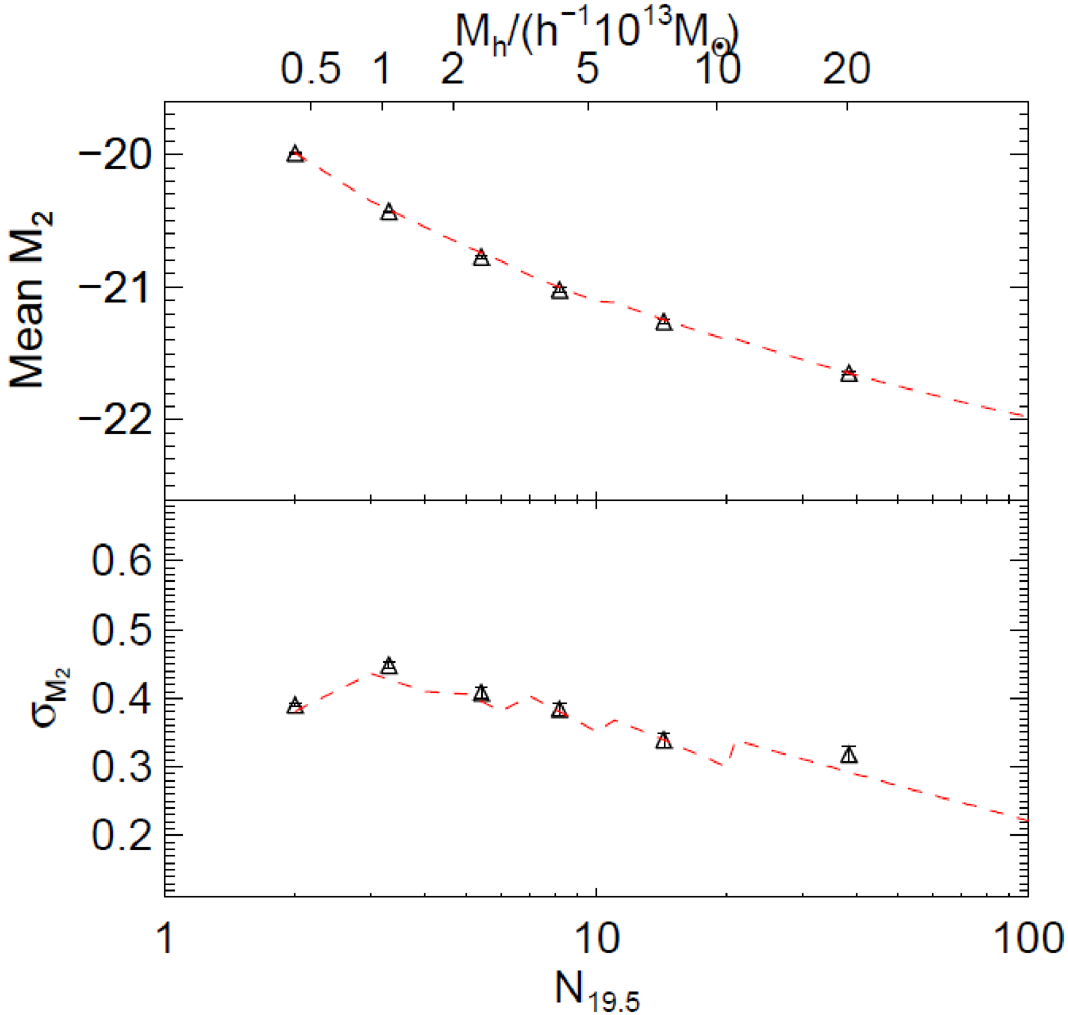
OS prediction VS observation: BGG



The OS predicted BGGs are systematically fainter than the real BGGs

The OS predicted correlation between the BGG luminosity and group richness(halo mass) is similar as observations.

The second brightest group galaxies



Model the BGGs

- At the time of group formation, the stochastic merging process makes the BGGs and other members follow the OS;
- After BGG settling into the center of the group, the local environmental effects further brighten the BGG, e.g. galaxy cannibalism, star formation in cooling flow etc.

BGG brightening: $M_1 = M_0 - \Delta M$

Dim the luminoisties of BGGs with magnitude correction Δ M

↓

For each richness bin, shuffle the members of the BGG-dimmed sample

↓

Build *K* statistical groups, the same $N_i(i=1,K)$ distribution as the real groups

↓

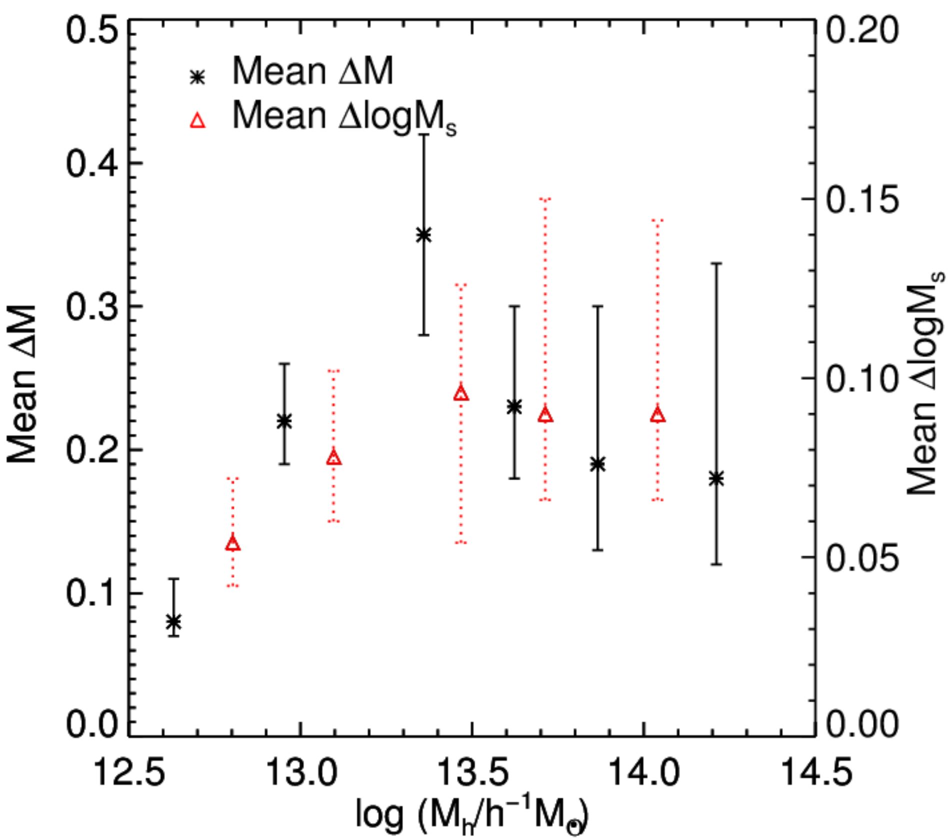
Model groups: apply BGG brightening ΔM on the statistical BGGs

