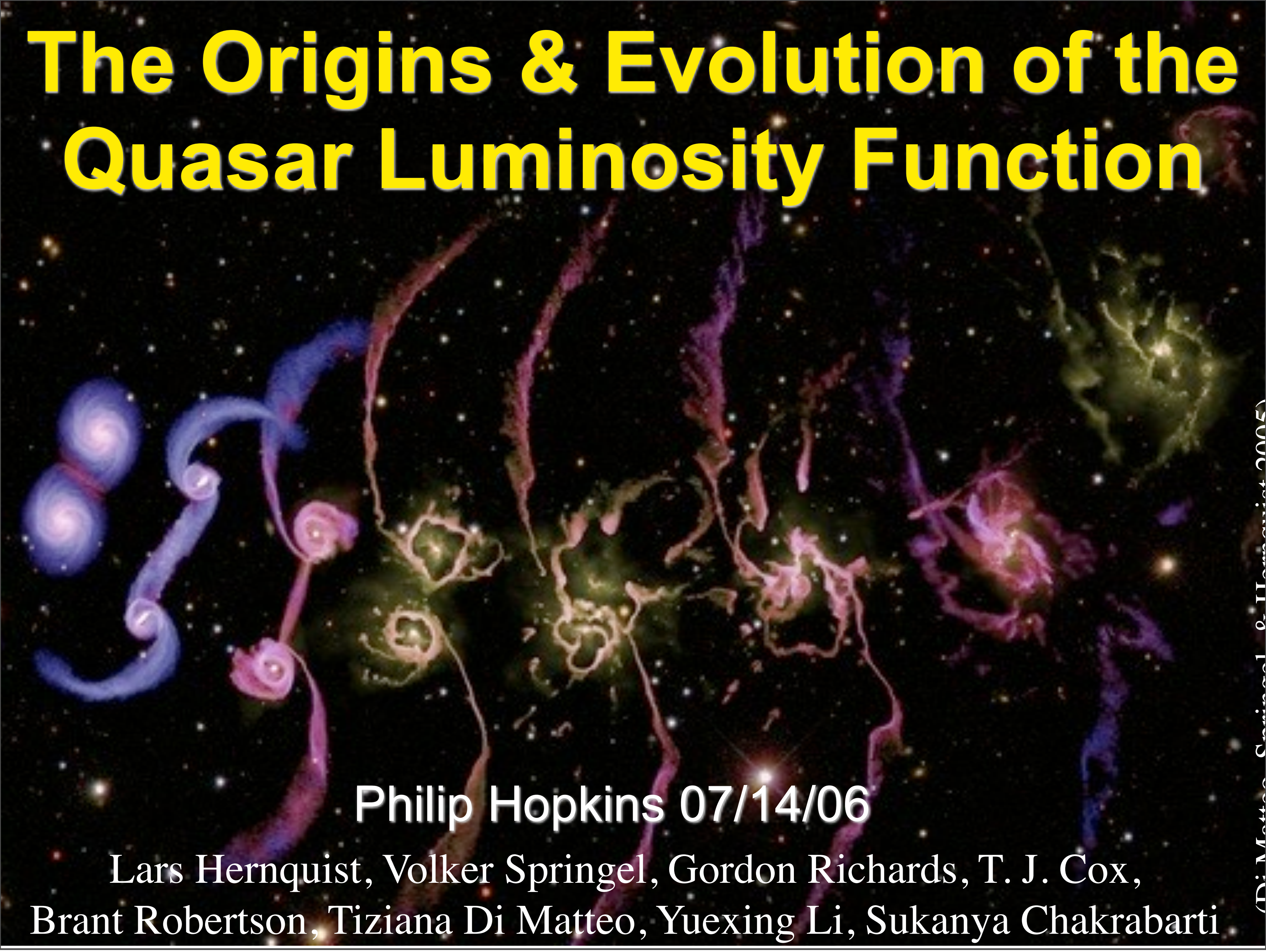

The Origins & Evolution of the
Quasar Luminosity Function
Philip Hopkins 07/14/06
Lars Hernquist, Volker Springel, Gordon Richards, T. J. Cox,
Brant Robertson, Tiziana Di Matteo, Yuexing Li, Sukanya Chakrabarti
(Di Matteo, Springel, & Hernquist 2005)

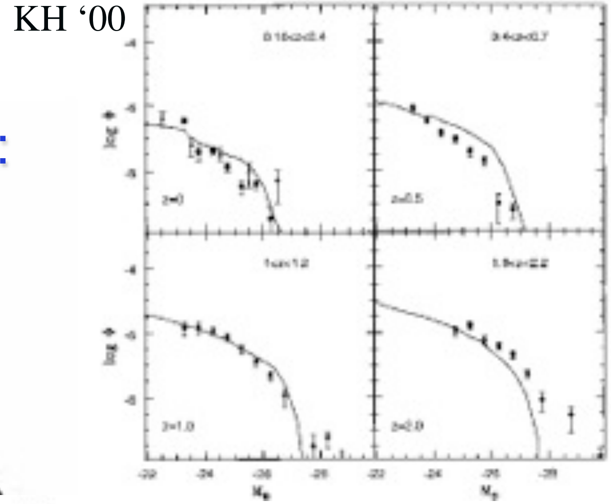
A subset of recent quasar samples...

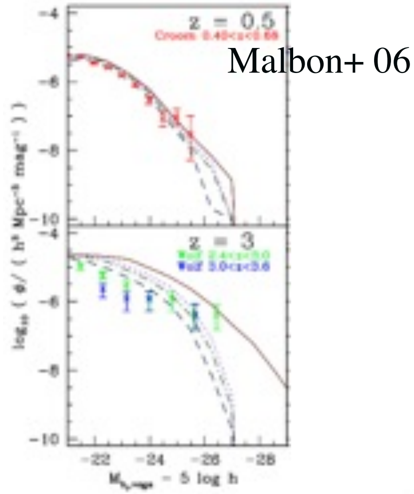
TABLE 1
MEASUREMENTS OF THE QLF

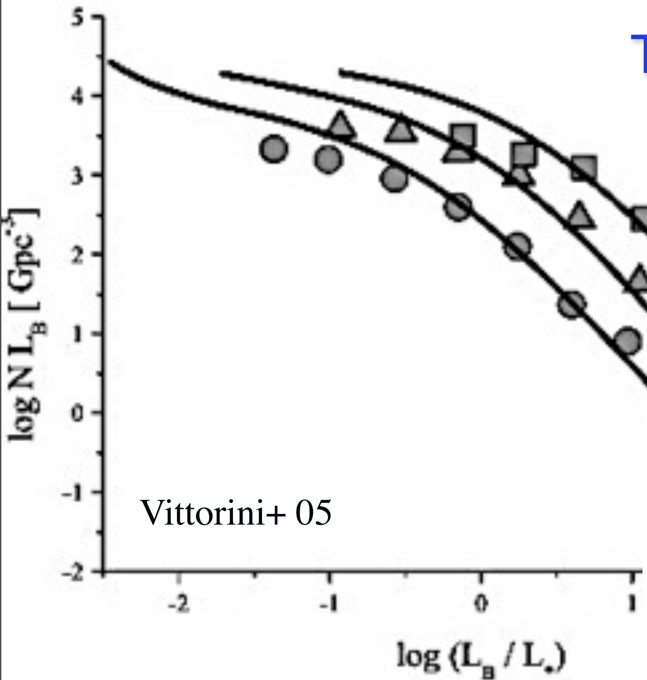
Reference	Survey/Field[a]	Rest Wavelength/Band	z Range[b]	Luminosity Range[b]	χ^2/ν[c]	N_{AGN}	Plotting Symbol
Optical:							
Cristiani et al. (2004)	GOODS	1450 Å	$\sim 4-5.2$	$-21 > M_{1450} > -23.5$	0.58/1	$1-4$	crosses
Croom et al. (2004)	2QZ/6QZ	B	$0.4-2.1$	$-20.5 > M_g > -28.5$	23.1/10	20,905	asterisks
Fan et al. (2001a)	SDSS (Equatorial Stripe)	1450 Å	$3.6-5.0$	$-25.5 > M_{1450} > -27.5$	6.21/9	39	pentagons
Fan et al. (2001b, 2003, 2004)	SDSS (Main & Southern Survey)	1450 Å	$\sim 5.7-6.4$	$-26.5 > M_{1450} > -28$	2.12/3	9	...
Hunt et al. (2004)	LBG survey	1450 Å	$\sim 2-4$	$-21 > M_{1450} > -27$	4.74/6	11	diamonds
Kennefick et al. (1995)	*POSS*	B	$4.0-4.5$	$-26.5 > M_B > -28.5$	14.8/2	10	triangles
Richards et al. (2005)	2dF-SDSS	g	$0.3-2.2$	$-21 > M_g > -27$	137/99	5,645	circles
Richards et al. (2006b)	SDSS (DR3)	$i(z=2) \sim 2500$ Å	$0.3-5.0$	$-22.5 > M_i > -29$	247/101	15,343	squares
Schmidt et al. (1995)	*PTGS*	B	$\sim 3.5-4.5$	$-25.5 > M_B > -27.5$	8.04/4	8	inverted triangles
Siana et al. (2006)	SWIRE (ELIAS-N1/N2)	1450 Å	$\sim 2.8-3.4$	$-23.5 > M_{1450} > -26.5$	4.74/6	$\sim$100	crosses
Wolf et al. (2003)	COMBO-17	1450 Å	$1.2-4.8$	$-23.5 > M_{1450} > -28.5$	54.2/27	192	stars
Soft X-ray:							
Hasinger et al. (2005)	*ROSAT* (RASS+RDS) + CDF-N/S	$0.5-2$ keV	$0.015-4.8$	$10^{42} < L_{0.5-2} < 10^{48}$ erg s^{-1}	169/51	2,566	circles
Miyaji et al. (2000, 2001)	*ROSAT* (RASS+RDS)	$0.5-2$ keV	$0.015-4.8$	$10^{41} < L_{0.5-2} < 10^{47}$ erg s^{-1}	112/41	691	stars
Silverman et al. (2005b)	CHAMP+*ROSAT* (RASS)	$0.5-2$ keV	$0.1-5$	$10^{44.5} < L_{0.5-2} < 10^{46}$ erg s^{-1}	24.1/9	217	squares
Hard X-ray:							
Barger et al. (2003a,b)	CDF-N	$2-8$ keV	$\sim 5-6.5$	$10^{43} < L_{2-8} < 10^{45}$ erg s^{-1}	1.02/1	1	diamonds
Barger et al. (2005)	CDF-N/S + CLASXS + *ASCA*	$2-8$ keV	$\sim 0.1-1.2$	$10^{42} < L_{2-8} < 10^{46}$ erg s^{-1}	41.0/30	601	squares
...	CDF-N/S + CLASXS	$2-8$ keV	$\sim 1.5-5.0$	$10^{42} < L_{2-8} < 10^{46}$ erg s^{-1}	15.5/9	$\sim$100	...
Barger & Cowie (2005)	CDF-N/GOODS-N	$2-8$ keV	$\sim 2-3$	$10^{43} < L_{2-8} < 10^{44.5}$ erg s^{-1}	1.73/1	136	...
La Franca et al. (2005)	HELLAS2XMM	$2-10$ keV	$0.0-4.0$	$10^{42} < L_{2-10} < 10^{46.5}$ erg s^{-1}	14.4/18	508	stars
Nandra et al. (2005)	GWS + HDF-N	$2-10$ keV	$2.7-3.2$	$10^{43} < L_{2-10} < 10^{44.5}$ erg s^{-1}	0.77/1	15	crosses
Sazonov & Revnivtsev (2004)	RXTE	$3-20$ keV	$0.0-0.1$	$10^{41} < L_{3-20} < 10^{46}$ erg s^{-1}	9.75/10	77	inverted triangles
Silverman et al. (2005a,c)	CHAMP	$0.3-8.0$ keV	$0.2-4.0$	$10^{42} < L_{0.3-8} < 10^{45.5}$ erg s^{-1}	26.3/15	368	triangles
Ueda et al. (2003)	*HEAO* 1 + AMSS-n/s + ALSS + *ASCA* + CDF-N	$2-10$ keV	$0.015-3.0$	$10^{41.5} < L_{2-10} < 10^{46.5}$ erg s^{-1}	26.5/35	247	circles
Mid-IR:							
Brown et al. (2006)	*Spitzer* Boötes (NDWFS)	8 μm	$\sim 1-5$	$10^{45} < L_{8\,\mu m} < 10^{47}$ erg s^{-1}	3.77/10	183	circles
Matute et al. (2006)	RMS + ELIAS + HDF-N/S	15 μm	$\sim 0.1-1.2$	$10^{42} < L_{15\,\mu m} < 10^{47}$ erg s^{-1}	23.4/18	148	squares
Emission Lines:							
Hao et al. (2005)	SDSS (main galaxy sample)	Hα	$0-0.33$	$10^5 < L_{H\alpha} < 10^9 L_\odot$	29.5/21	$\sim$3000	pentagons
...	...	[OII]	...	$10^5 < L_{OII} < 10^8 L_\odot$	...	...	...
...	...	[OIII]	...	$10^5 < L_{OIII} < 10^9 L_\odot$	...	...	...

And yet...

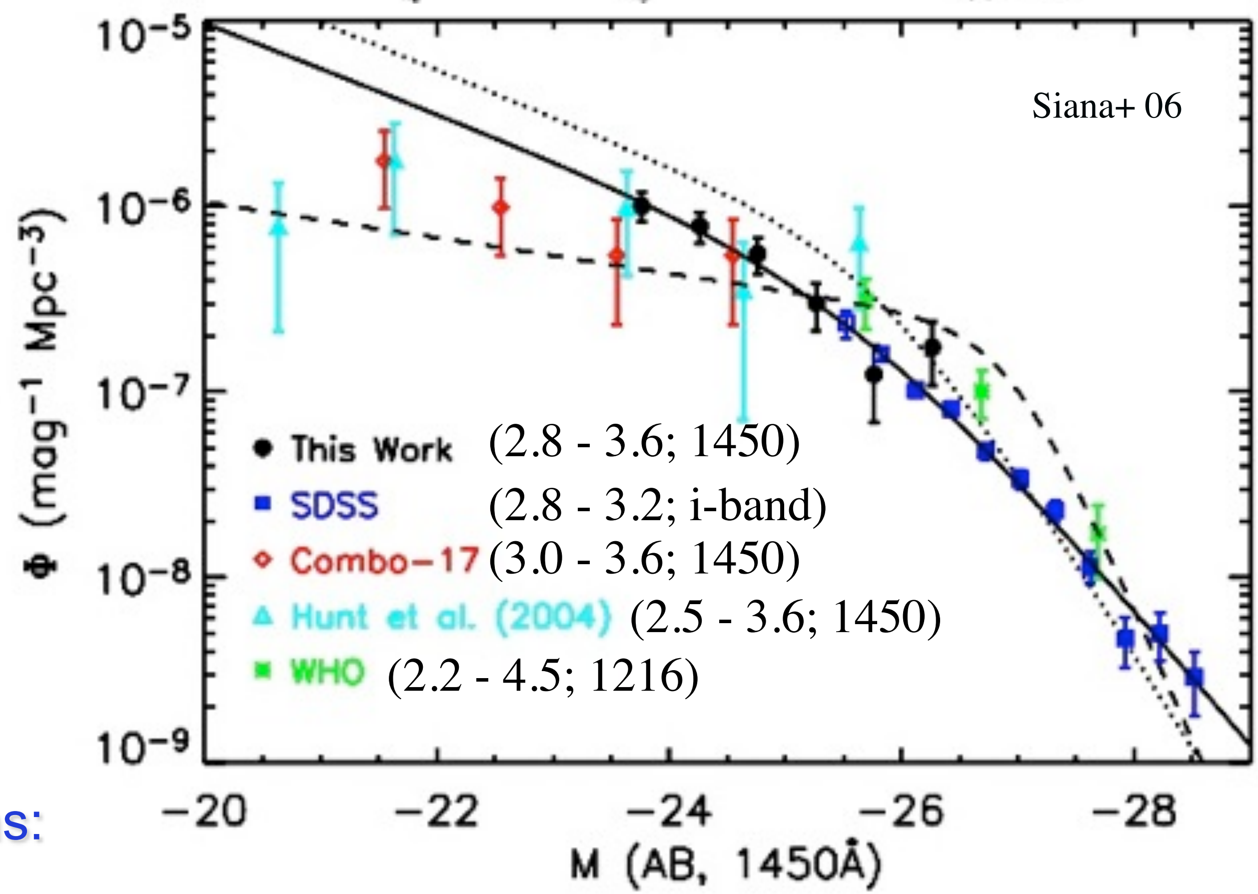
Theory:

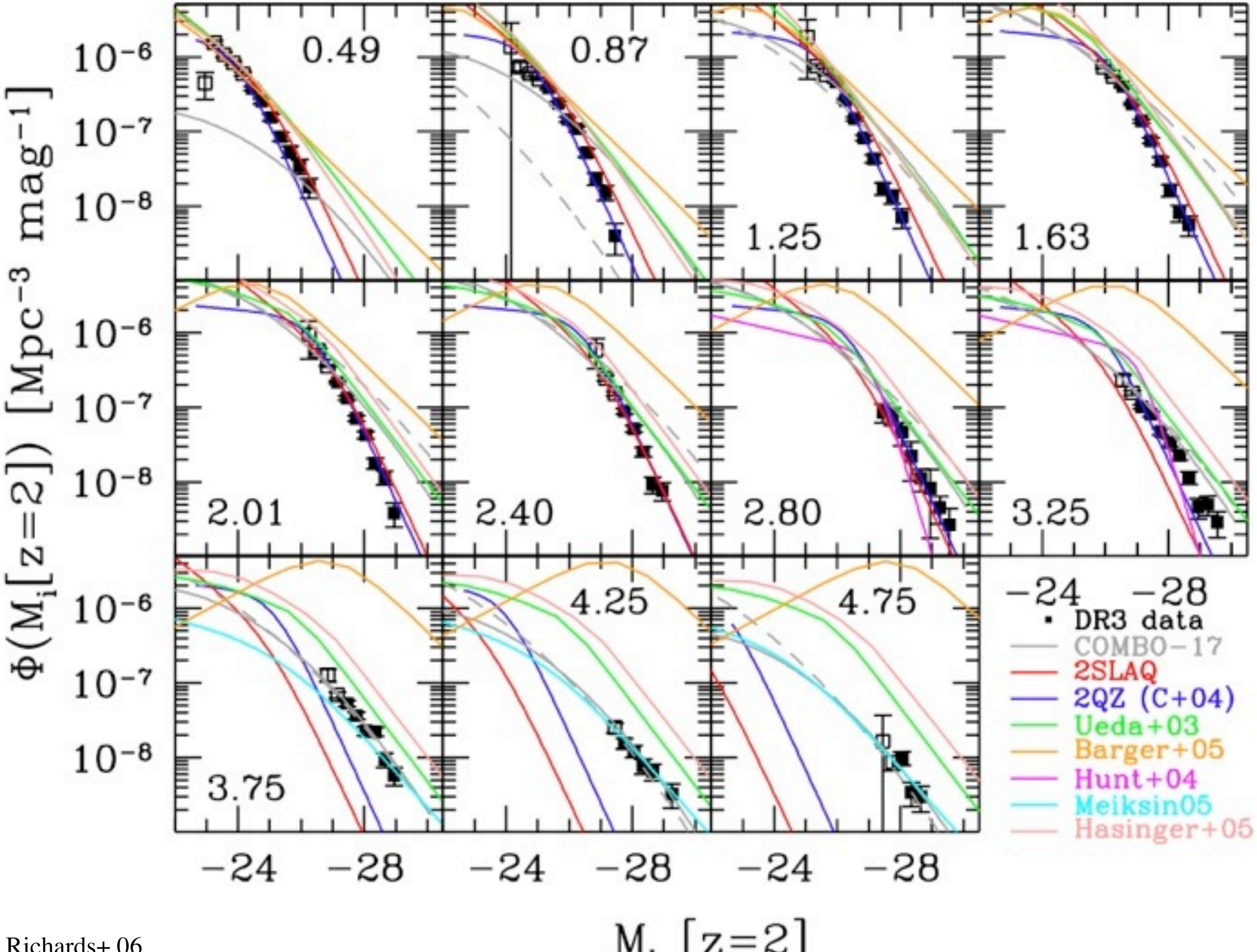






Observations:





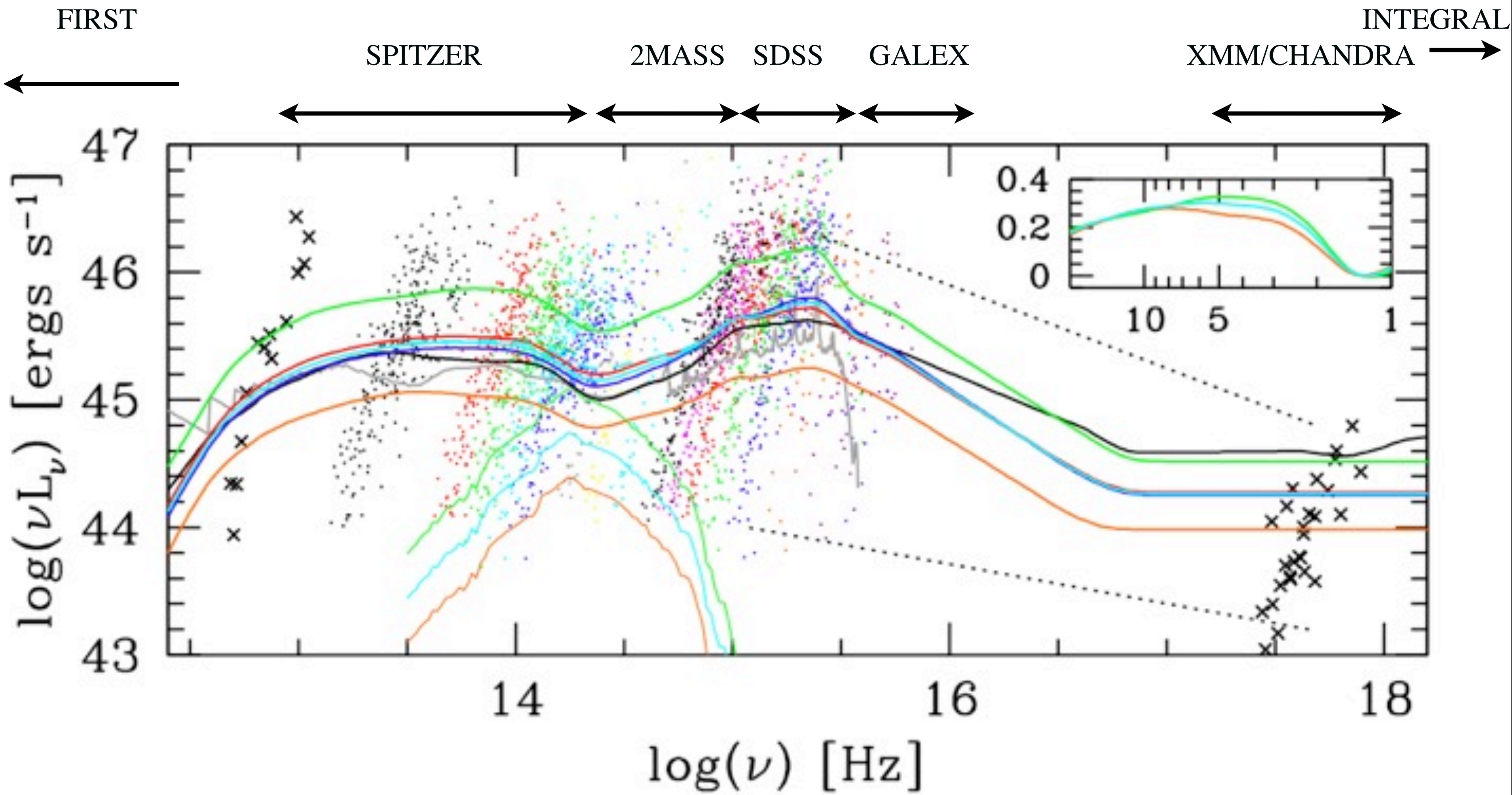
0.49
0.87
1.25
1.63
2.01
2.40
2.80
3.25
3.75
4.25
4.75
10^{-6}
10^{-7}
10^{-8}
−24
−28
DR3 data
COMBO-17
2SLAQ
2QZ (C+04)
Ueda+03
Barger+05
Hunt+04
Meiksin05
Hasinger+05
$\Phi(M_i[z=2])$ [Mpc^{-3} mag^{-1}]
M_i [z=2]

Richards+ 06

How to Address This?

METHODOLOGY

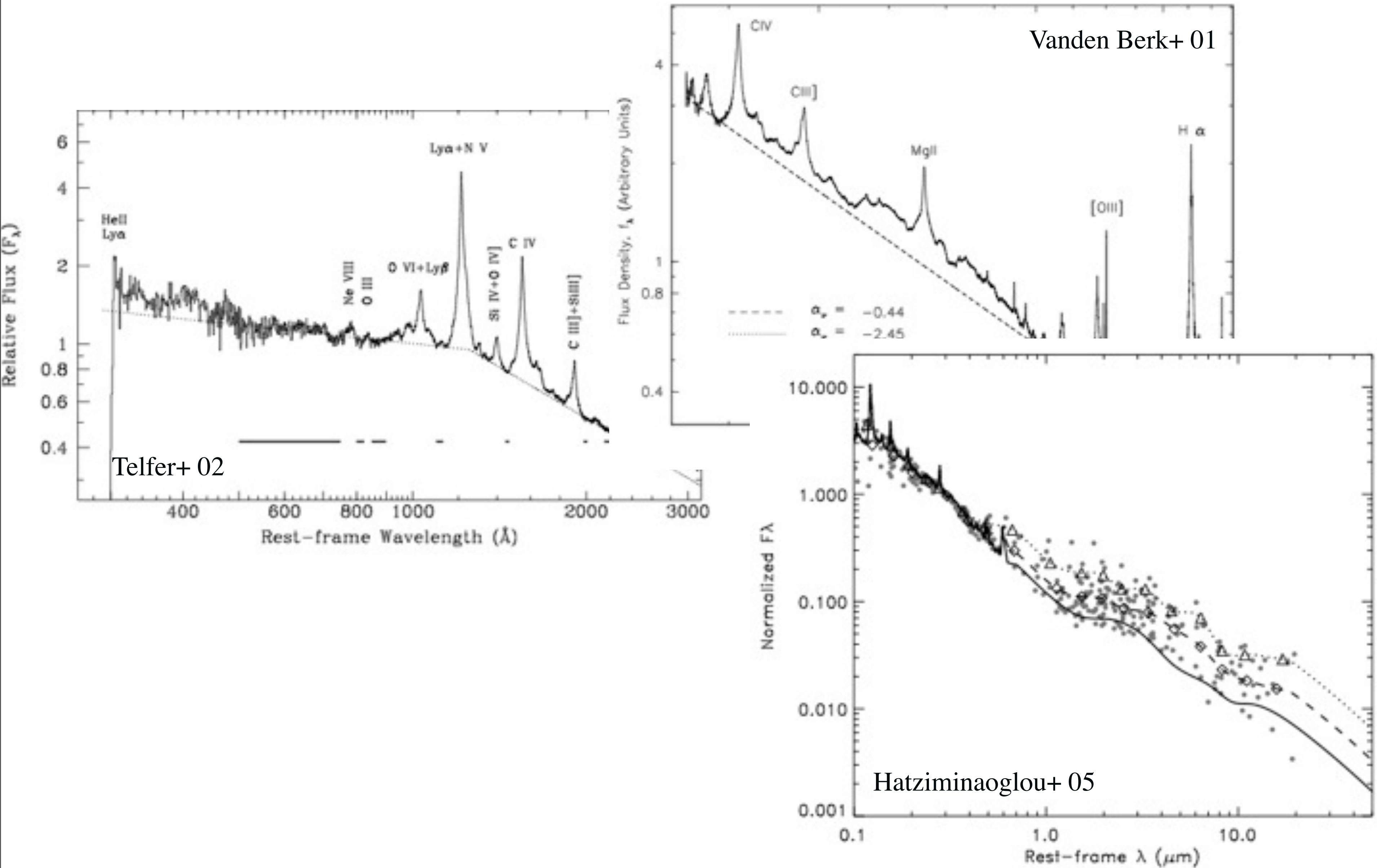
- Given bolometric Phi(L), convolve over SEDs:



Elvis+ 94; Vanden Berk+ 01; Telfer+ 01;
Ueda+ 03; Hatziminaoglou+ 05; Richards+ 06;

Methodology

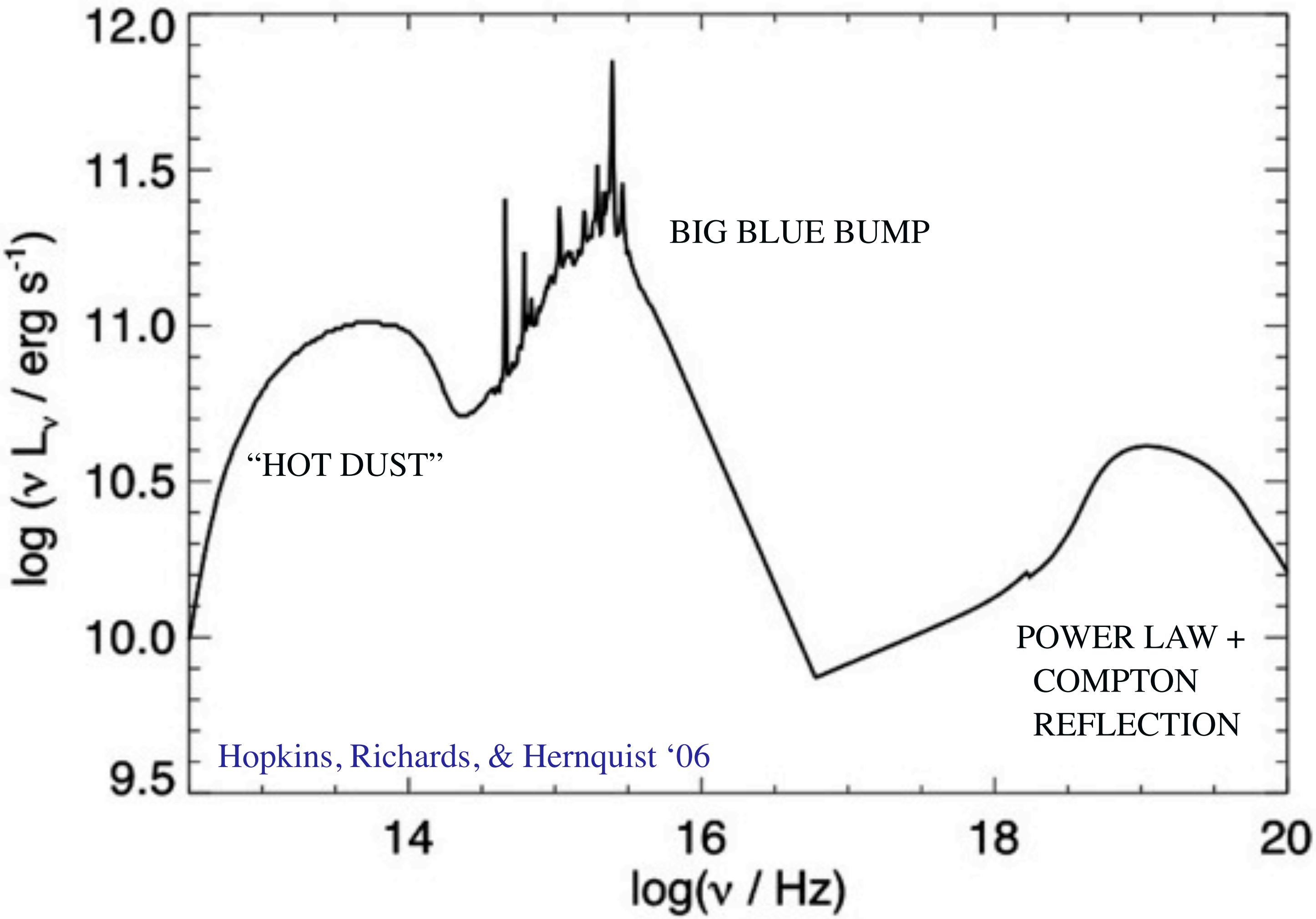
GIVEN A BOLOMETRIC PHI(L), CONVOLVE OVER KNOWN SEDs



Methodology

GIVEN A BOLOMETRIC PHI(L), CONVOLVE OVER KNOWN SEDs

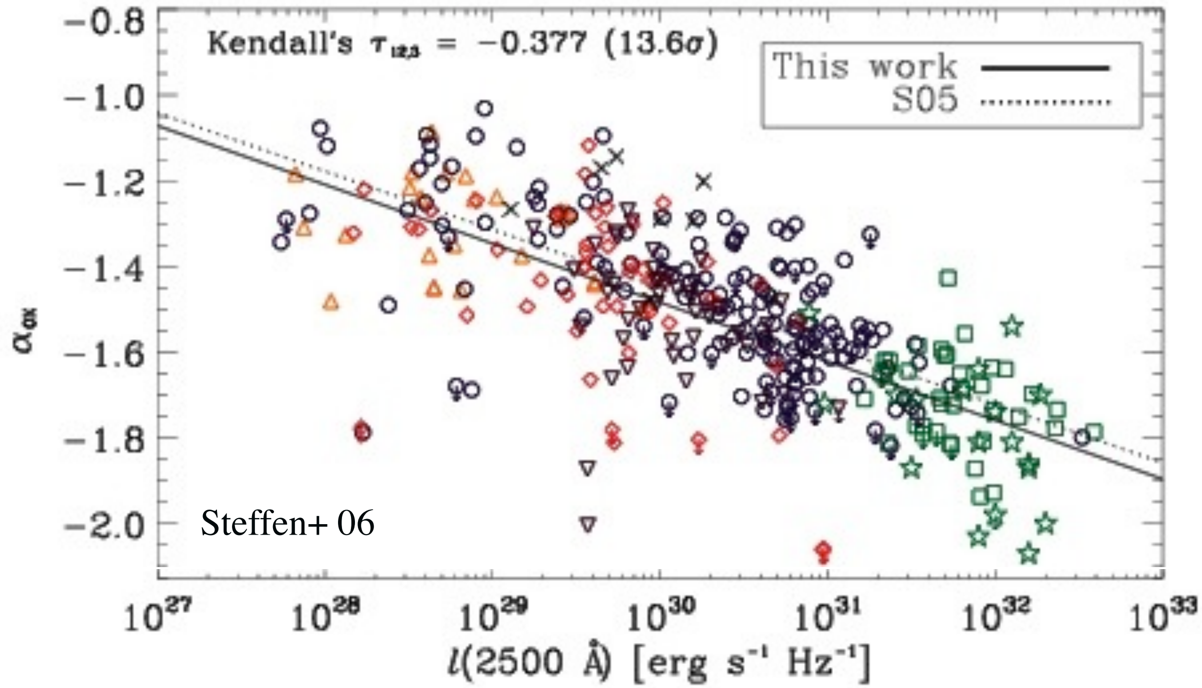
- Want the “intrinsic” SED (e.g. Marconi+ ‘04)
  - Type 1, un-obscured/un-reddened, subtract host light