↓

test the distributions of the real group members VS the model groups

The average brightening of BGGs

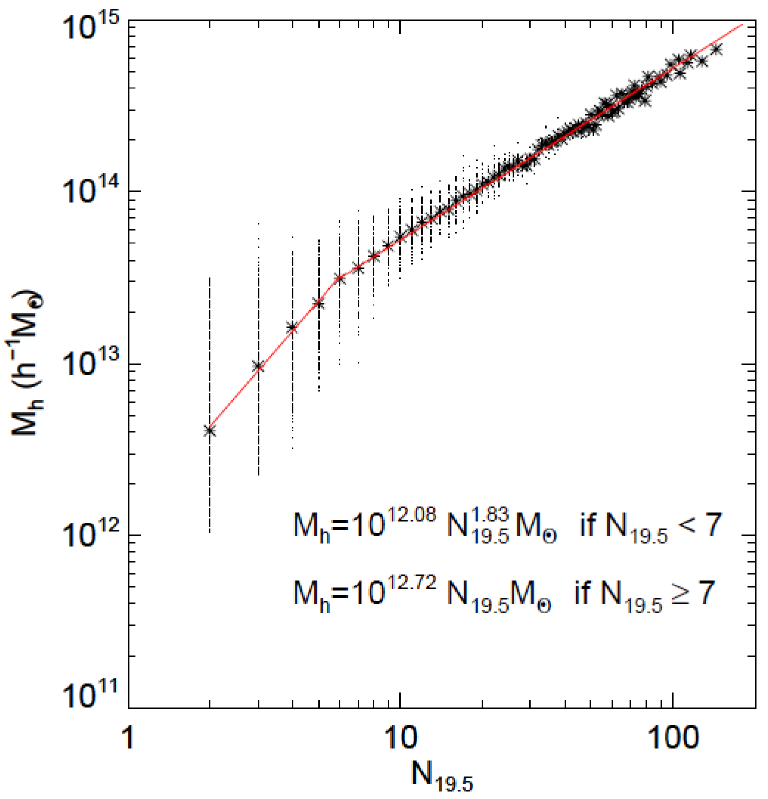
- The BGGs are averagely brightened ~0.2 mag
- Corresponding to a stellar mass increment of about 20 percent
- Consistent with the minor merge scenario of the central galaxies(e.g. Edwards & Patton 2012)



The BGG brightening(ΔM) is not stochastic, but depends on how prominent is the BGG inside the group $\Delta M = 0.3\ G_{1,2}$

A simple HOD and CLF modelling

- For given halo M_h, estimate the group richness *N*;
- Assume a conditional luminosity function;
- Assign *N* members to halo according to CLF;
- Pick up the brightest one as the central;
- Brighten the luminosity of the central according to $\Delta M \approx 0.5 G_{1,2}{}^*$

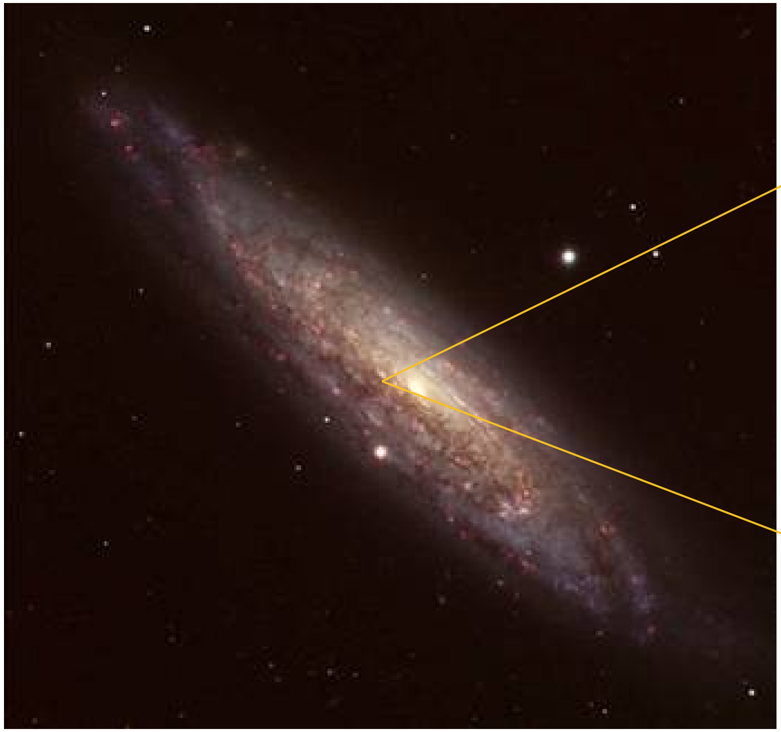


Summary on the statistical nature of BGGs

- The brightest group/cluster galaxies(BGGs) are special, but not distinct from other members.

- The BGGs are consistent with a scenario that they are formed in a statistical process and later brightened (~0.2 mag) by local processes.

(II) The tilt between accretion disk and stellar disk (Shen, Shao & Gu,2010, ApJL)



Any alignment between the Kpc scale stellar disk and sub-pc scale dust tours(accretion disk)?

AGN unification model

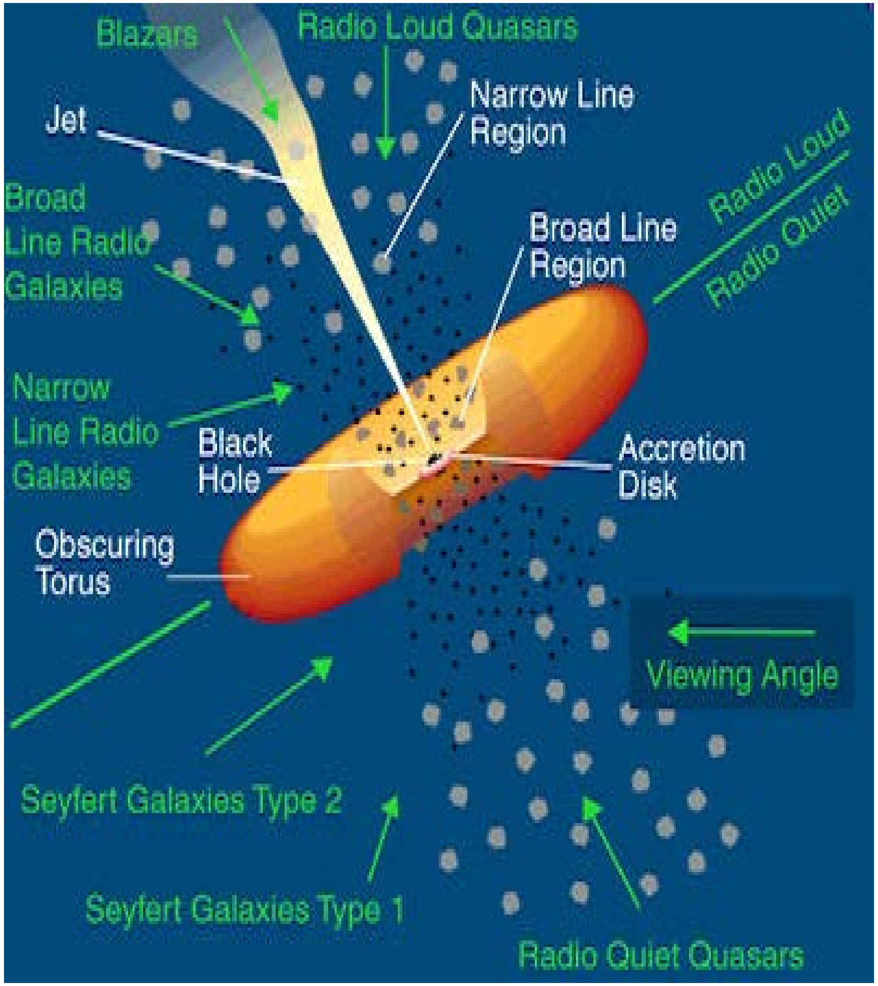
Orientation:

the key parameter of the AGN schema

Type II AGNs:

edge-on view from obscuring torus(accretion disk)

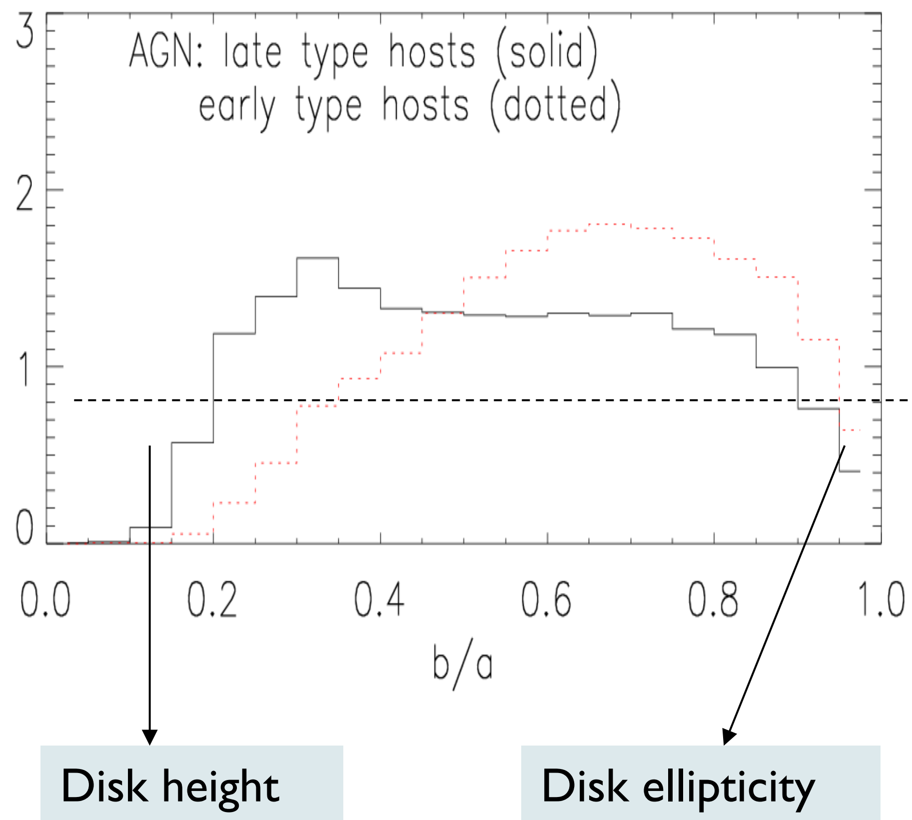
Hypothesis: if the stellar disks show alignment with accretion disk, the host galaxies of type II AGNs will also be biased to edge-on

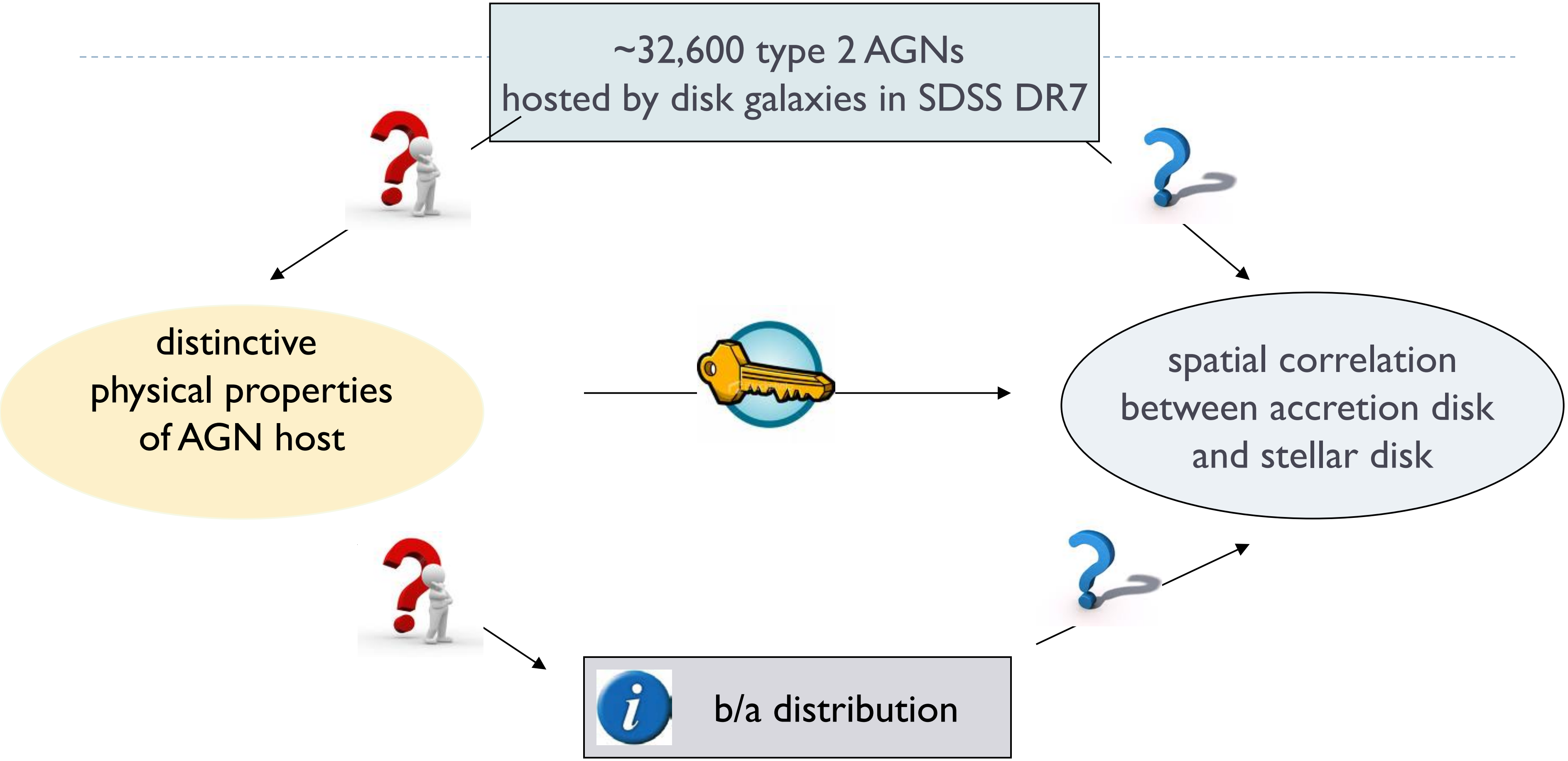


AGNs hosted by disk galaxies

- b/a of disk galaxies
  - approximate the inclination of disk
- fracDev<0.5: select disk galaxies
  - $F_{comp} = \text{fracDeV}\ F_{deV} + (1 - \text{fracDeV})\ F_{exp}$
  - ~40% of galaxies are spiral
- AGNs hosted by disk galaxies
  - BPT diagram
  - ~30% of AGNs hosted by spirals