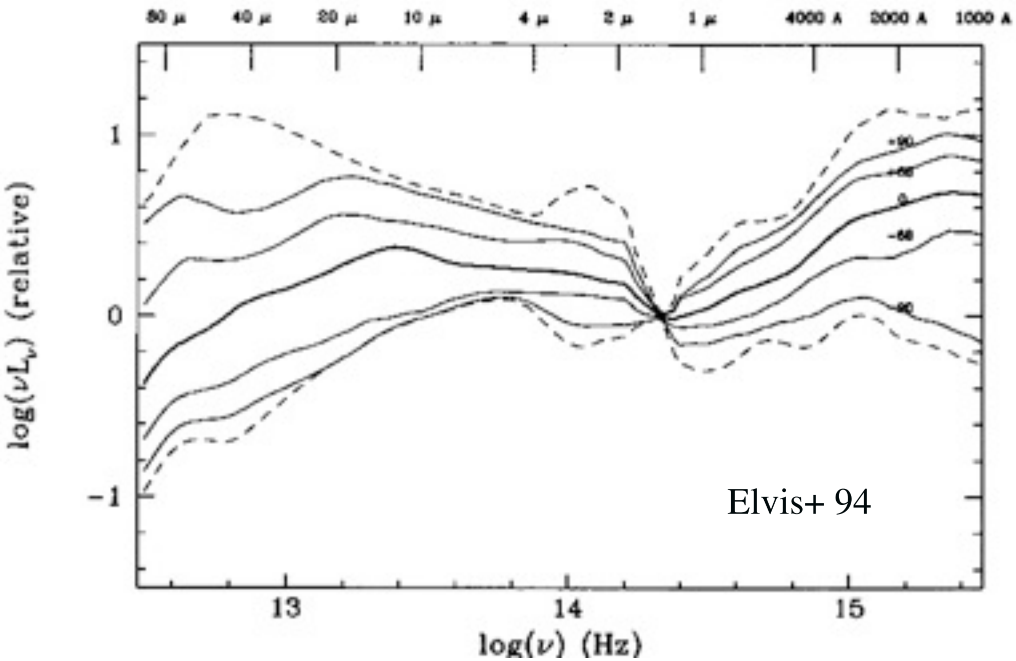


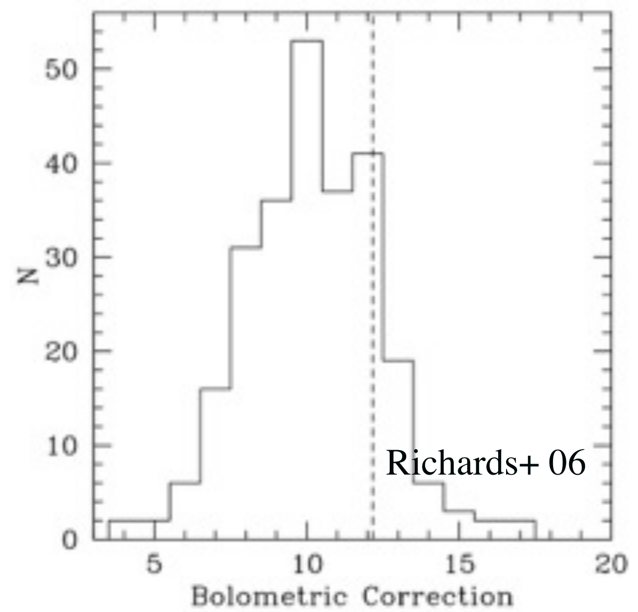
Methodology

MORE THAN ONE SED

- Dependence on L
- Distribution of SED shapes
  - Remove obscuration component



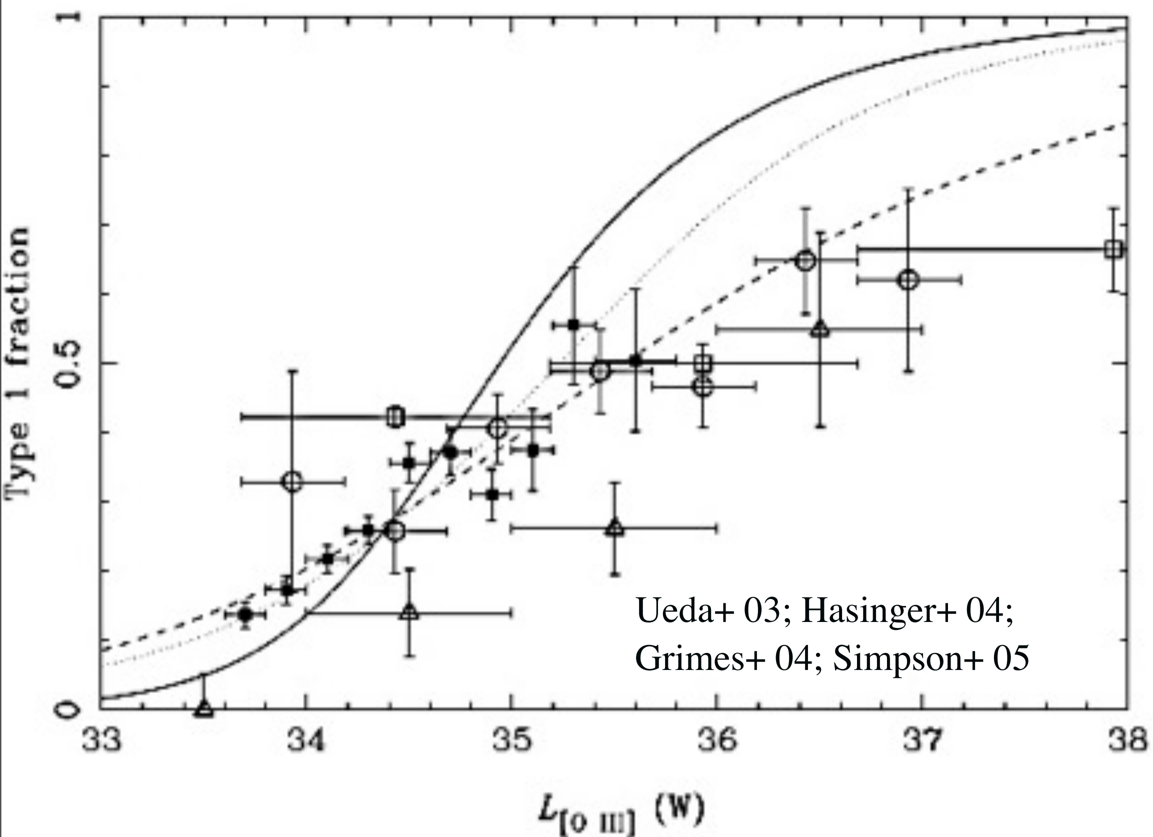


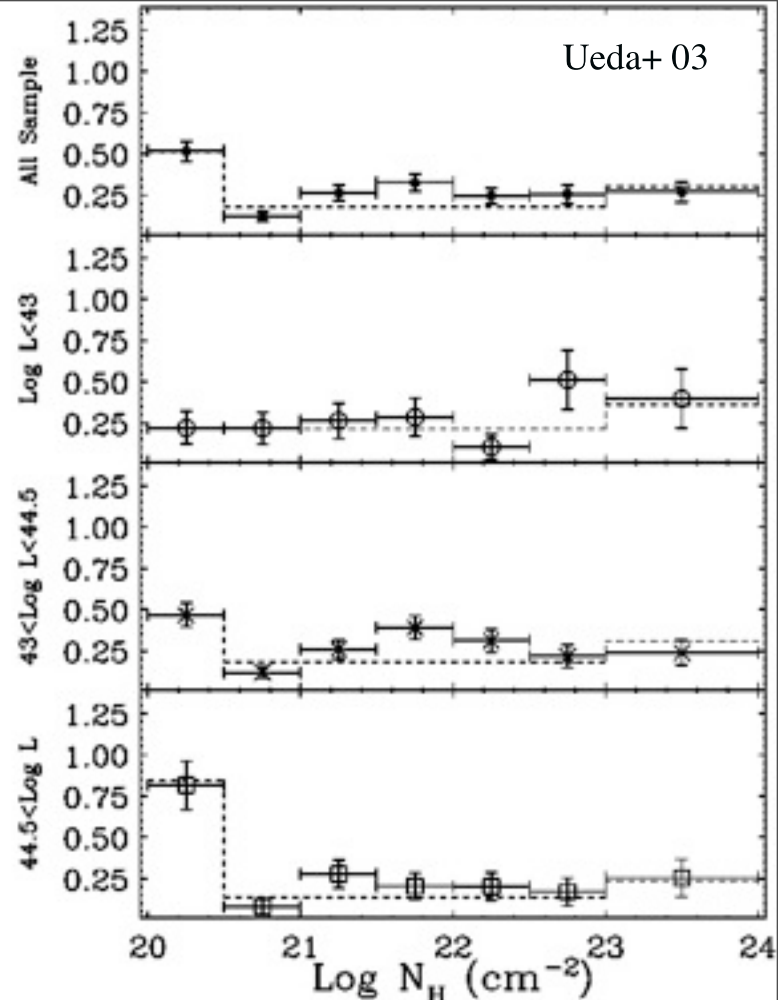


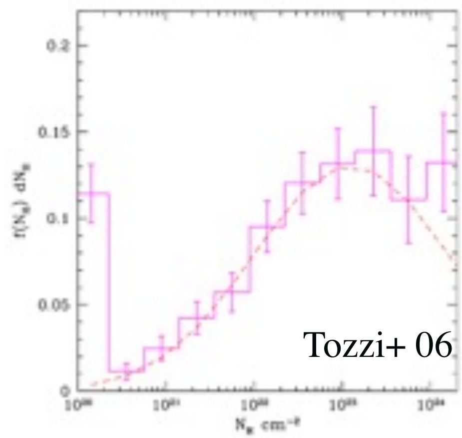
Methodology

OBSCURATION

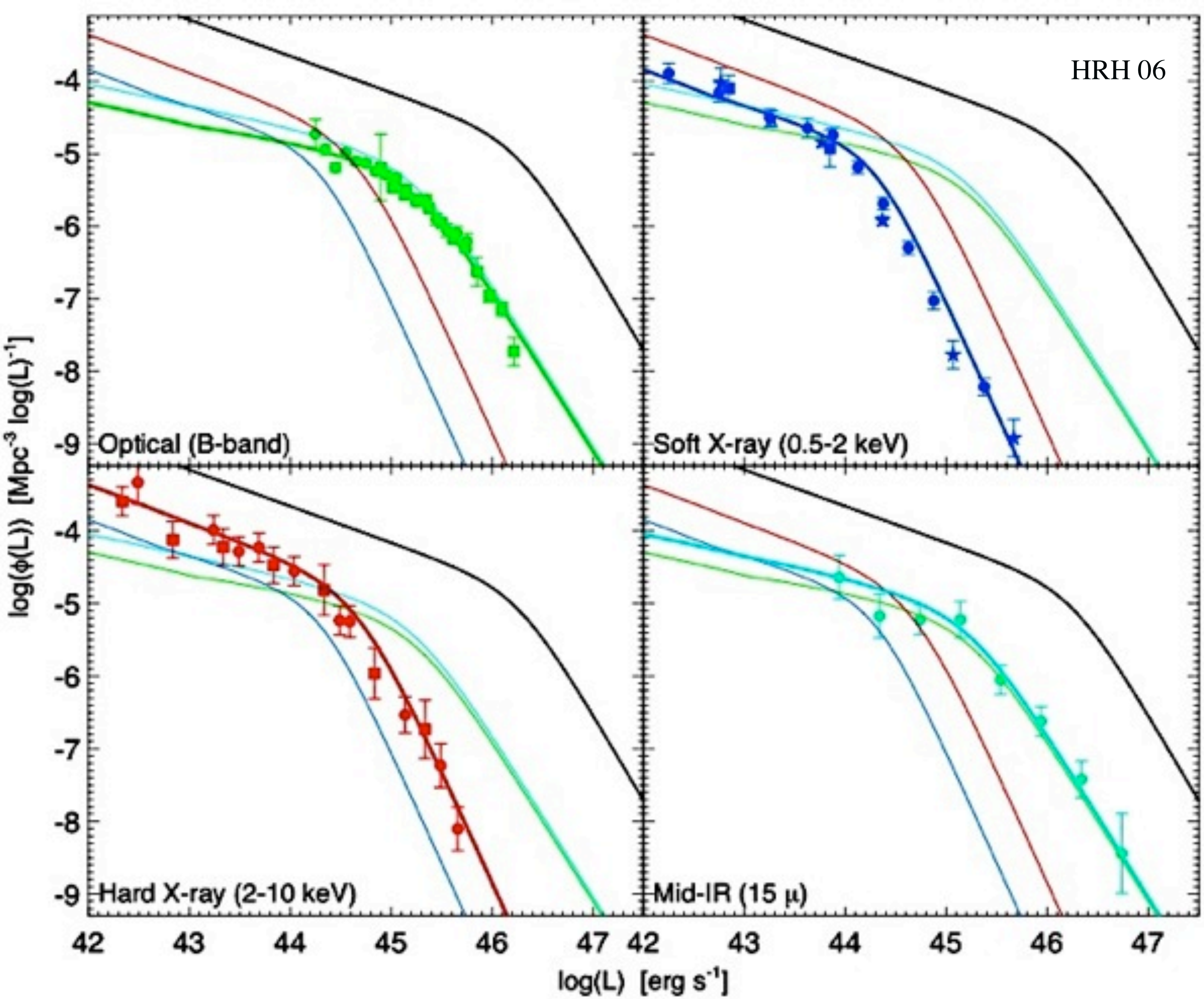
- Then convolve over NH distributions
  - Include Compton-thick
  - Dependence on L:





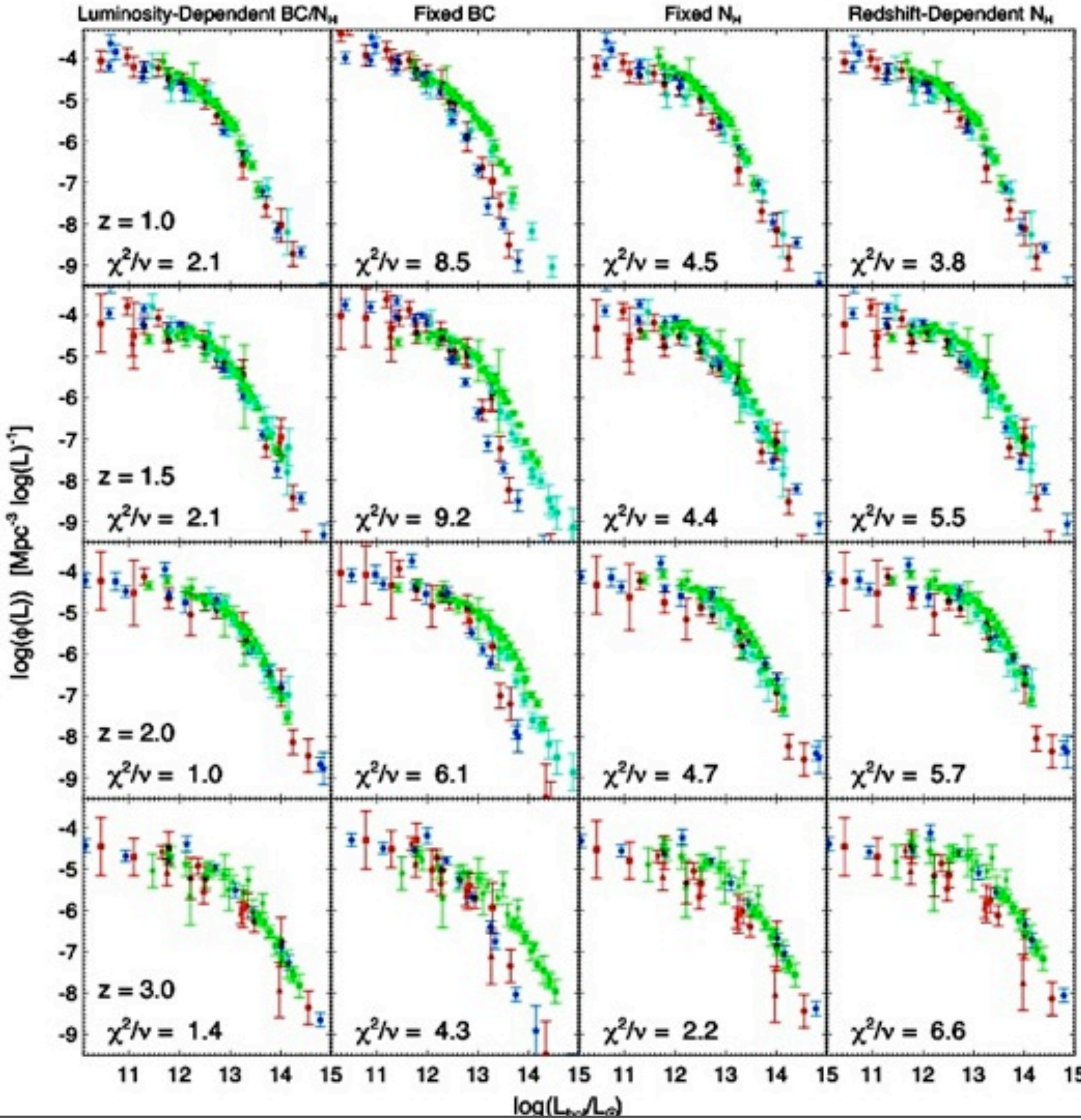


Obtain Phi(L) specific to observed band, L_obs, and redshift:



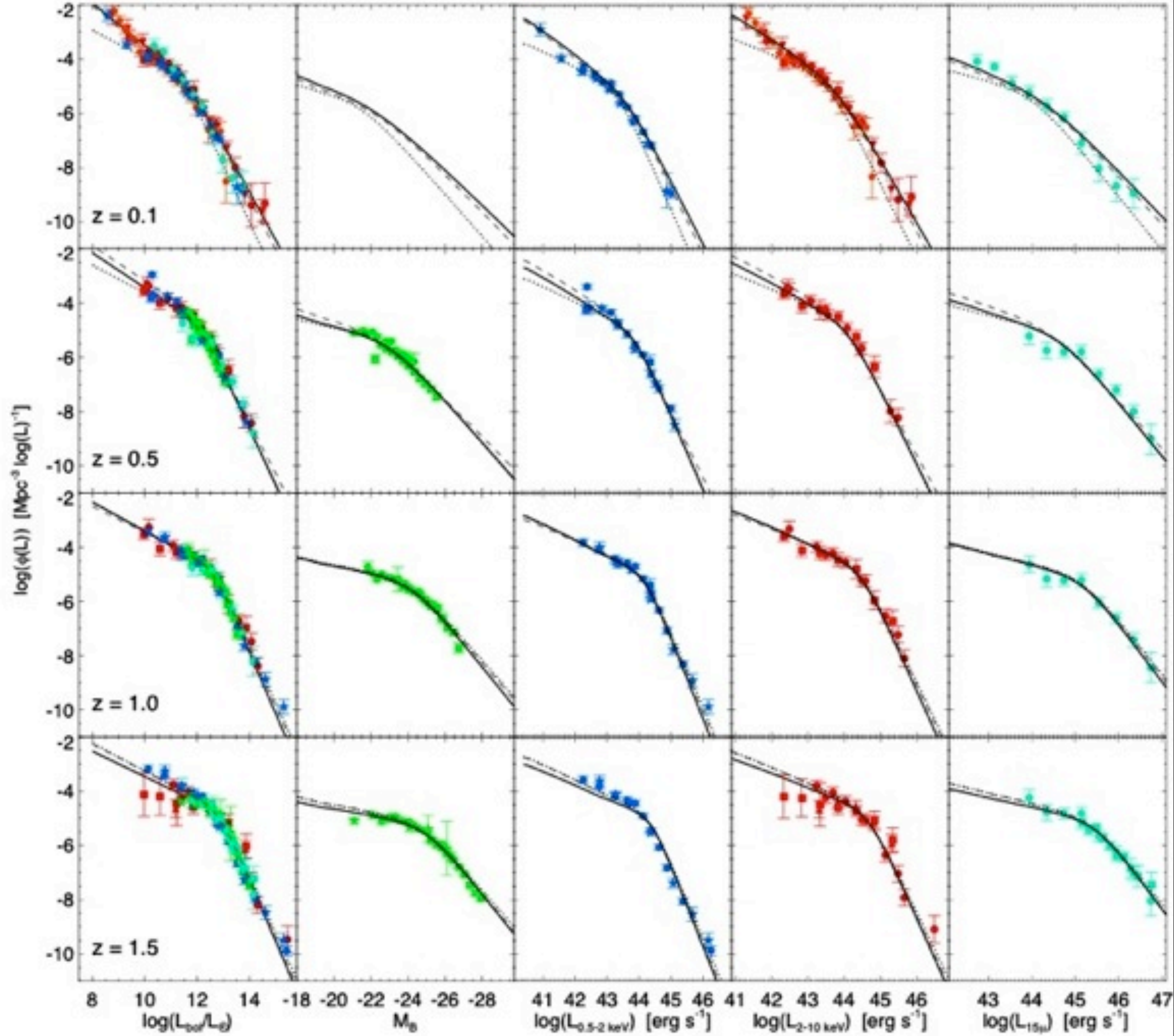
Luminosity-Dependence

TEST DIFFERENT BOLOMETRIC CORRECTIONS, ETC.