$N_{AGN,spiral}$=32,618

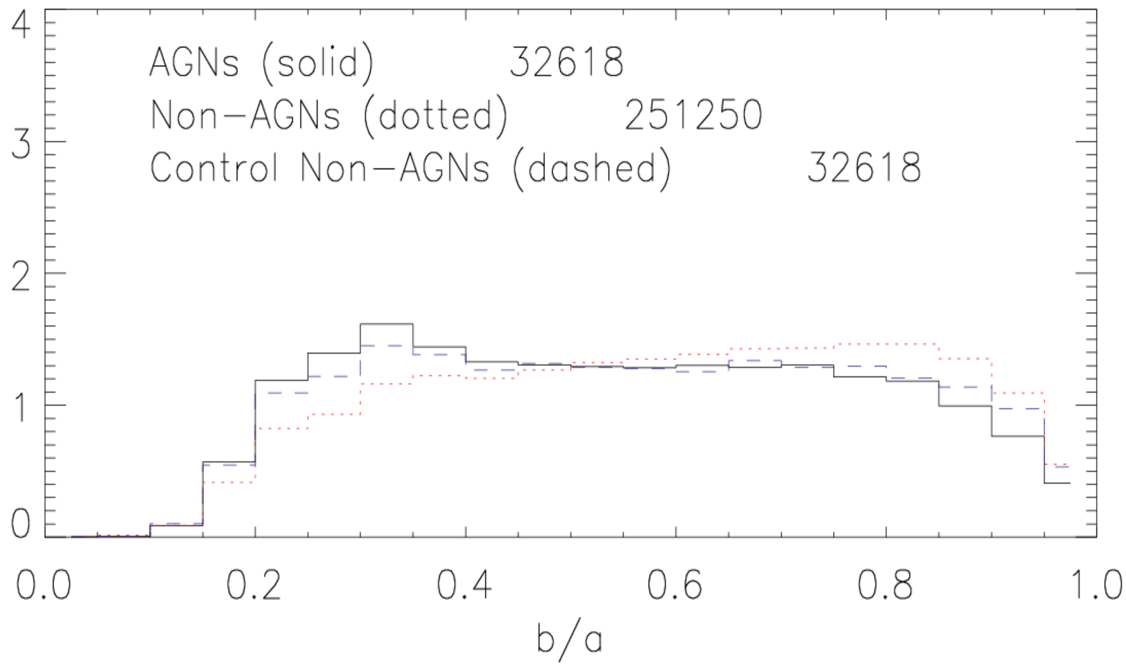




A control sample with the same physical properties as AGN hosts

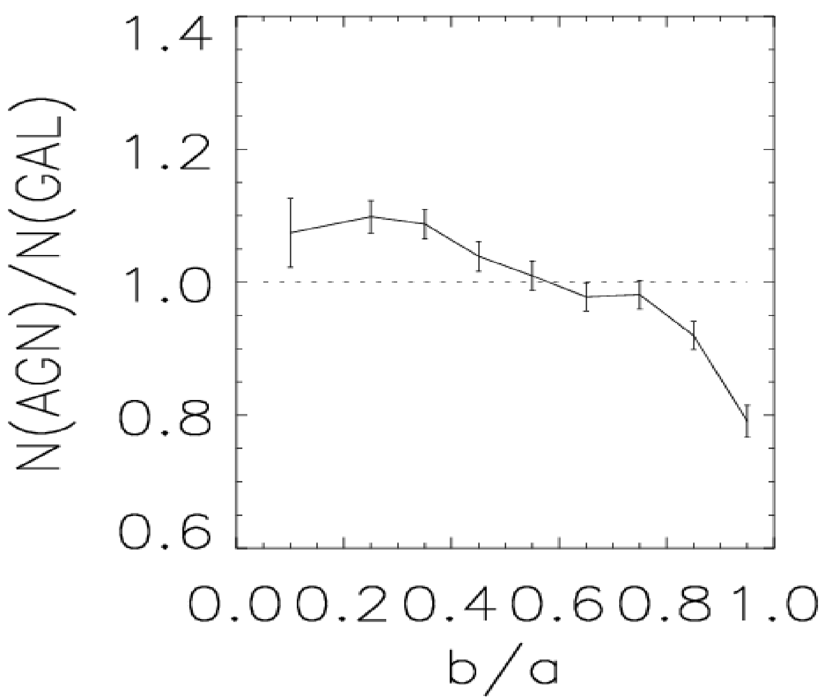
Control sample of non-AGN galaxies

- The same distributions of
  - ✓ Stellar mass
  - ✓ Redshift
  - ✓ Concentration
  - ✓ D4000
  - ✓ R50
  - ✓ FracDev



Type 2 AGN hosts are biased to low inclination(edge-on) disks!

The orientation of the accretion disk and stellar disk is correlated.



How to quantify this result?

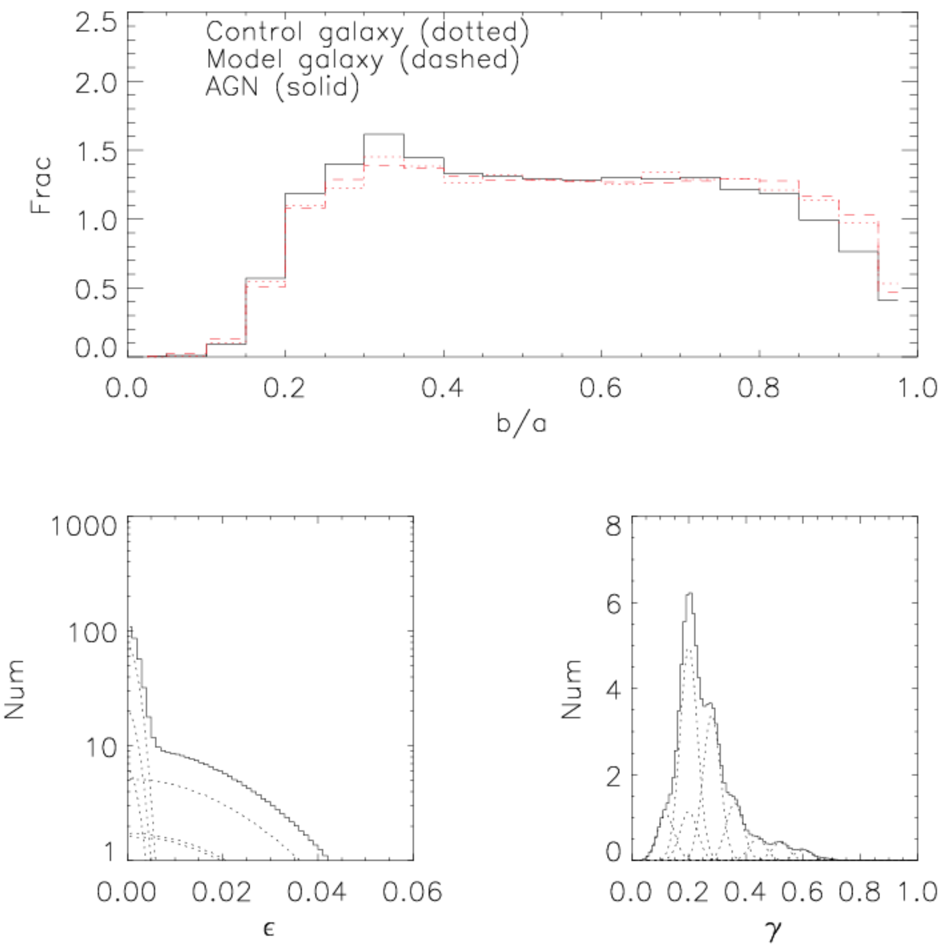
The shape of spiral galaxies

- Incl= f(b/a| $\gamma,\varepsilon,\theta,\psi$)

- (γ, ε) stellar disk structure parameter
  - γ= C/A :disk height
  - ε= (1-B/A) : disk ellipticity
  - AGN hosts have the same (γ, ε) distribution as control galaxies!

- (θ, ψ) viewing angle
  - θ: inclination ψ : position angle
  - Control galaxies: random
  - AGN hosts: preferred angle?

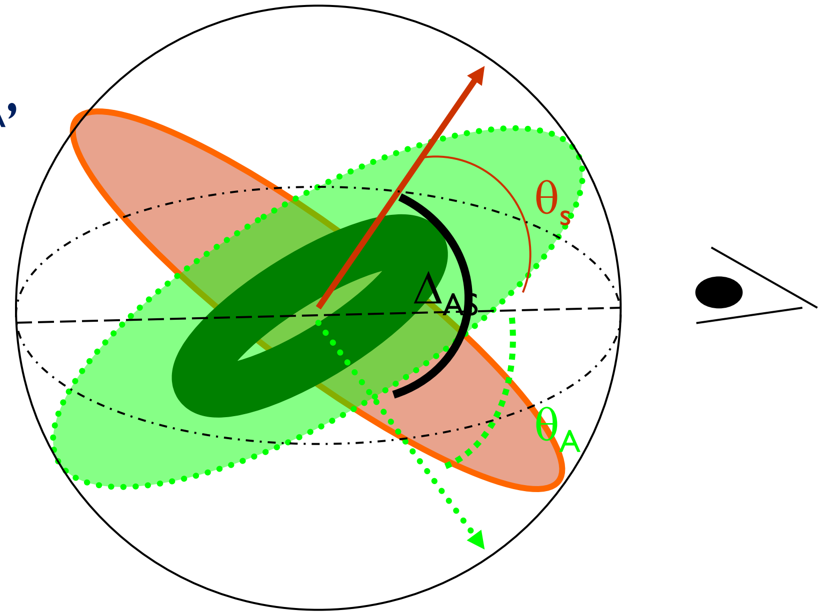
γ , ε distributions

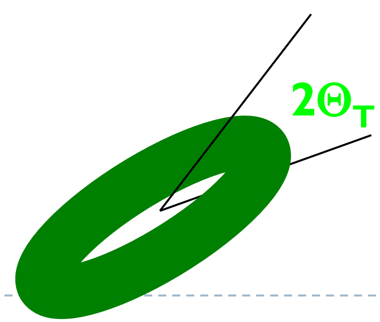


Non-negative least square linear regression

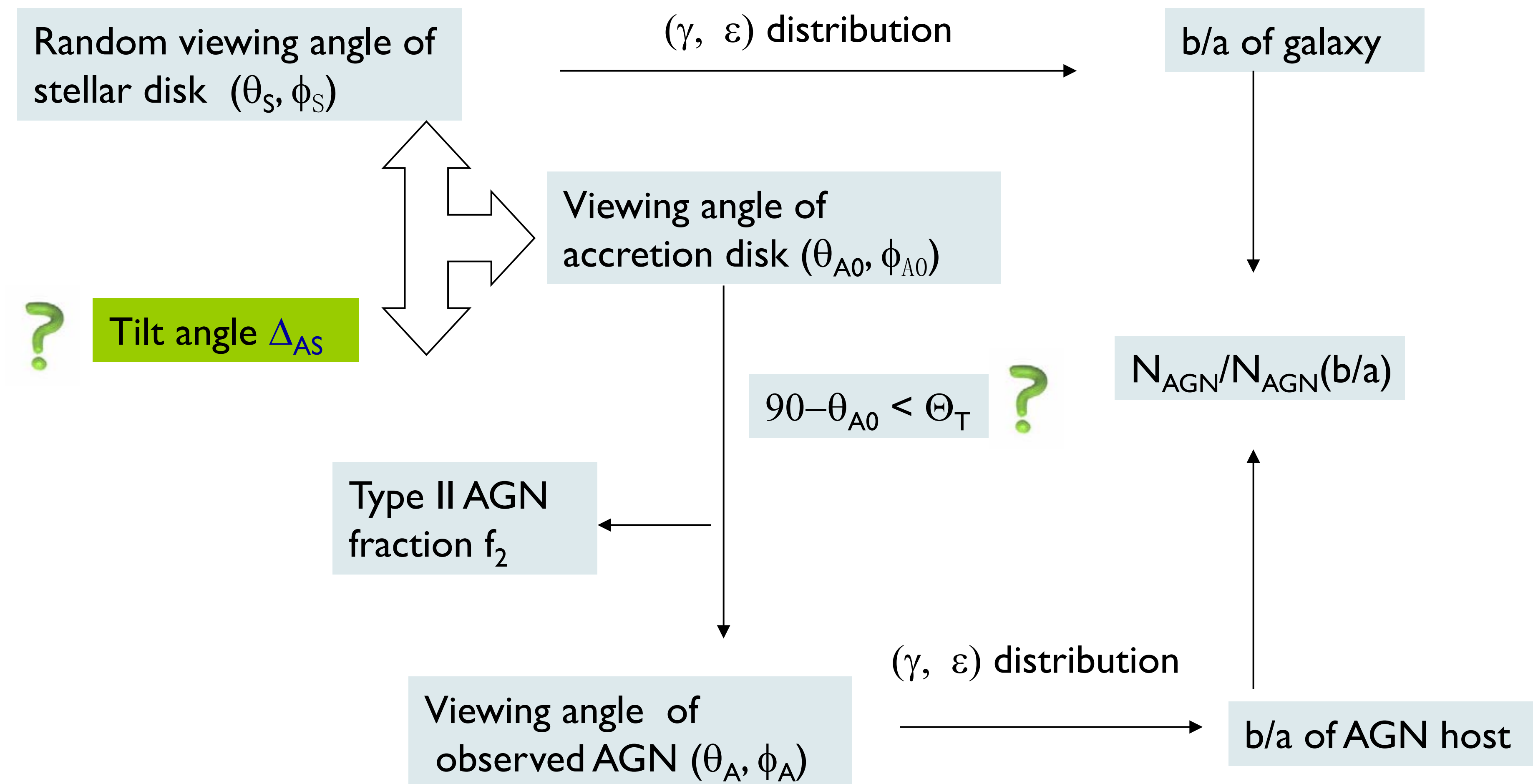
viewing angle of AGN hosts

- Viewing angle of stellar disk (θ_S, ϕ_S)
- Viewing angle of accretion disk (θ_A, ϕ_A)
- Tilt angle between accretion disk and Tilt stellar disk Δ_{AS}
- Opening angle of torus Θ_T
  - Type II AGN: $90-\theta_A < \Theta_T$