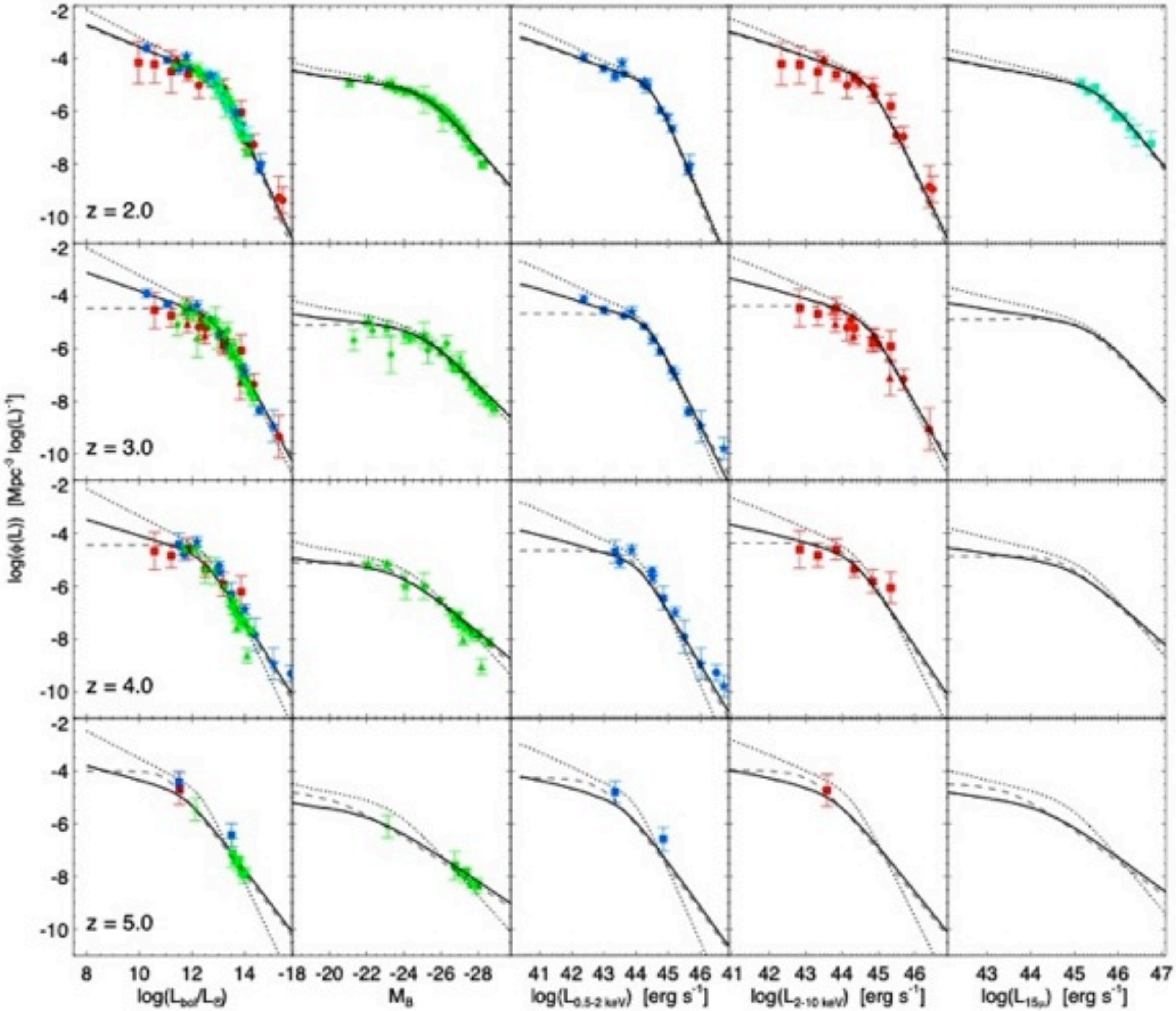
LF vs. Redshift

UV THROUGH IR



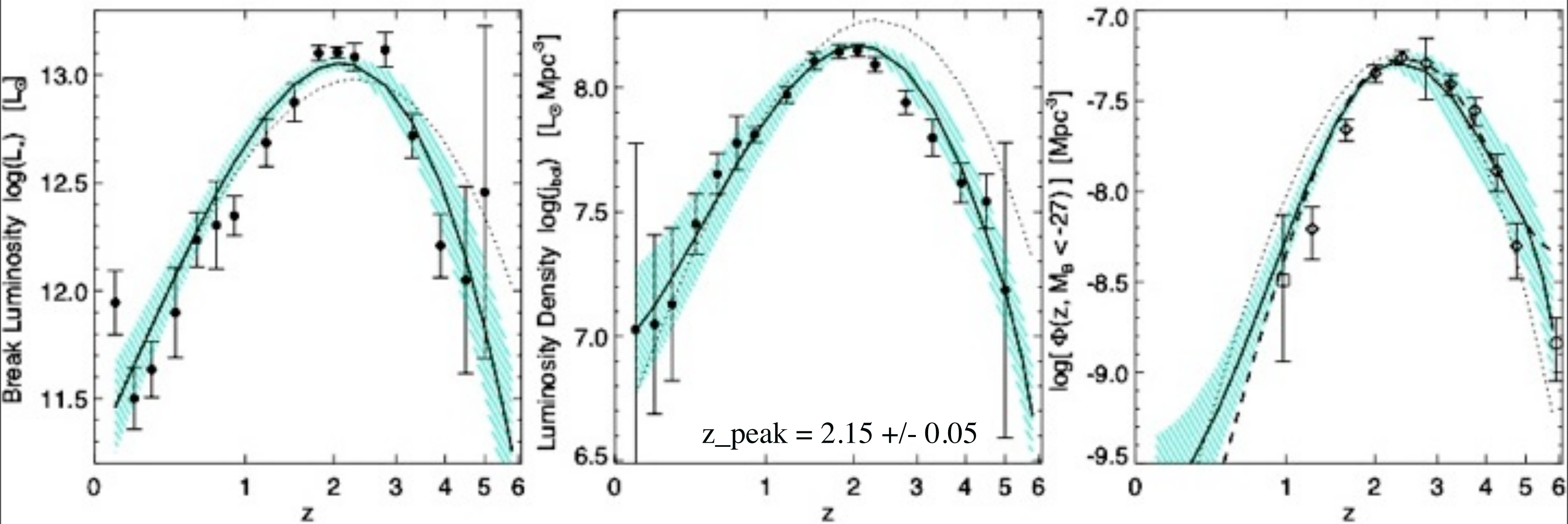
LF vs. Redshift

UV THROUGH IR



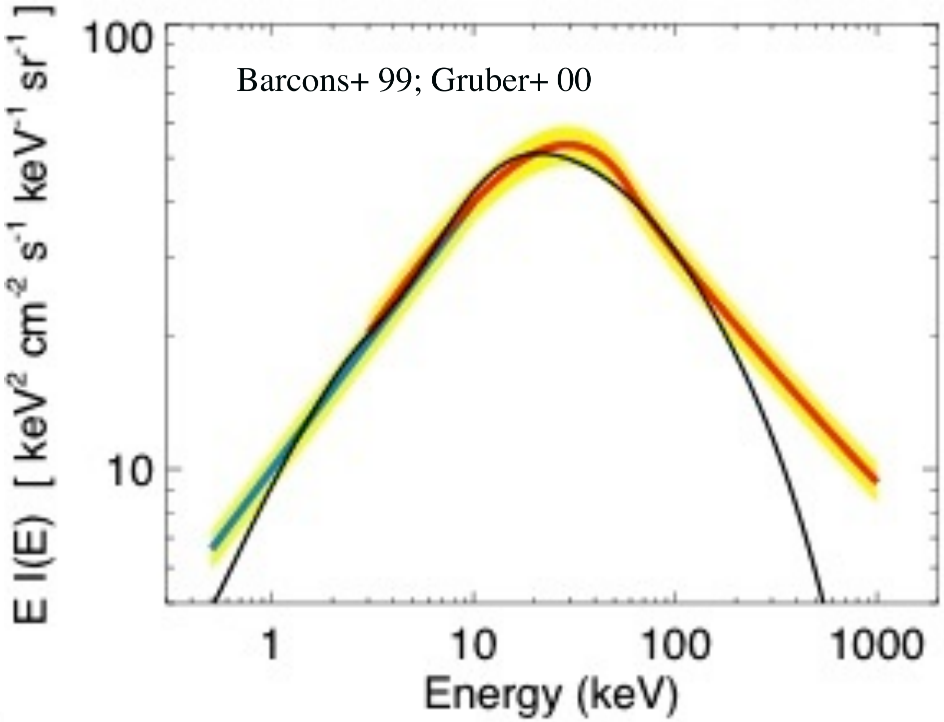
What Do We Learn?

“ZERO-TH ORDER”

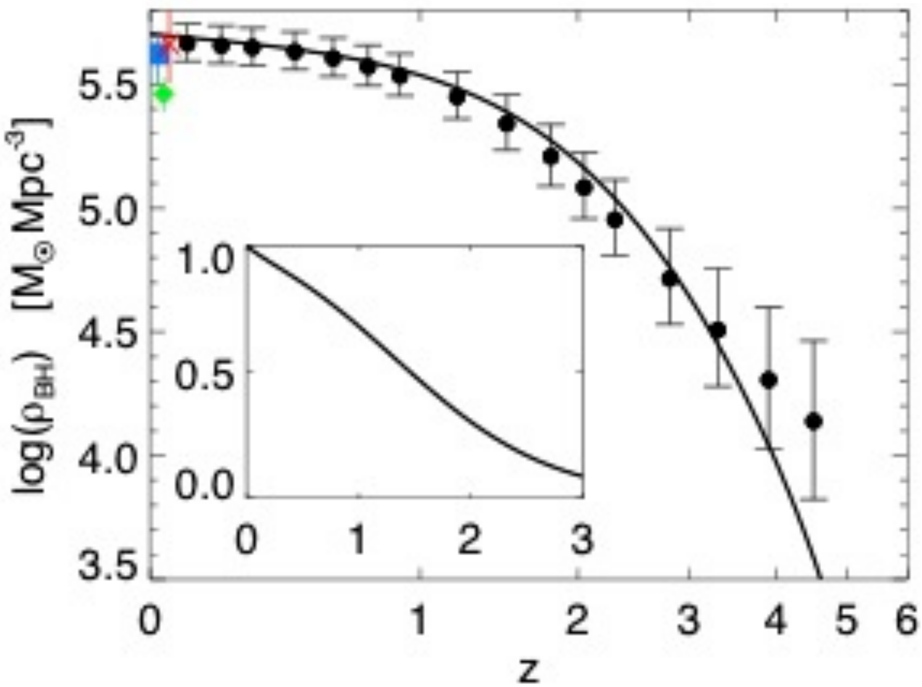


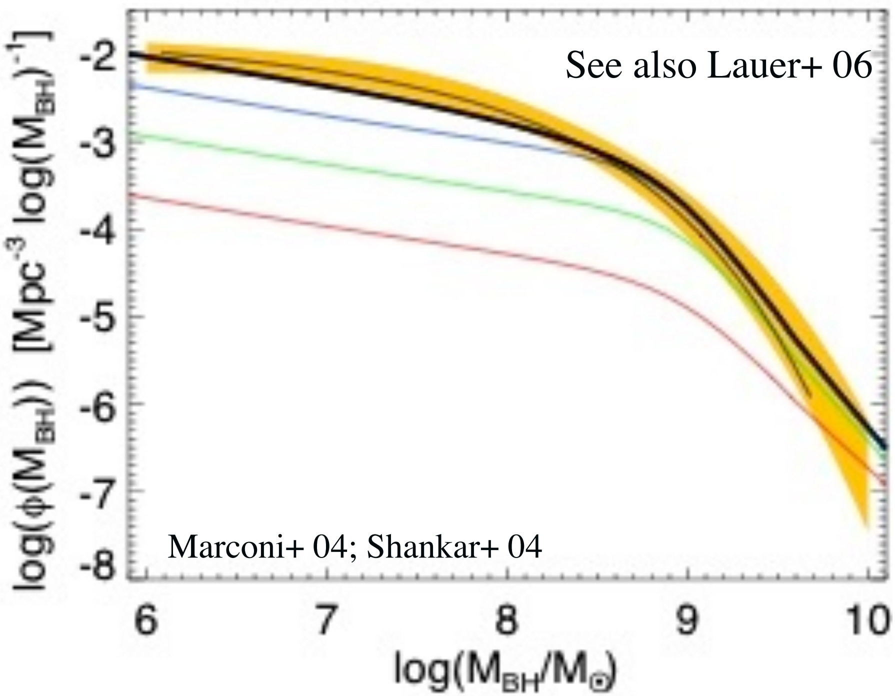
What Do We Learn?

"ZERO-TH ORDER"



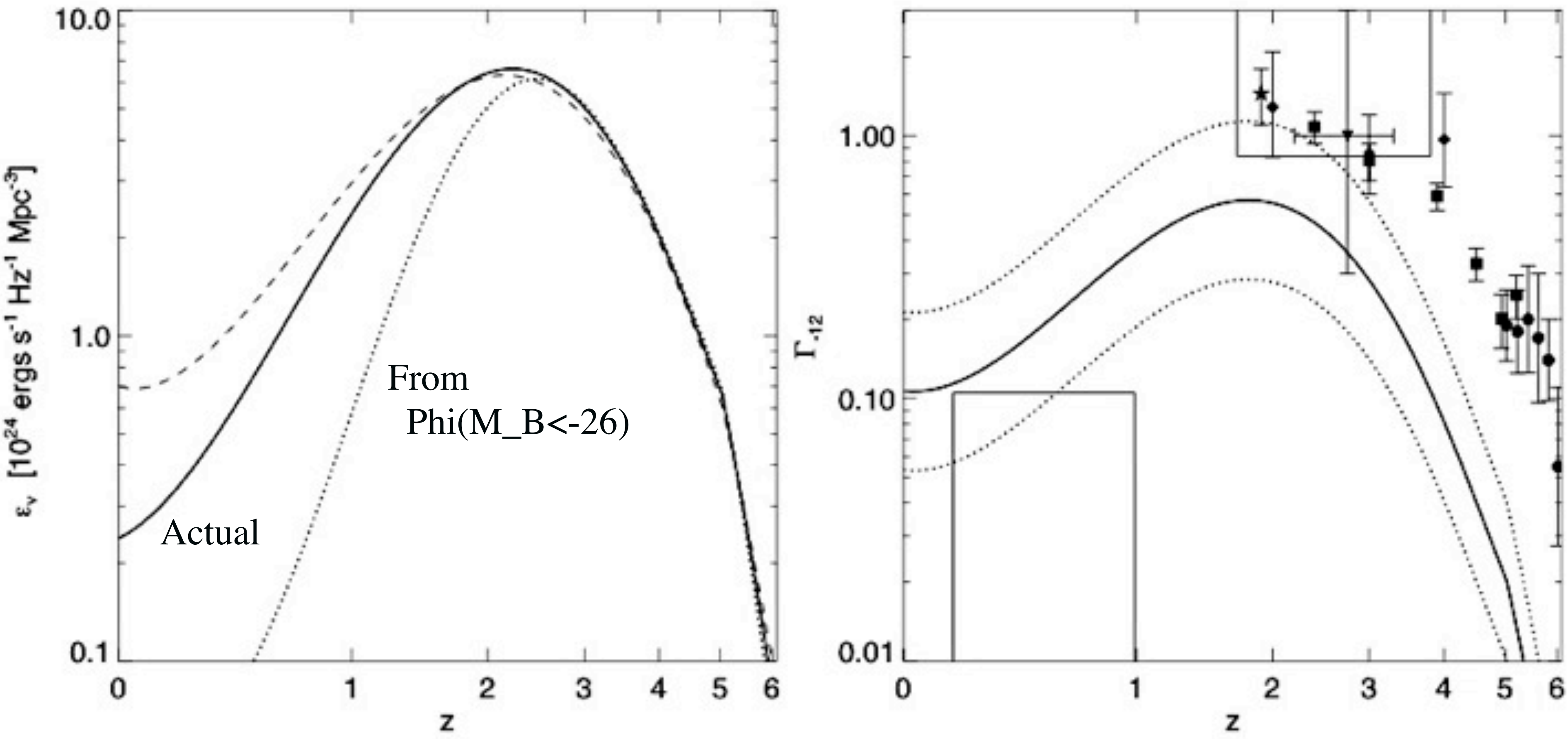
Marconi+ 04; Shankar+ 04; Tremaine+ 02





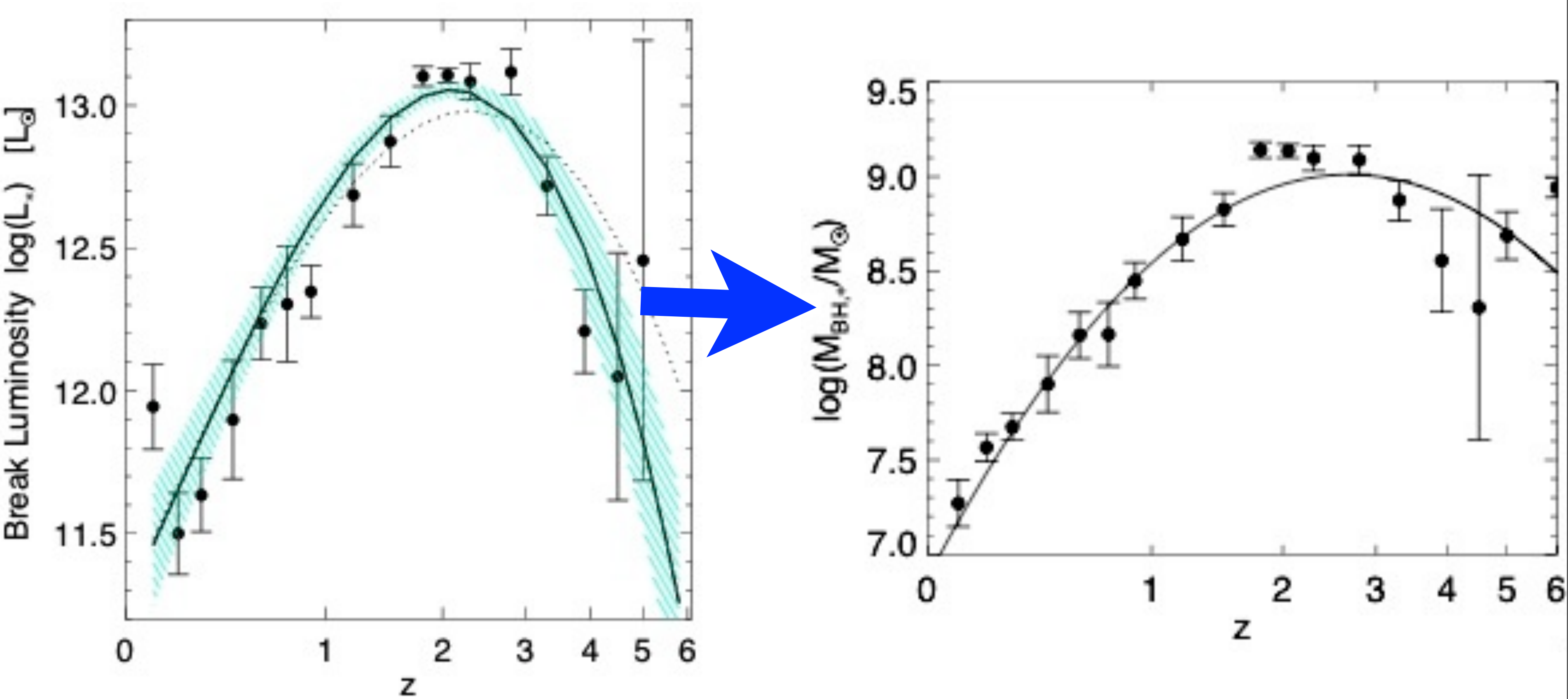
What Do We Learn?

“ZERO-TH ORDER”



What Do We Learn?