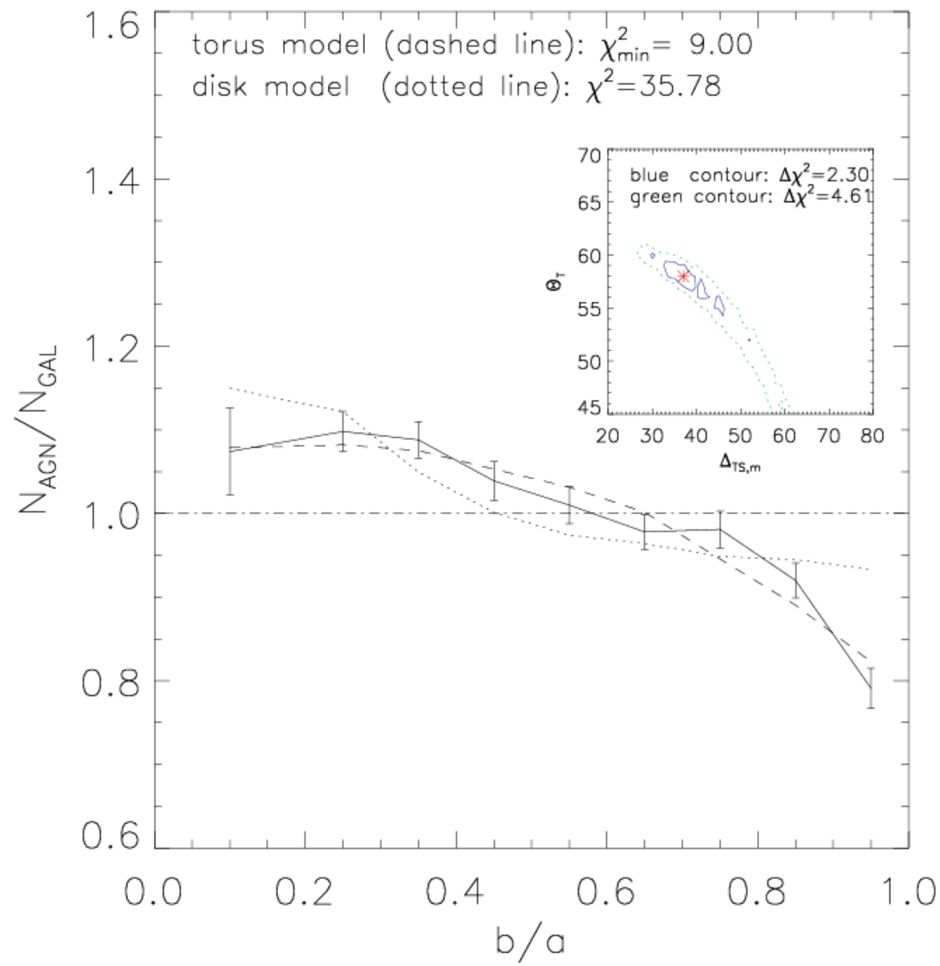


Toy model


Random viewing angle of stellar disk (θ_S, ϕ_S)
(γ, ε) distribution
b/a of galaxy
Viewing angle of accretion disk (θ_{A0}, ϕ_{A0})
Tilt angle Δ_{AS}
$N_{AGN}/N_{AGN}(b/a)$
$90-\theta_{A0} < \Theta_T$
Type II AGN fraction f_2
(γ, ε) distribution
Viewing angle of observed AGN (θ_A, ϕ_A)
b/a of AGN host

Model results

- If Δ_{AS} random
  - $\cos\Delta_{AS}$: uniform distribution
  - $N_{AGN}/N_{GAL}=1$
- Non-random Assumption
  - $\cos\Delta_{AS}$ follows Gaussian distribution, with most probable value $\Delta_{AS}=0$, scatter $\Delta_{As,m}$
  - $\Delta_{AS,m}=37$ deg
- Θ_T: free parameter
  - $\Theta_T=58$ deg
  - $f_2=80\%$: in excellent agreement with the results in literature!



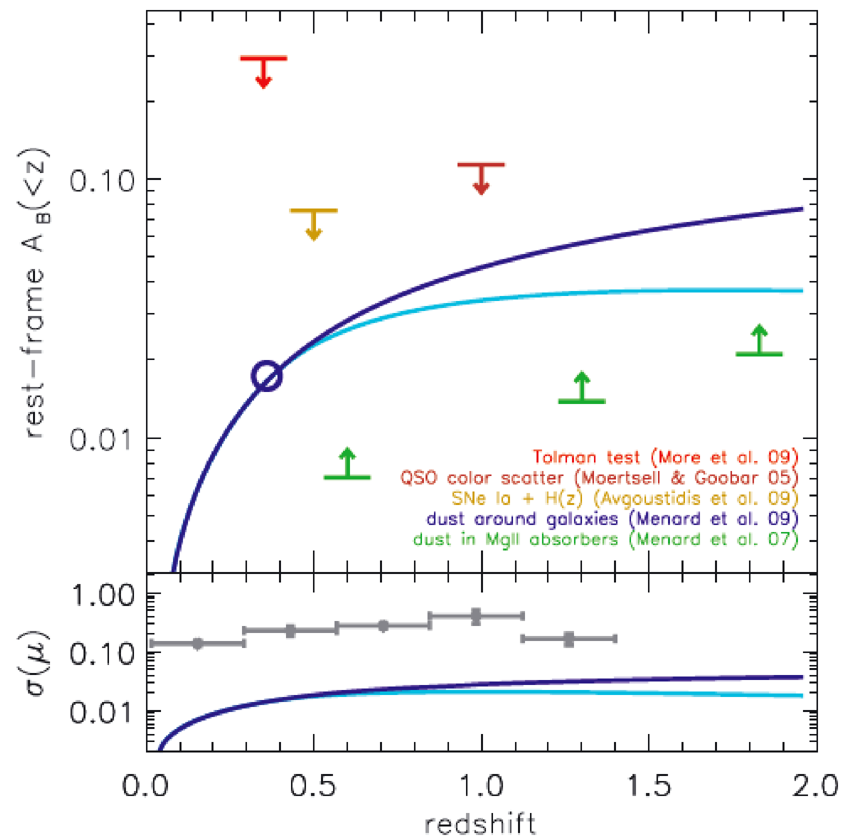
Summary on the tilt angle between accretion disk and stellar disk

- The AGN host galaxies(if they are spirals) are more likely to be viewed as edge-on.
  - Consistent result from radio AGNs (new, arXiv:1412.5602)

- The bias in the axis ratio (inclination) of the AGN hosts can be explained with a simple model that
  - the opening angle of the torus is ~60 degree
  - the mean tilt angle between the accretion disk and stellar disk is ~30 degree

(III) The cosmic dust extinction (Xie, Shen & Shao, 2014, ApJL submitted)

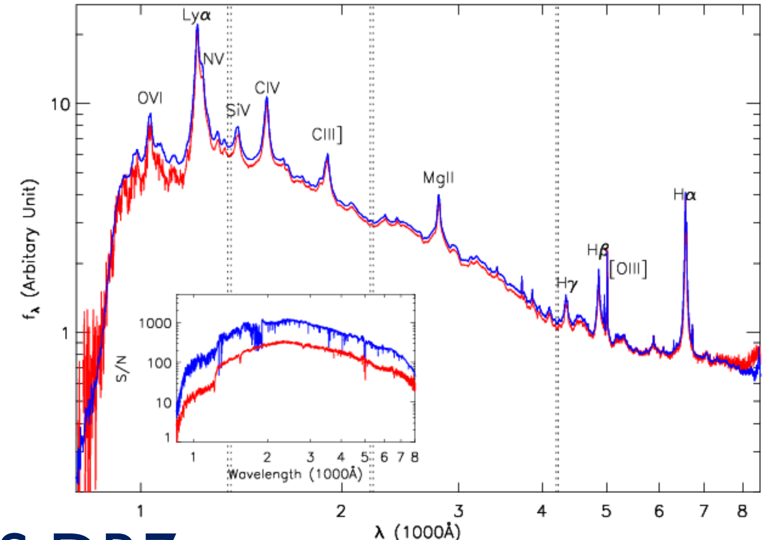
- SN Ia cosmology
  - Standard candle
- Cosmic dust extinction?
  - How to measure it?
    - Reddening of background sources(Menard et al. 2010)
    - Compare luminosity distance and angular distance (More et al. 2009)
    - Quasar color (Johanson & Mortsell 2012)



Menard et al. 2010

The quasar composite spectrum

- The mean quasar spectrum
  - High S/N
  - large wave-length coverage
  - Quasar spectra are similar



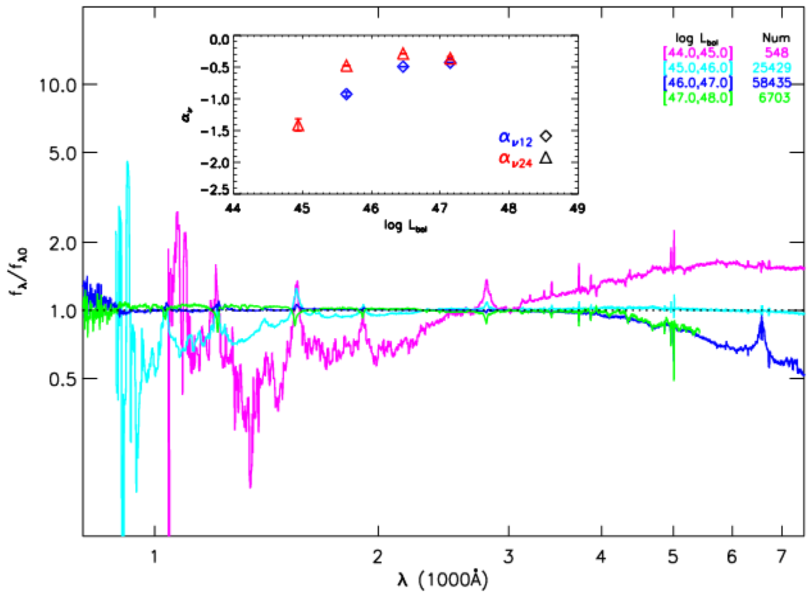
- Composite spectrum from SDSS DR7
  - Better redshifts (Hewett & Wild 2010)
  - Better Sky subtraction(Wild & Hewett 2010)
  - Physical parameters of each quasar (Shen et al. 2010)
  - Exclude radio-loud and broad absorption line quasars

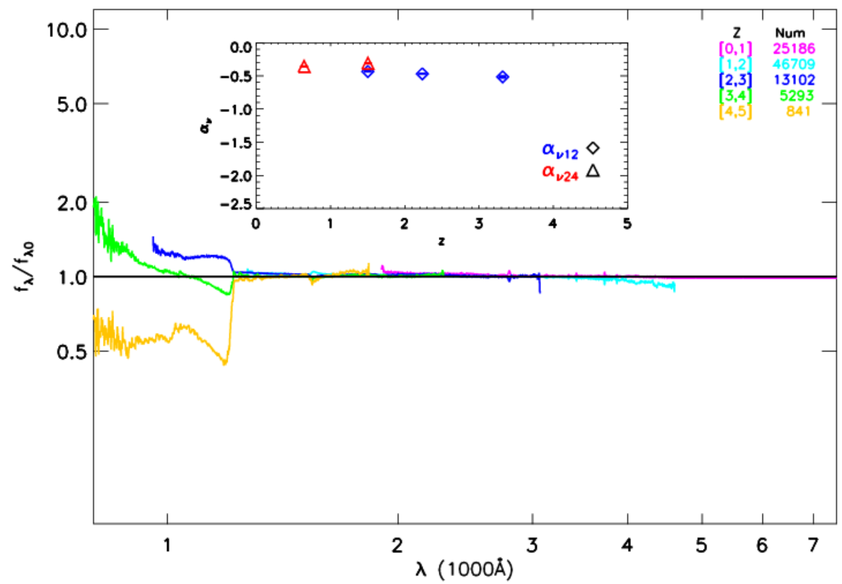
Quasar spectrum: any dependence?

- Luminosity dependence
  - UV continuum of higher luminosity quasars is harder (Telfer et al. 2002; Davis et al. 2007; Carballo et al. 1999).

- Redshift dependence (evolution)?
  - slight hardening of the spectra towards higher redshift (Kuhn et al. 2001; Carballo et al. 1999
  - no evolution (Pentericci et al. 2003)
  - Shallow (redder) at high redshifts (Wright 1981)