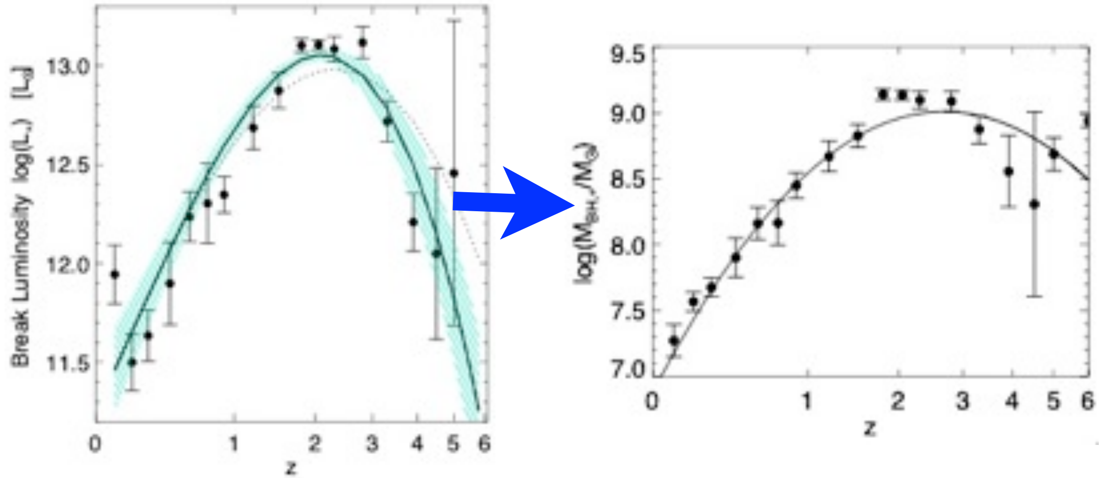
"FIRST ORDER"

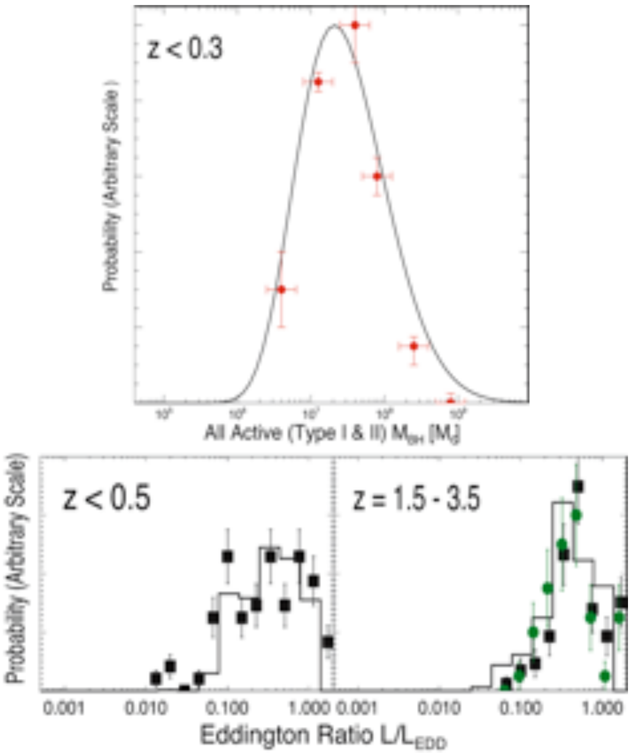


What Do We Learn?

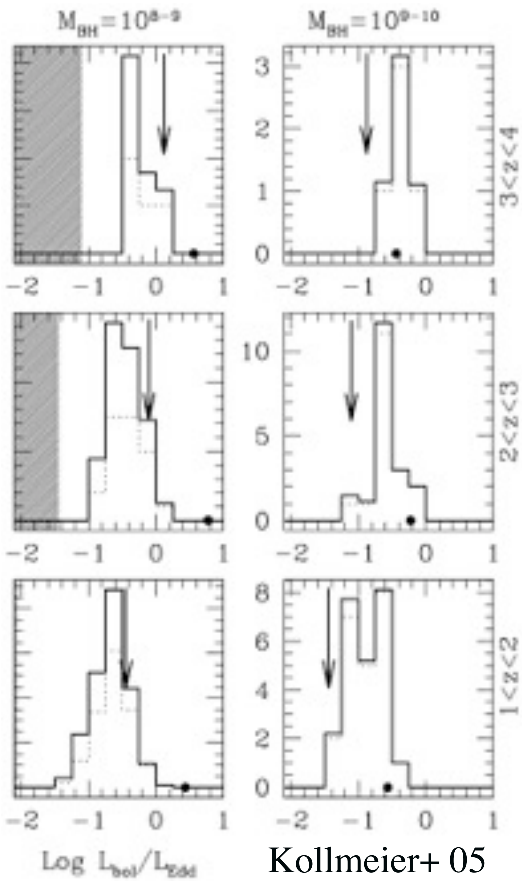
“FIRST ORDER”

- Little ambiguity in L-M mapping
  - Model-independent
    - Simulations
    - Observed mdot

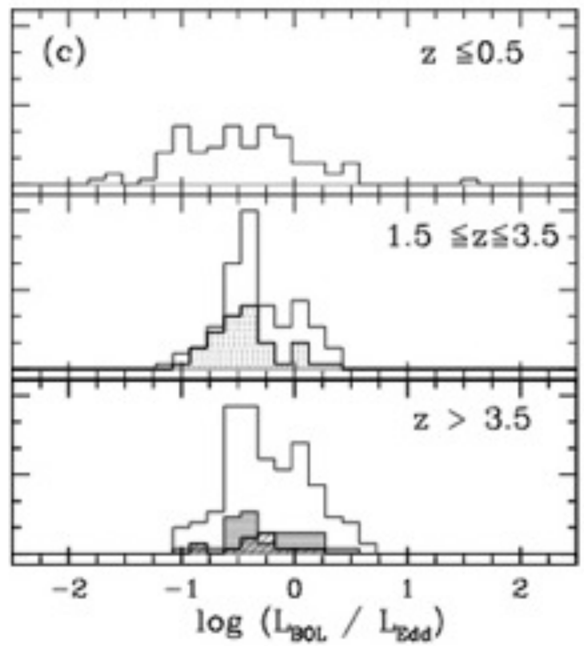




Hopkins+ 06



Kollmeier+ 05

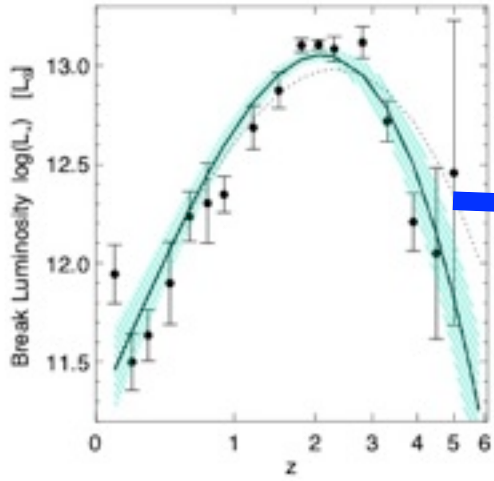


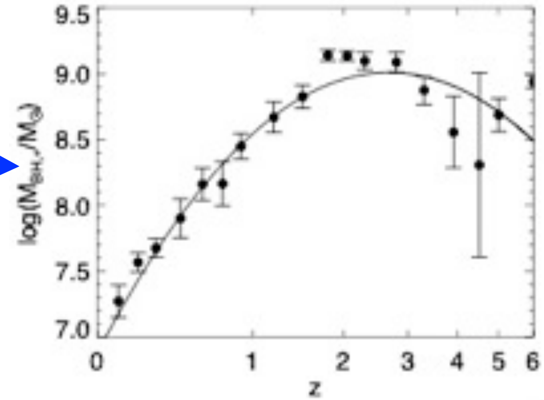
Vestergaard+ 04

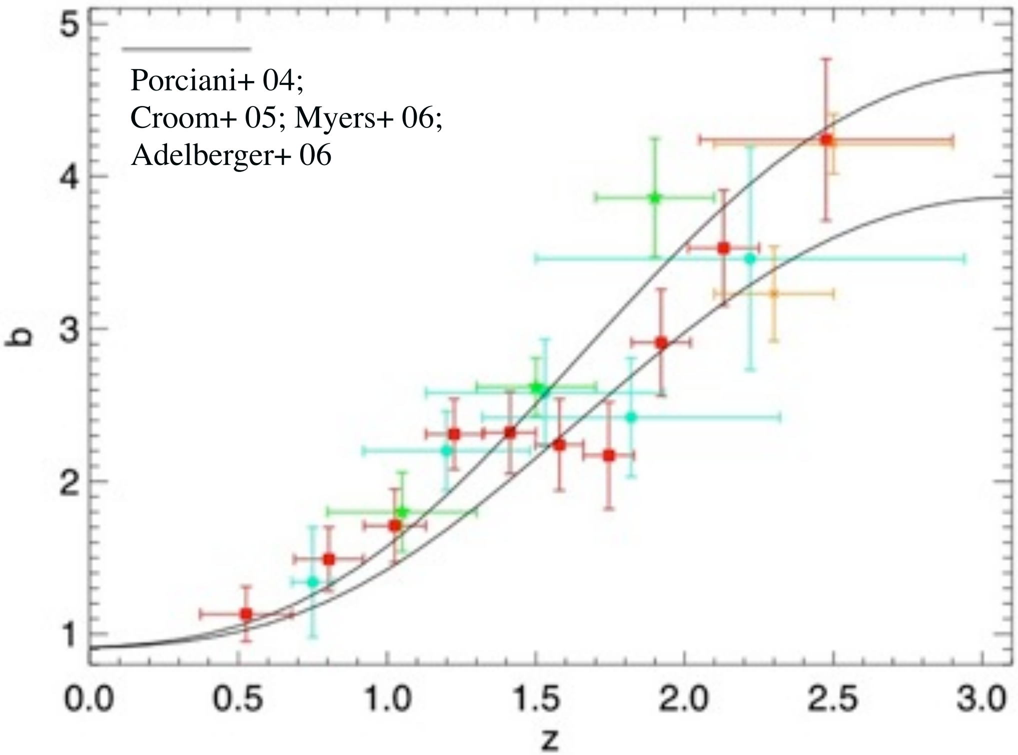
What Do We Learn?

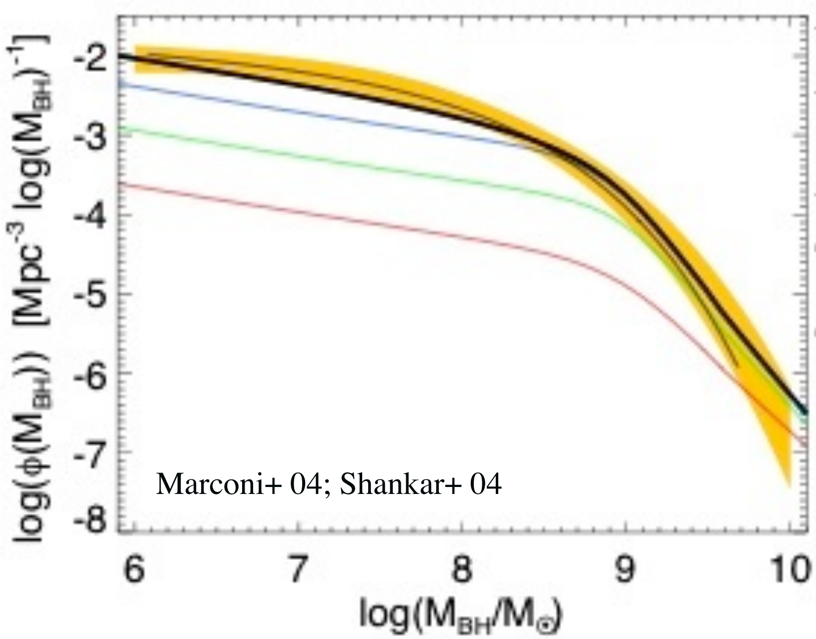
"FIRST ORDER"

- Little ambiguity in interpretation at z < 2
  - High-z can't get bigger
    - Observed mdot
    - Observed clustering
    - Local BHMF





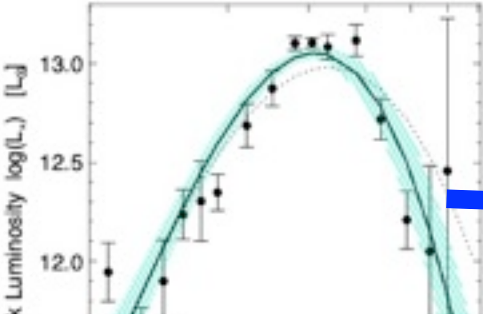


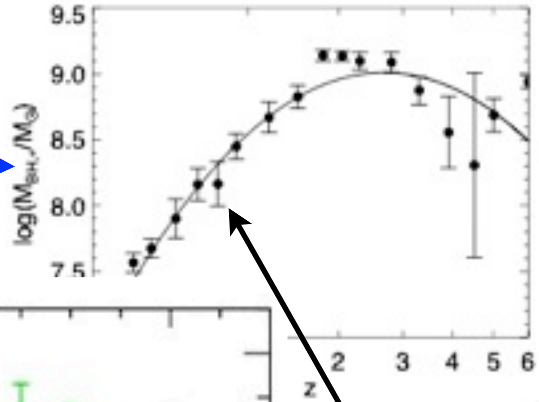


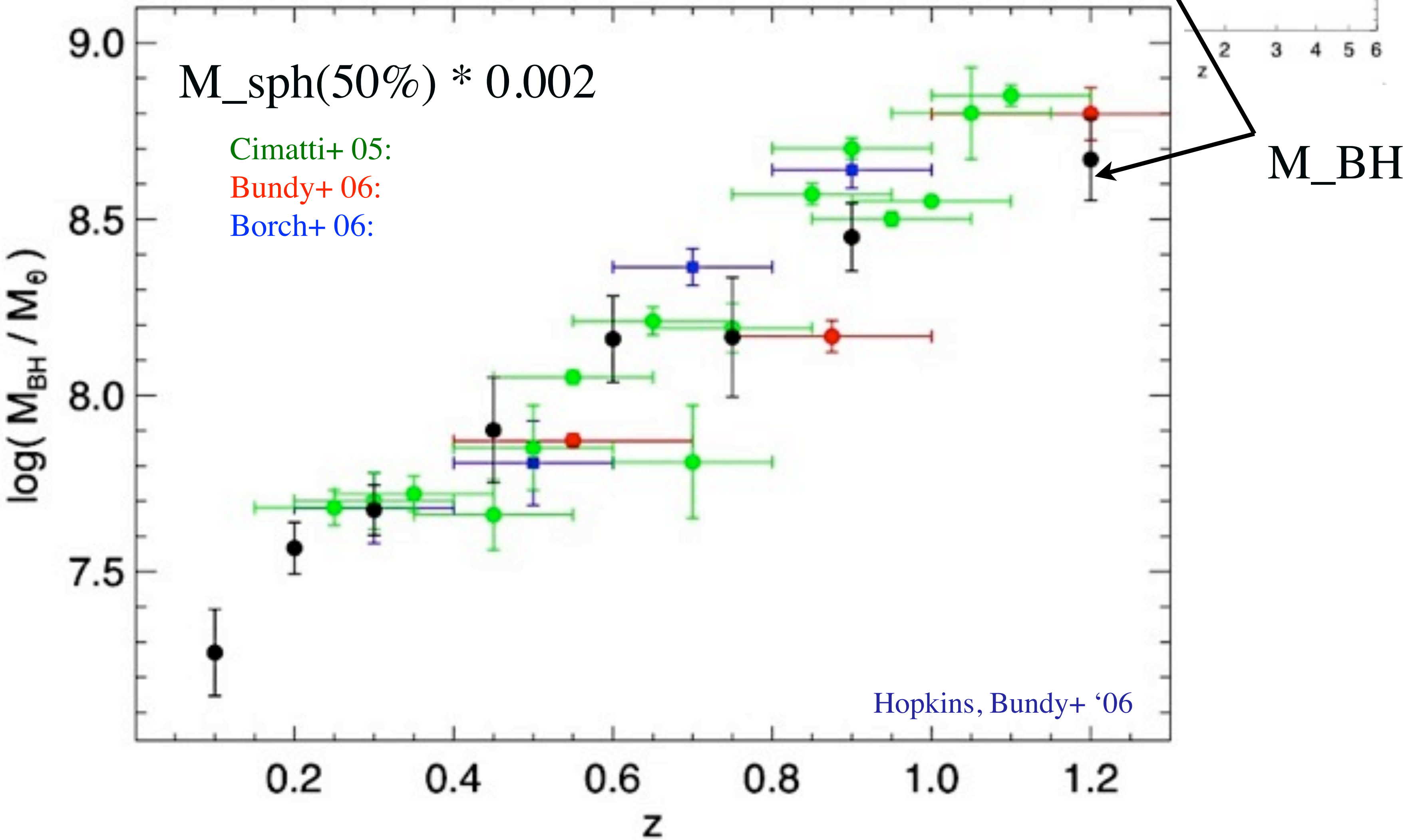
What Do We Learn?

"FIRST ORDER"

- Suggestive: sites of BH/spheroid co-formation?



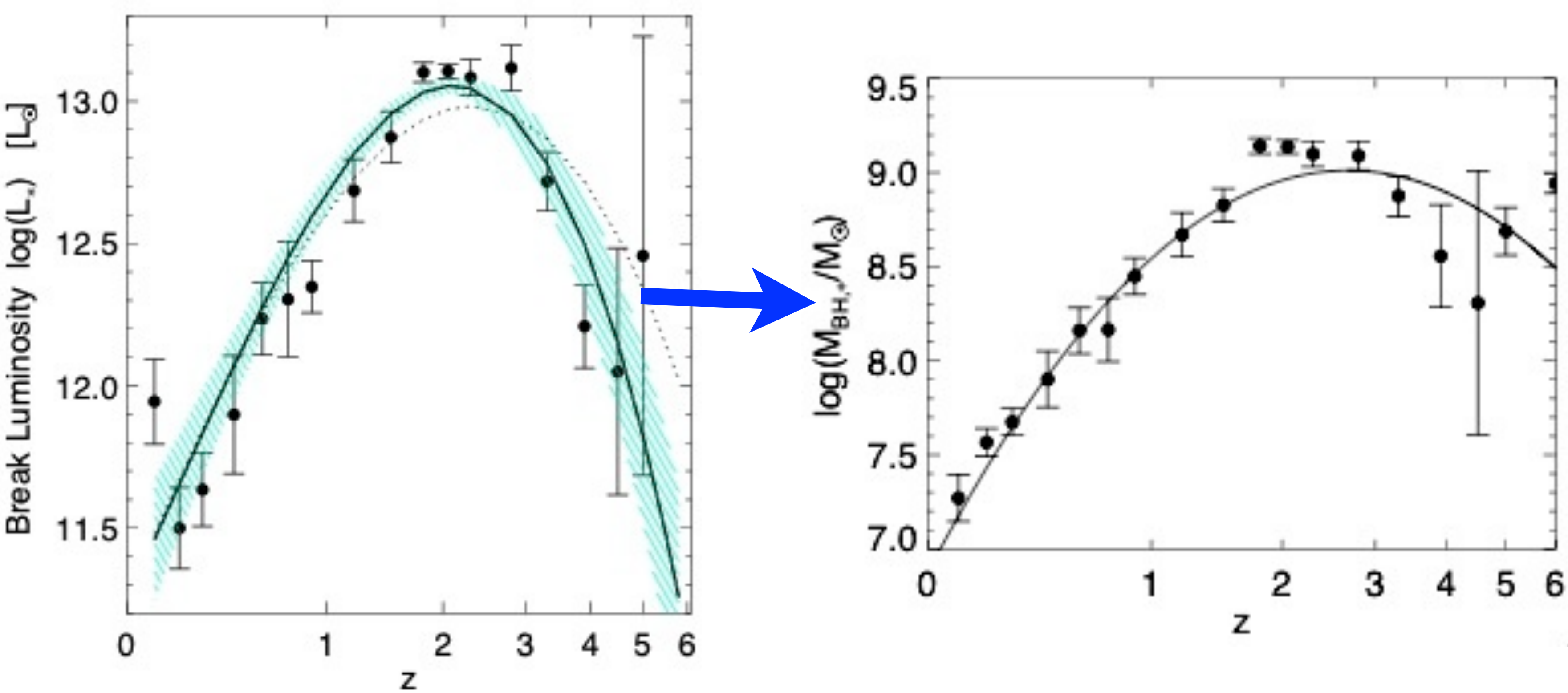




What Do We Learn?

“FIRST ORDER”

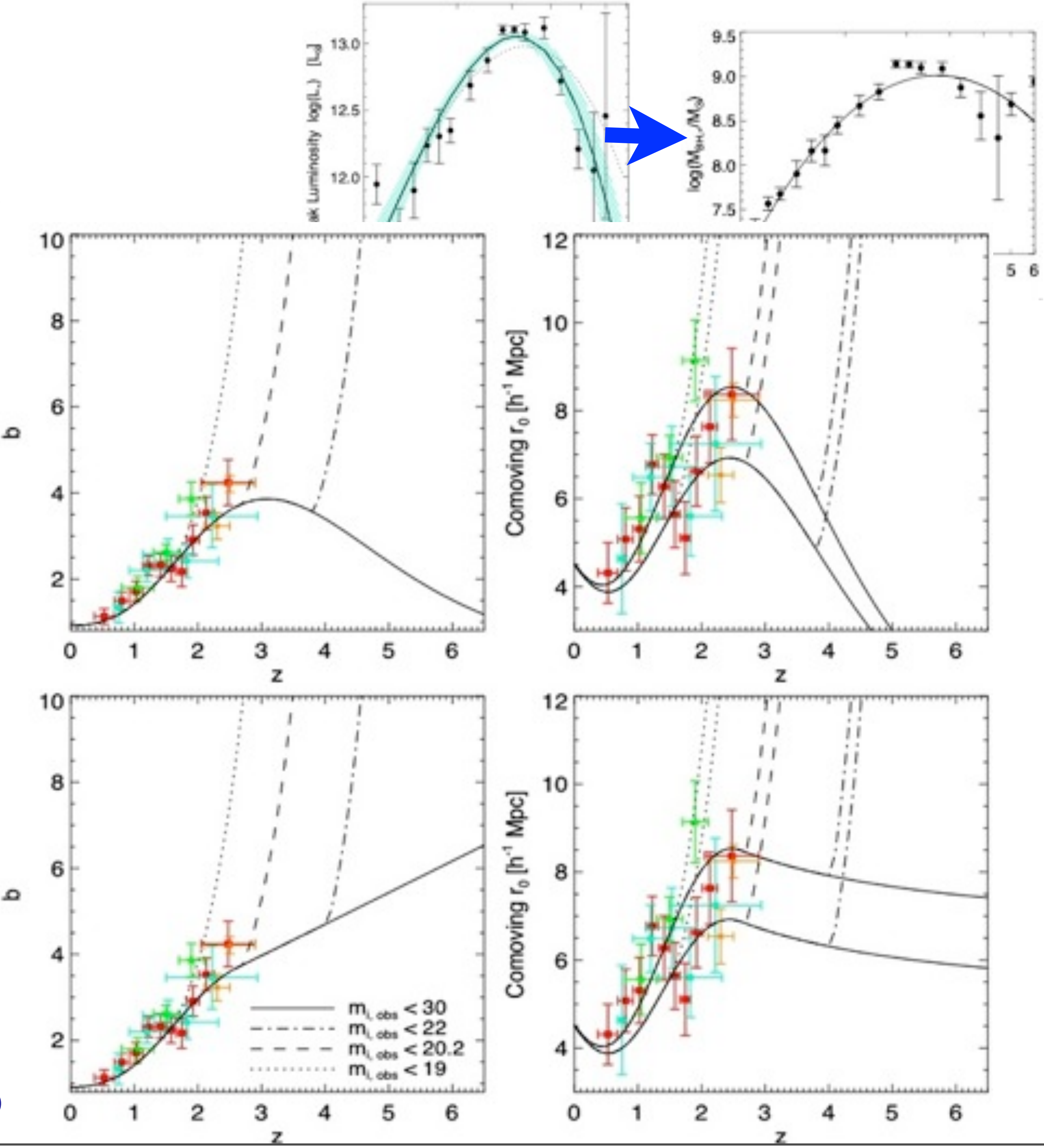
- High-z :: low-M_bh, or still building up?
    - M_BH vs. M_BH_final



What Do We Learn?

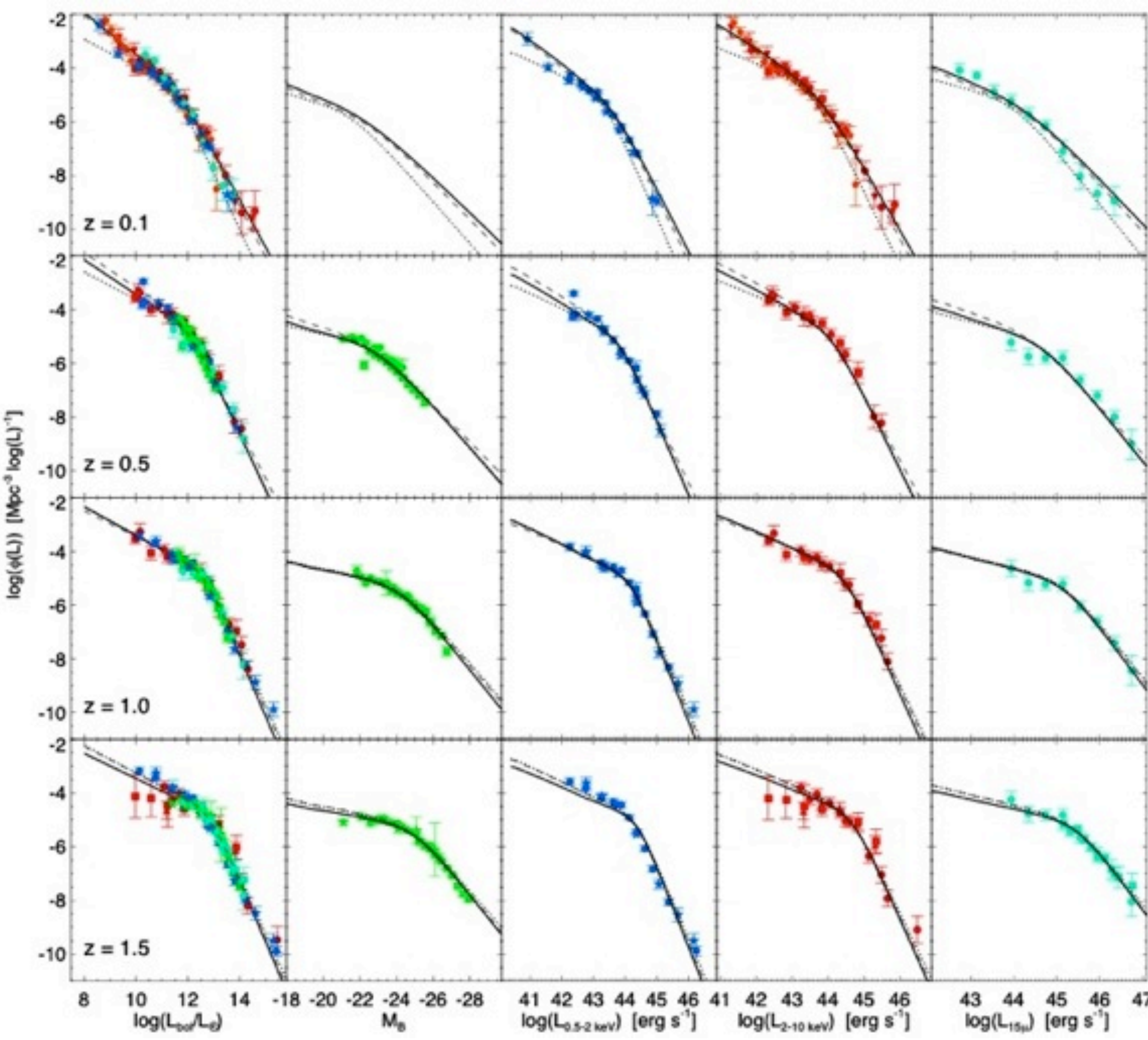
"FIRST ORDER"

- High-z :: low-M_bh, or still building up?
  - Host masses?
  - Clustering



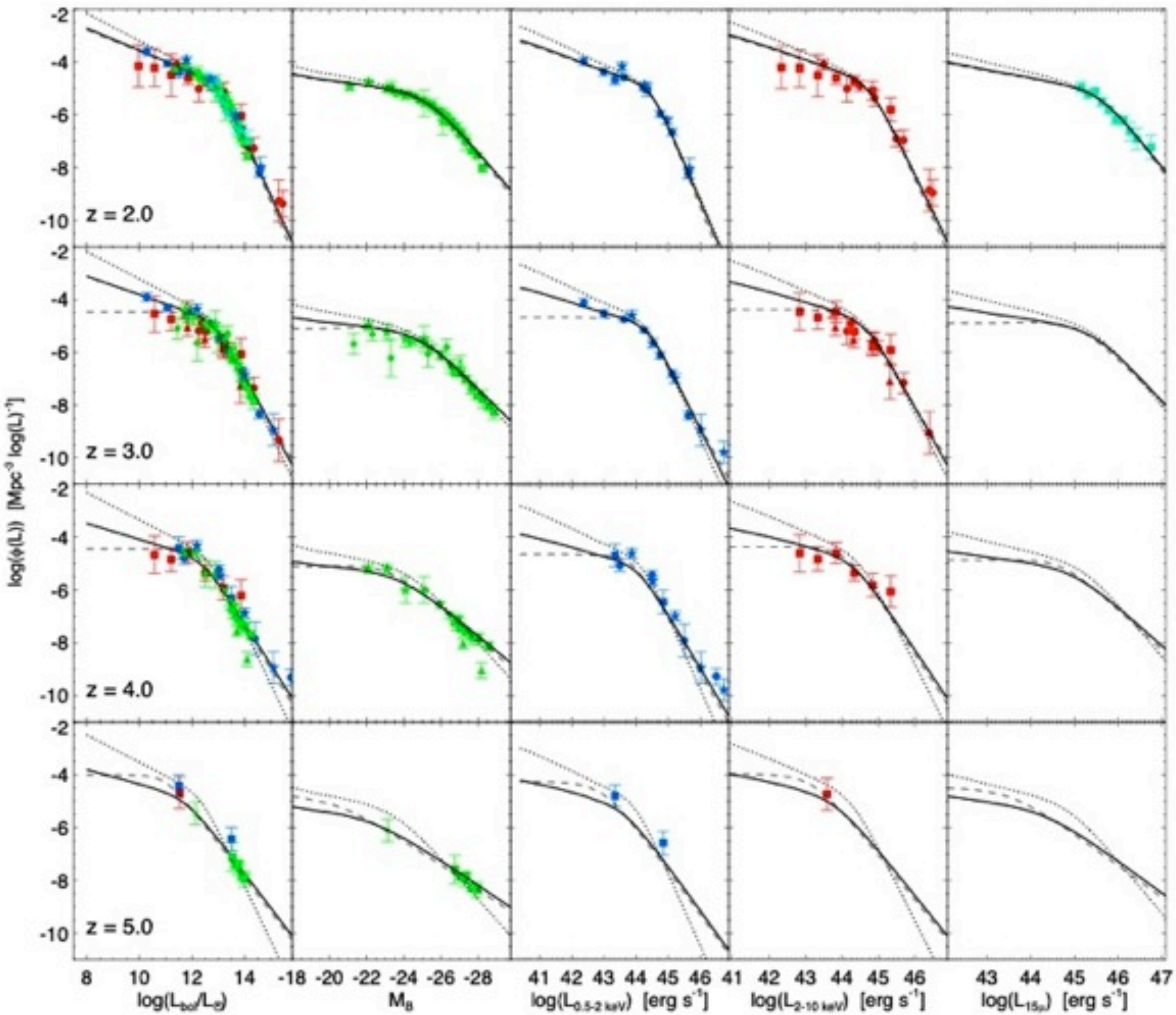
(in prep)

Recall...



z = 0.1
z = 0.5
z = 1.0
z = 1.5
log(φ(L)) [Mpc⁻³ log(L)⁻¹]
log(L_bol/L_⊙)
M_B
log(L_0.5-2 keV) [erg s⁻¹]
log(L_2-10 keV) [erg s⁻¹]
log(L_15μ) [erg s⁻¹]

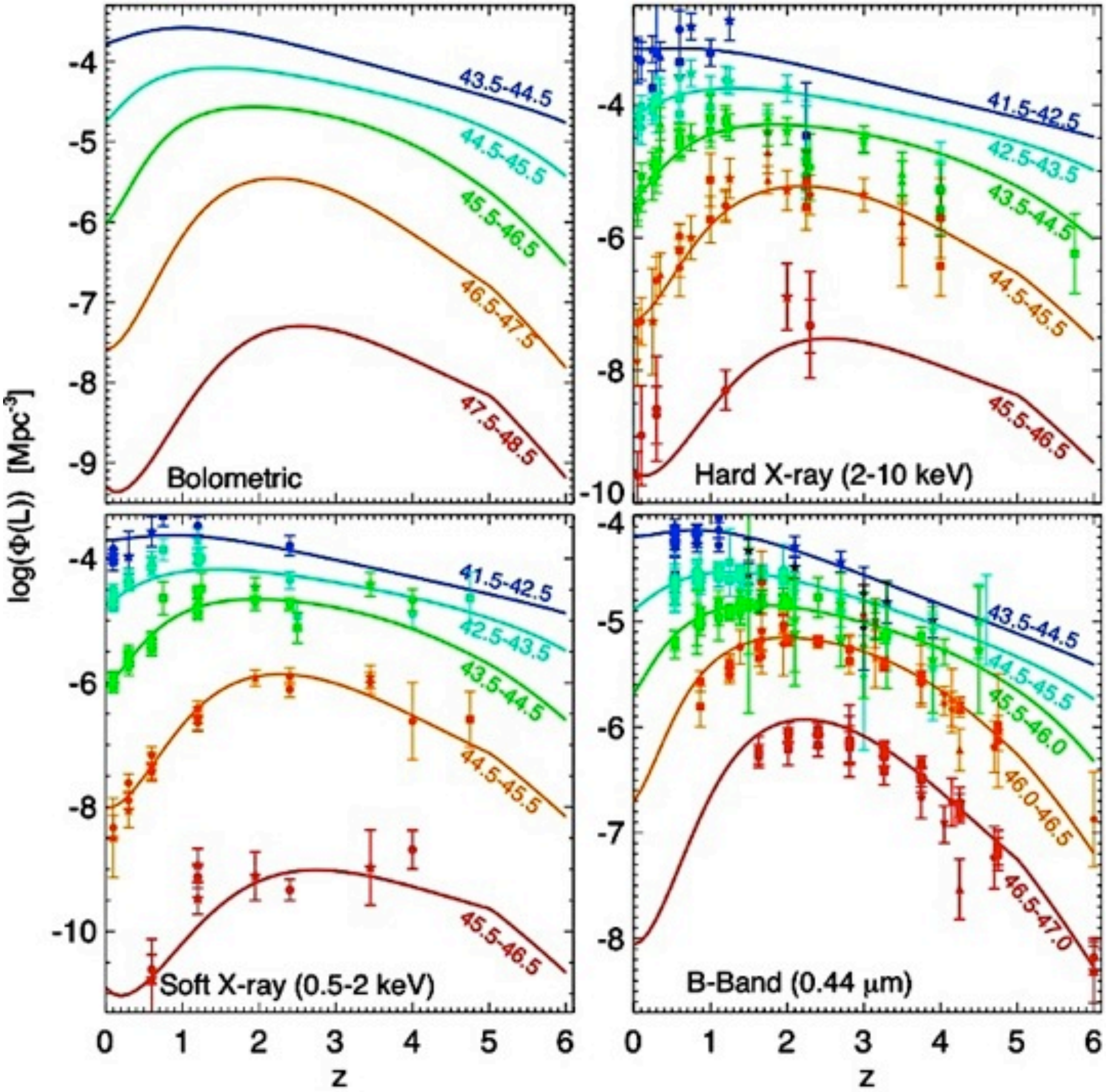
Recall...



z = 2.0
z = 3.0
z = 4.0
z = 5.0
log(φ(L)) [Mpc^-3 log(L)^-1]
log(L_bol/L_⊙)
M_B
log(L_0.5-2 keV) [erg s^-1]
log(L_2-10 keV) [erg s^-1]
log(L_15μ) [erg s^-1]

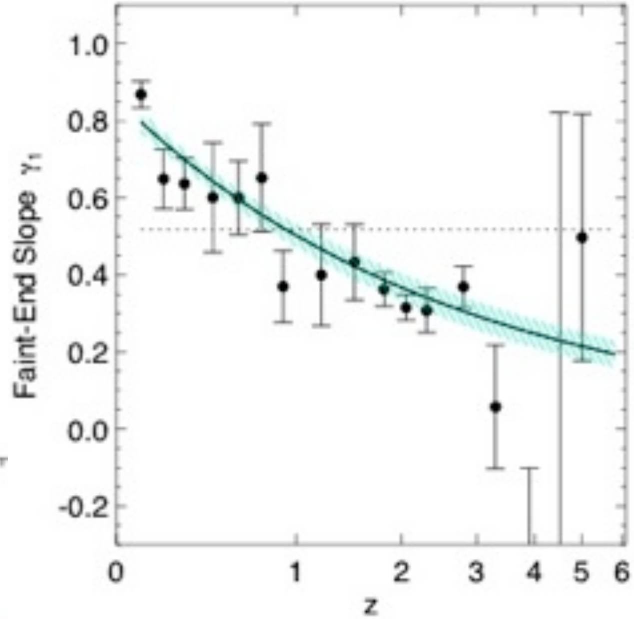
Luminosity-
Dependent
Density Evolution

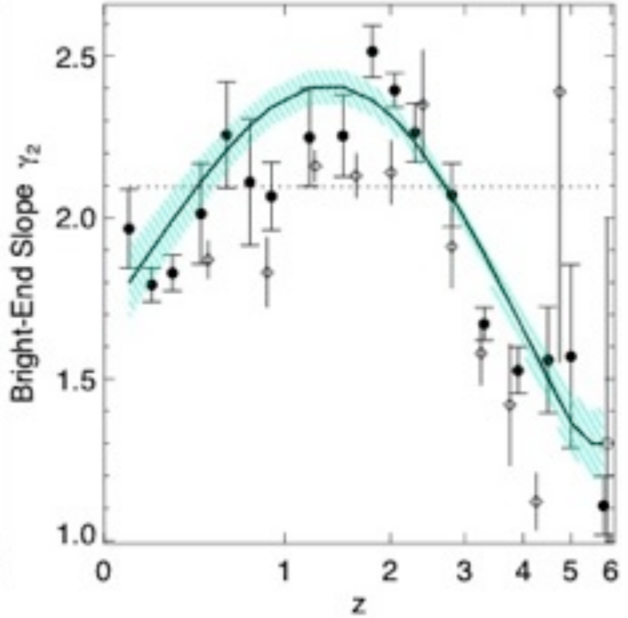
"SECOND ORDER"