Our results



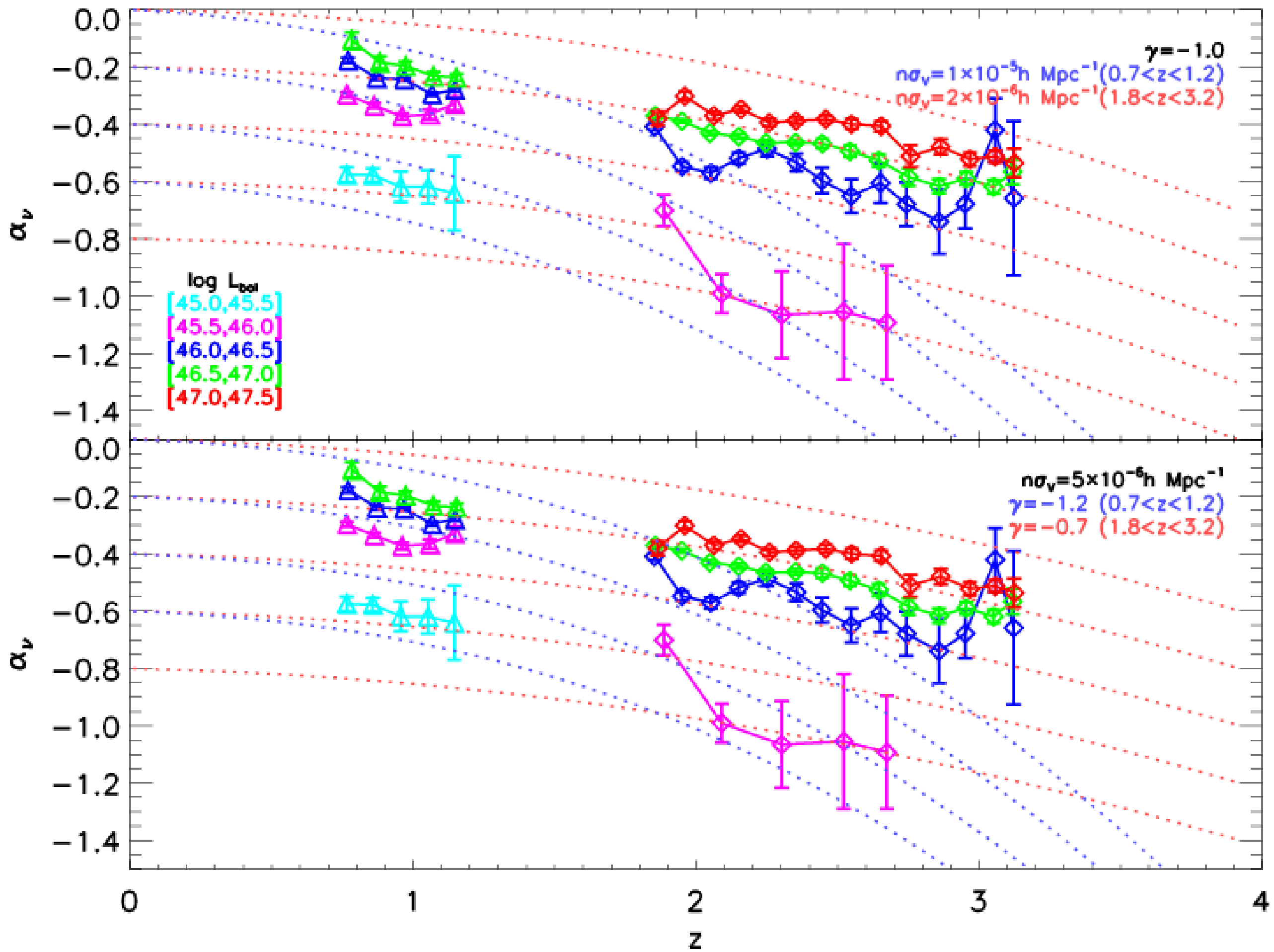


Luminosity dependence!

No redshift dependence?

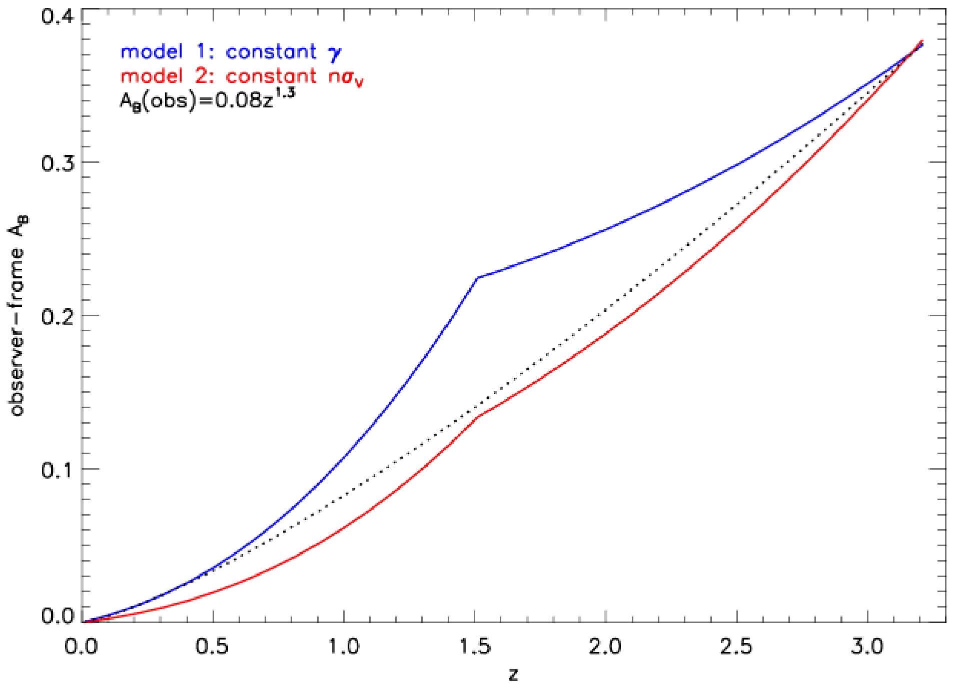
SDSS quasars are flux-limited sample, correlation between luminosity and redshift!

Redshift dependence after luminosity constrained



What makes the quasars at higher redshifts being redder?

- Physical evolution?
- Quasar host galaxies?
  - High z galaxies are more transparent
- Selection effects?
- Cosmic dust extinction
  - A_B ~0.1 z
  - Up to redshift z~3



Summary on the redshift dependence of quasar composite spectrum

- We find a redshift dependence of the UV slope of the quasar spectrum
  - The quasars are redder at higher redshift.

- This reddening can be explained by the cosmic dust extinction
  - The average extinction is about $A_B \approx 0.1z$.

Summary

- Modern galaxy survey , like the Sloan Digital Sky Survey(SDSS), provides unprecedented large sample of galaxies and AGNs(QSOs) for statistical study.

- Besides the classical statistical studies, e.g. (conditional) distribution function, scaling relations,
  - the large sample of galaxies and AGNs can be used to test many hypothesis in the modelling of the galaxy formation and evolution
  - once the selection effects have been properly taken into account

Key ingredients of statistical applications

- Large sample
  - Case I: the statistical nature of the brightest group galaxies
    - Thanks to the largest group catalog of Yang et al.
- Selection effects: control sample
  - Case II: the tilt between the accretion disk and stellar disk
    - A control sample of non-AGN galaxies with the other properties controlled
- Statistical hypothesis
  - Case III: the cosmic dust extinction: implications from quasar composite spectrum
    - Our key assumption: Quasars are redder at higher redshifts due to the cosmic dust extinction.

Take-home message

- Out statistical applications show
  1. The brightest group/cluster galaxies are special, but not distinct from other members. They are formed in a statistical process and later brightened (~0.2 mag) by local processes.

  2. There is an alignment between the accretion disk and stellar disk for AGNs hosted by spirals, the typical tilt angle ~30 deg.

  3. The cosmic dust extinction can be probed from the composite quasar spectra up to z~3, the typical extinction A_B~0.1*z.

Thanks for your attention

MERRY CHRISTMAS