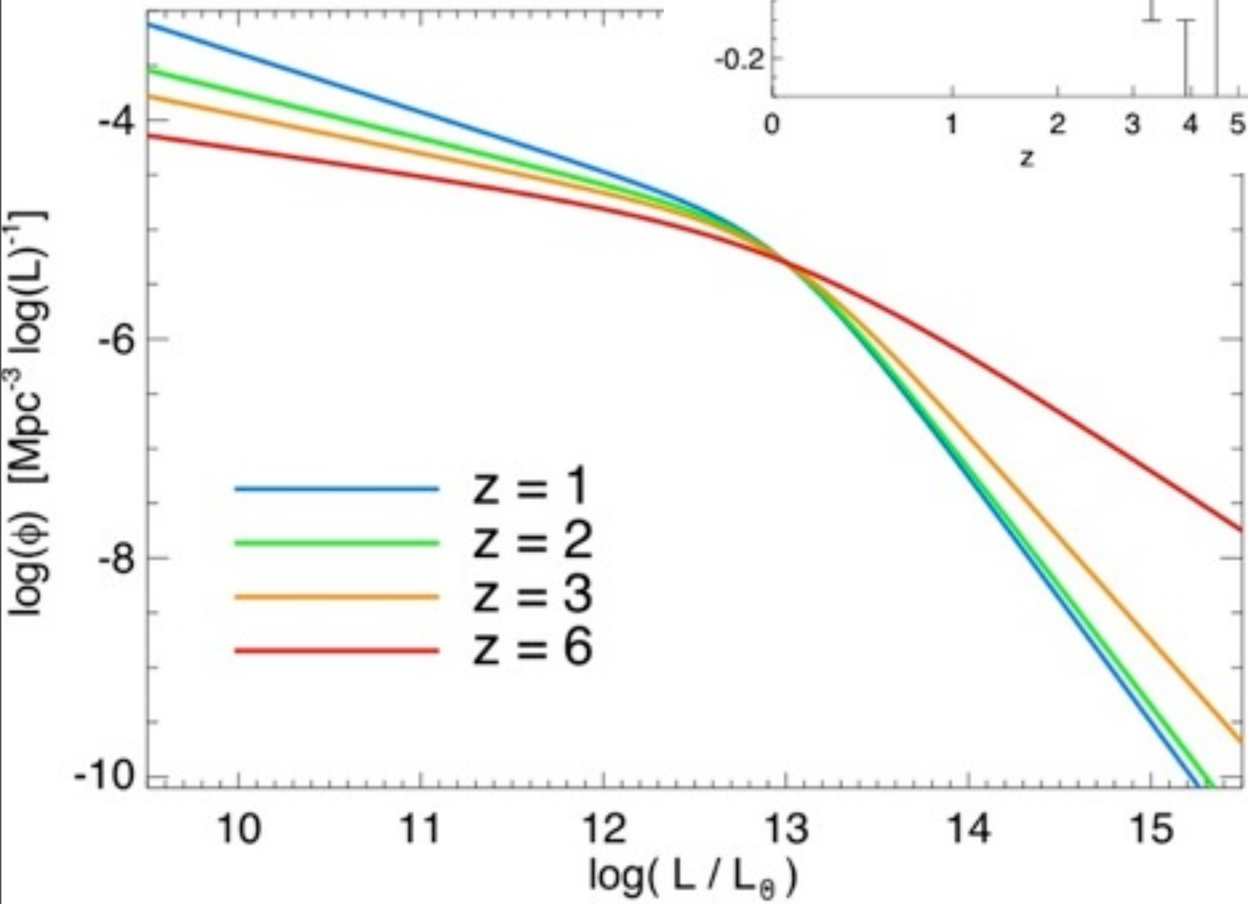


What Do We Learn?

“SECOND ORDER”







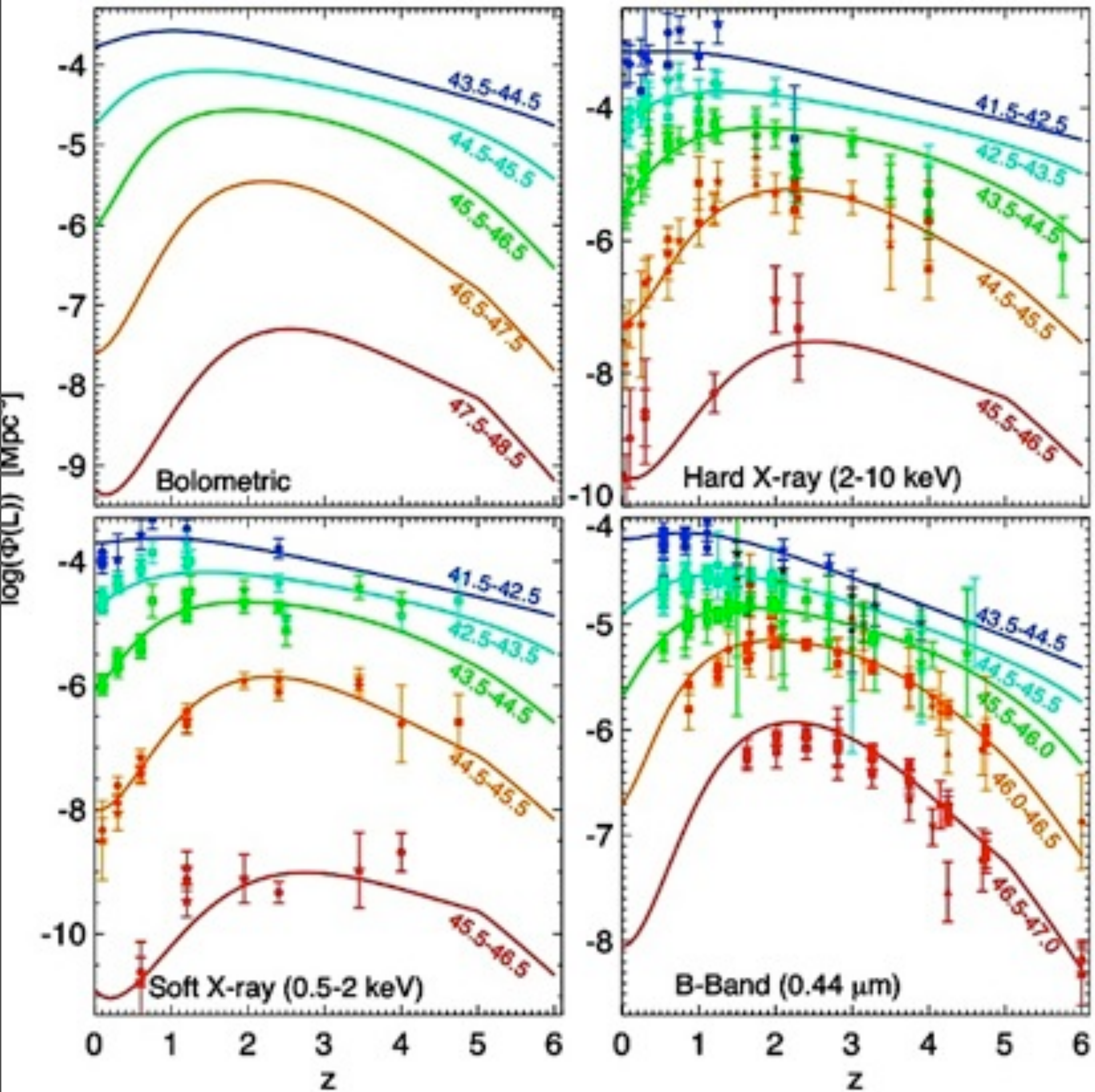
- Equivalently, slopes flatten with z

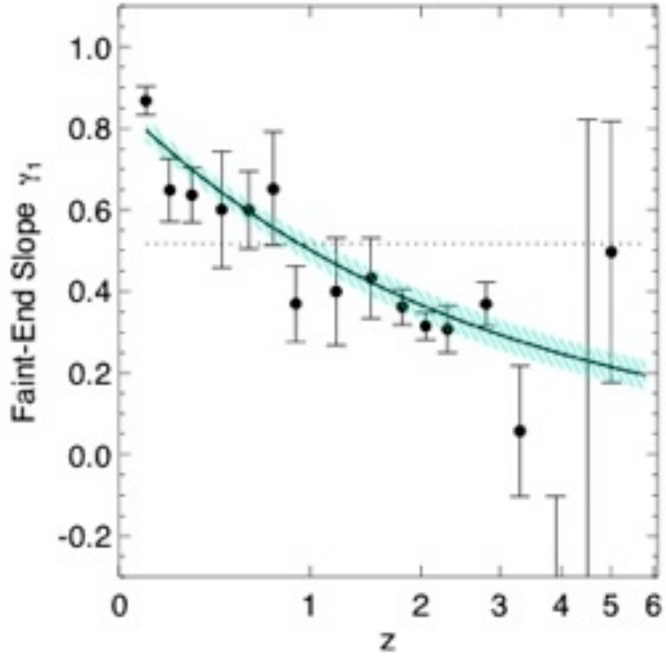
What Do We Learn?

"SECOND ORDER"

- Faint End (X-ray "LDDE")
  - Incompleteness?

Smooth; Low z





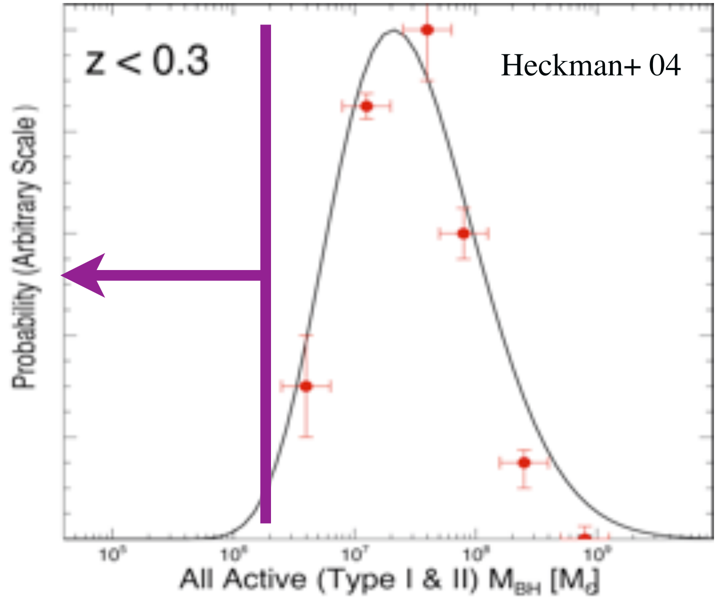
All bands/samples?

- Want faint-end slope over large-z from single surveys

What Do We Learn?

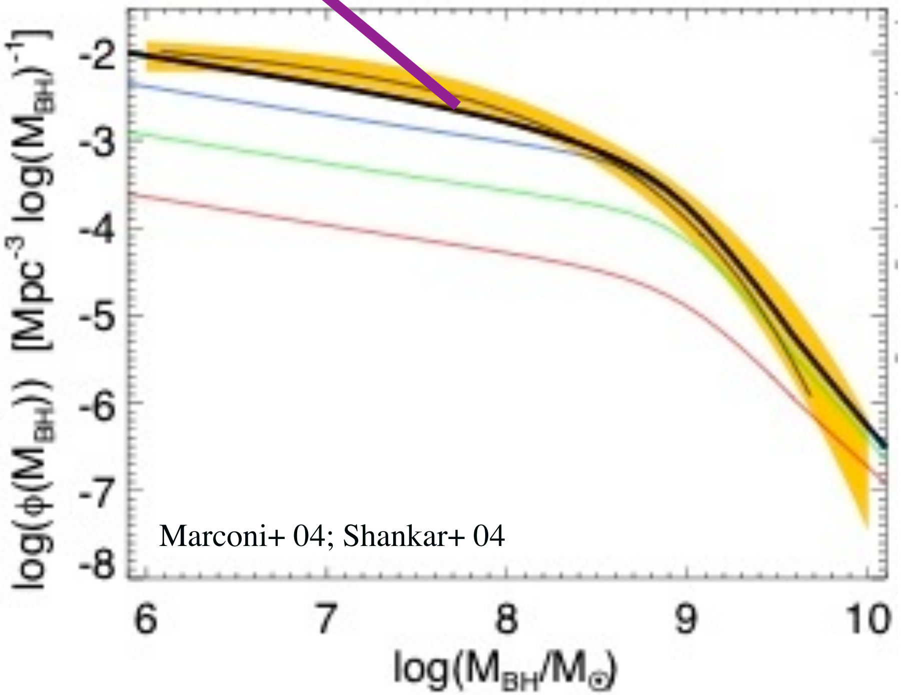
"SECOND ORDER"

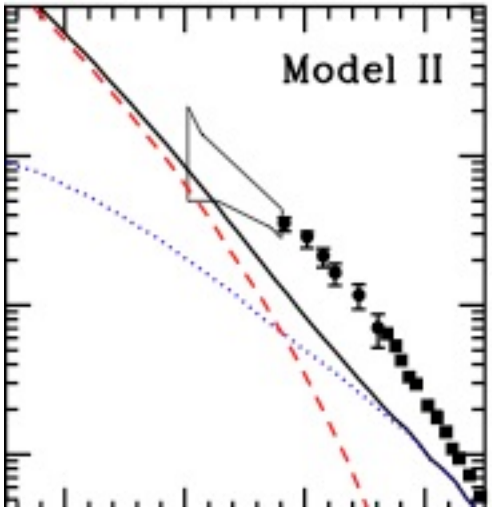
- Faint End (X-ray "LDDE")
  - Incompleteness?
  - Lots of (very) low-M active BHs?
    - No faint-end Lqso-Lhost correlation (Bahcall+; Hao+; Vanden Berk+)



Light-weighted BHMF

Local (Hao+05) faint-end slope



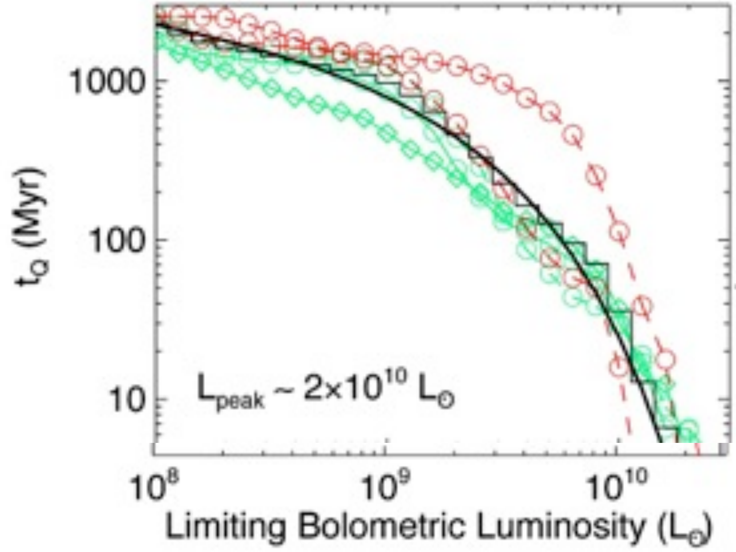


radio counts (Haiman+ 04)
X-ray counts (Volonteri+ 06)

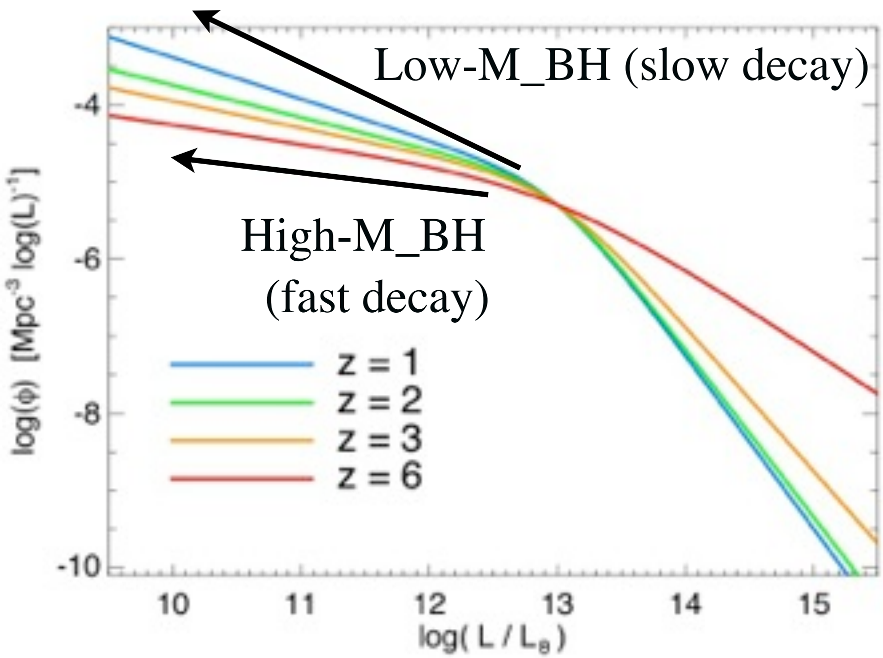
What Do We Learn?

"SECOND ORDER"

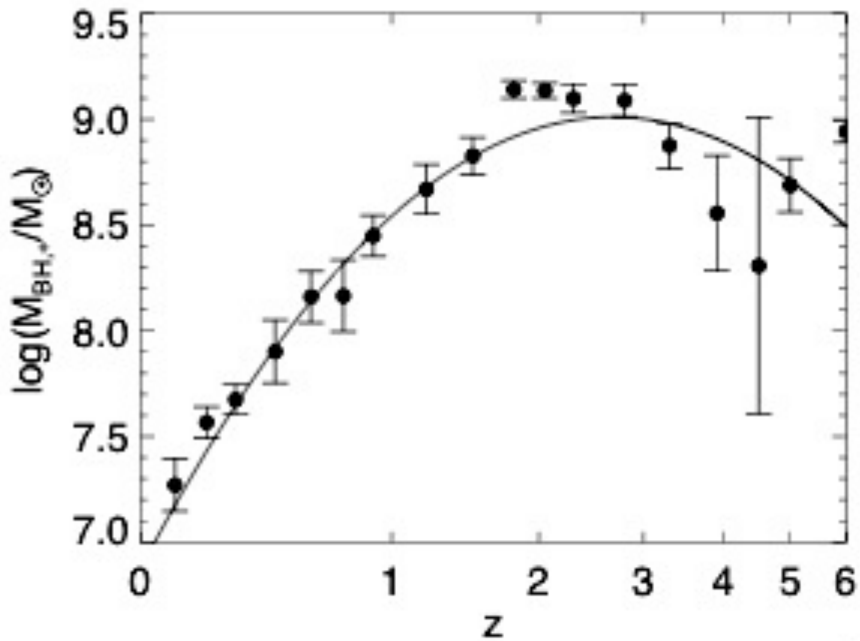
- Faint End (X-ray "LDDE")
  - Incompleteness?
  - Lots of (very) low-M active BHs?
  - Change in effective duty cycle/lifetime for more massive BHs at low mdot



Luminosity-Dependent Quasar Lifetimes

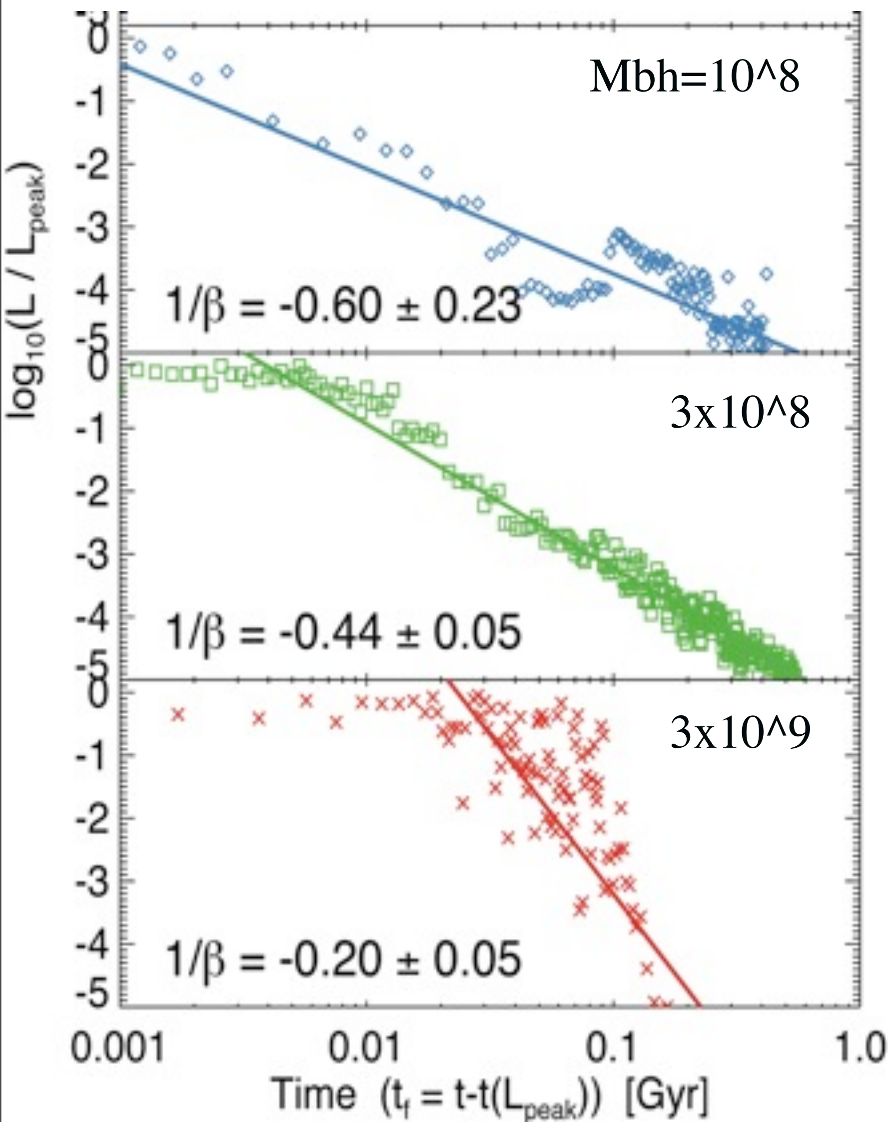


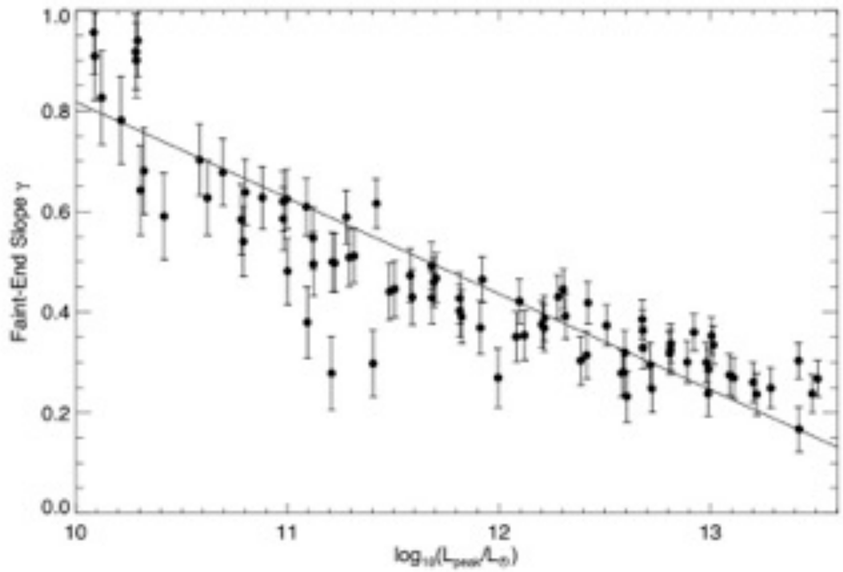
+

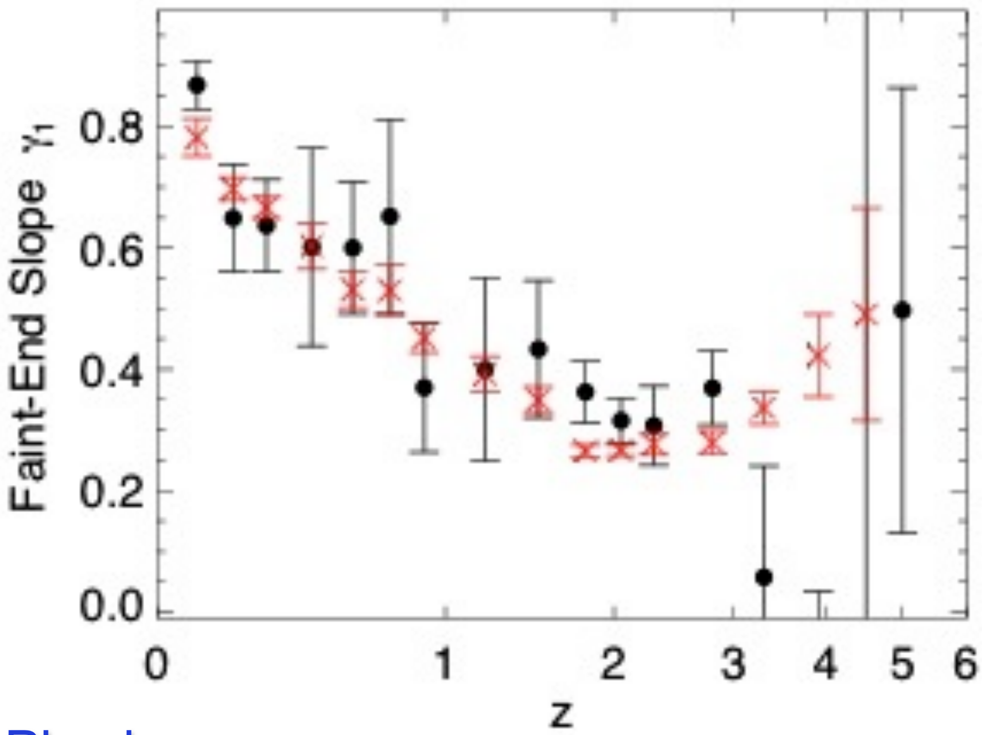


What Do We Learn?

"SECOND ORDER"





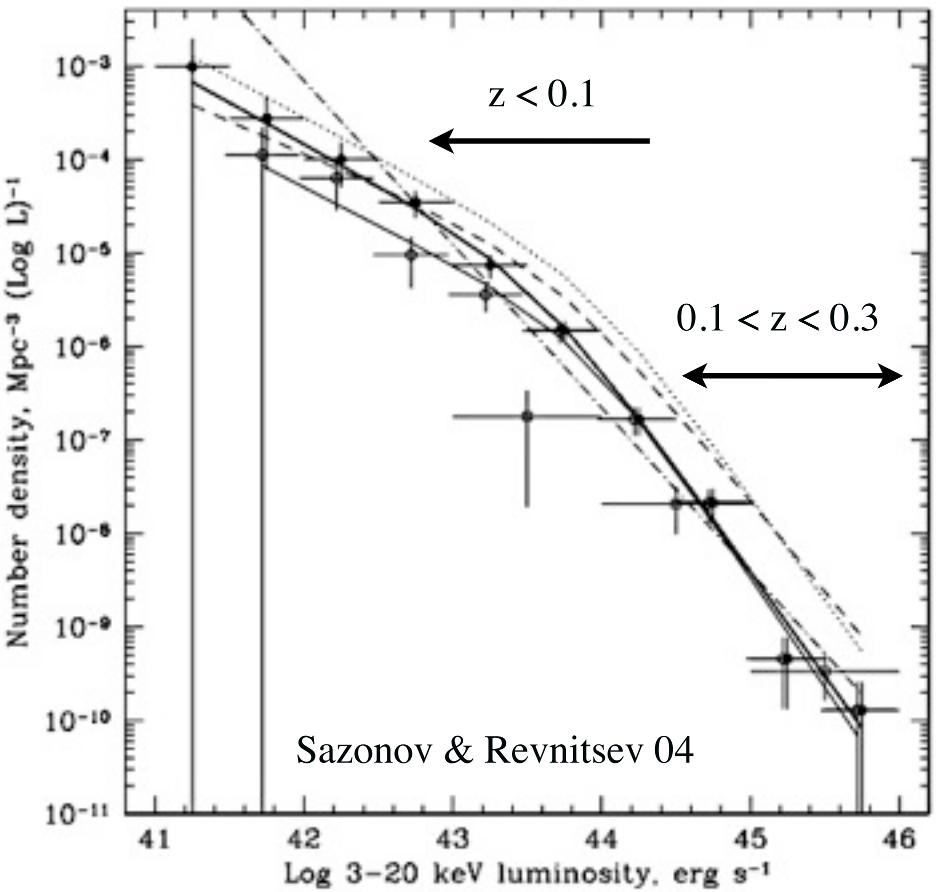


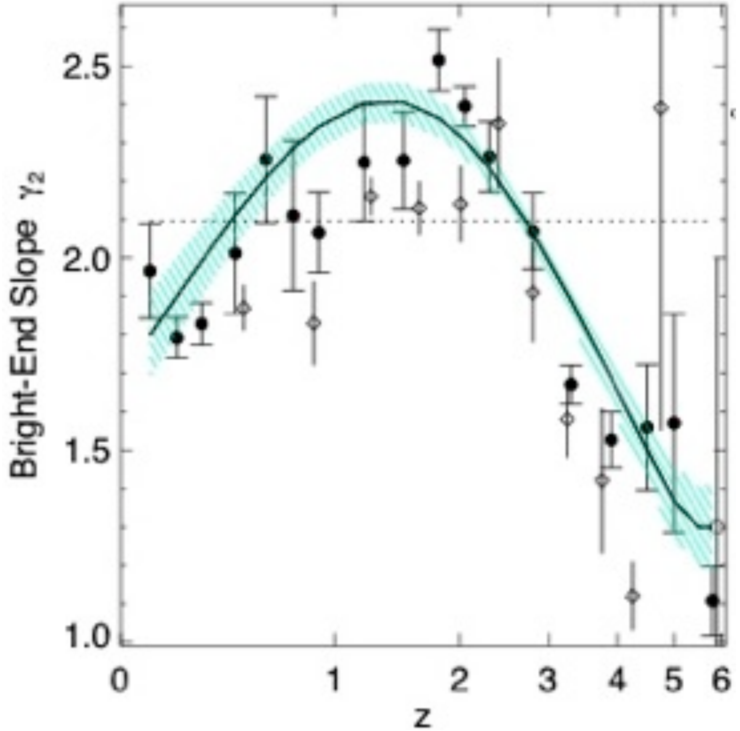
- Constrain Lifetimes + Feedback Physics

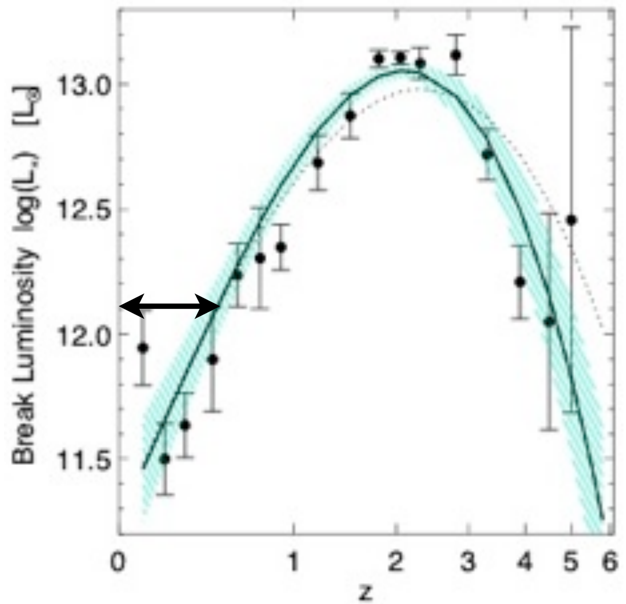
What Do We Learn?

"SECOND ORDER"

- Bright End
  - Binning?
    - Probably important at z<1





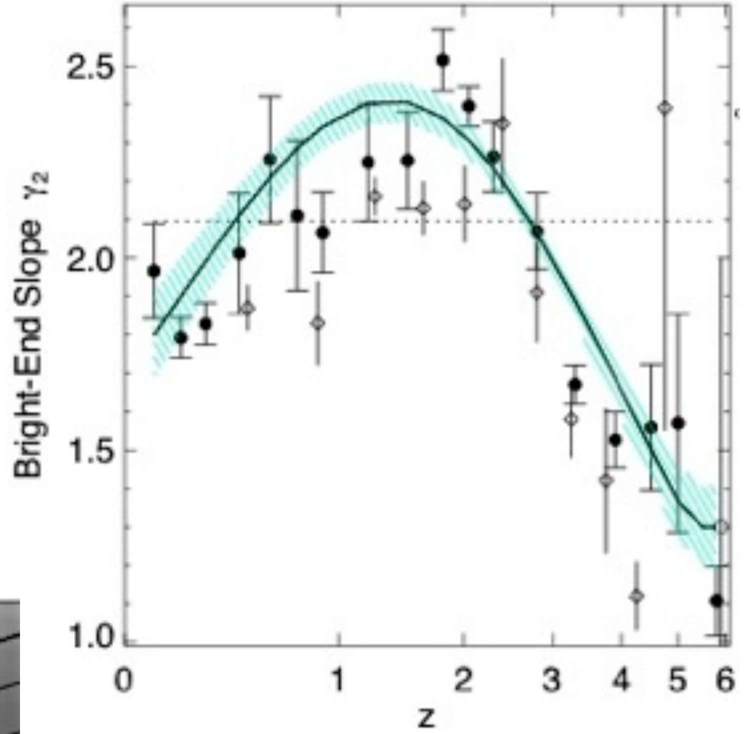


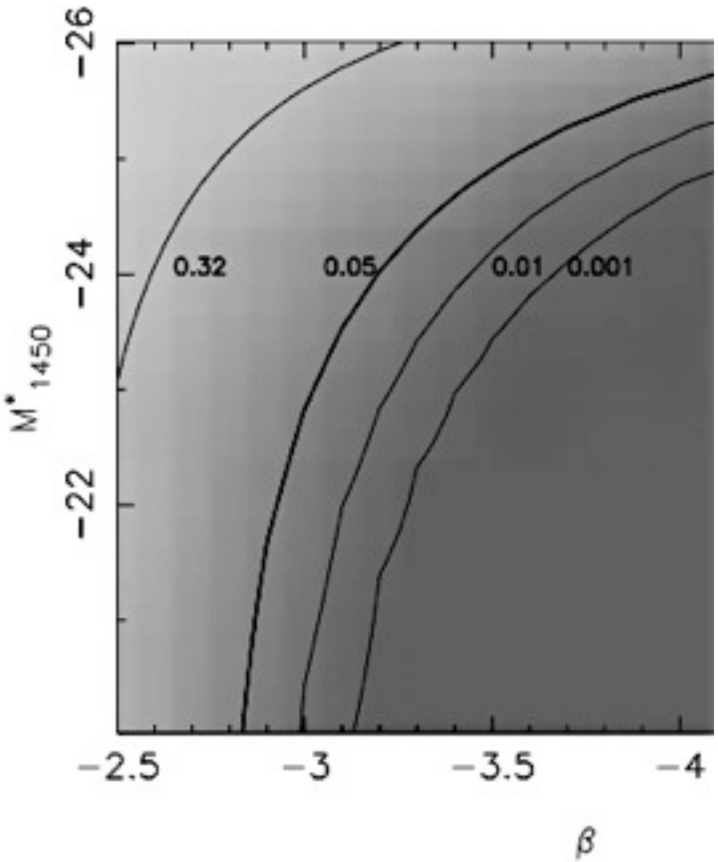
- Very unlikely with SDSS DR3 (bin-bin dz<0.03)

What Do We Learn?

"SECOND ORDER"

- Bright End
  - Binning?
  - Lensing?



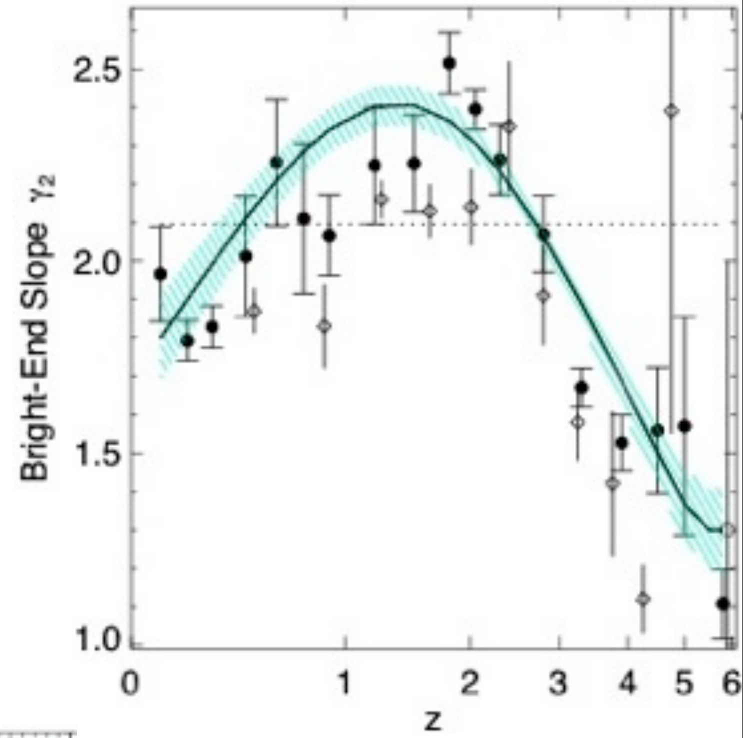


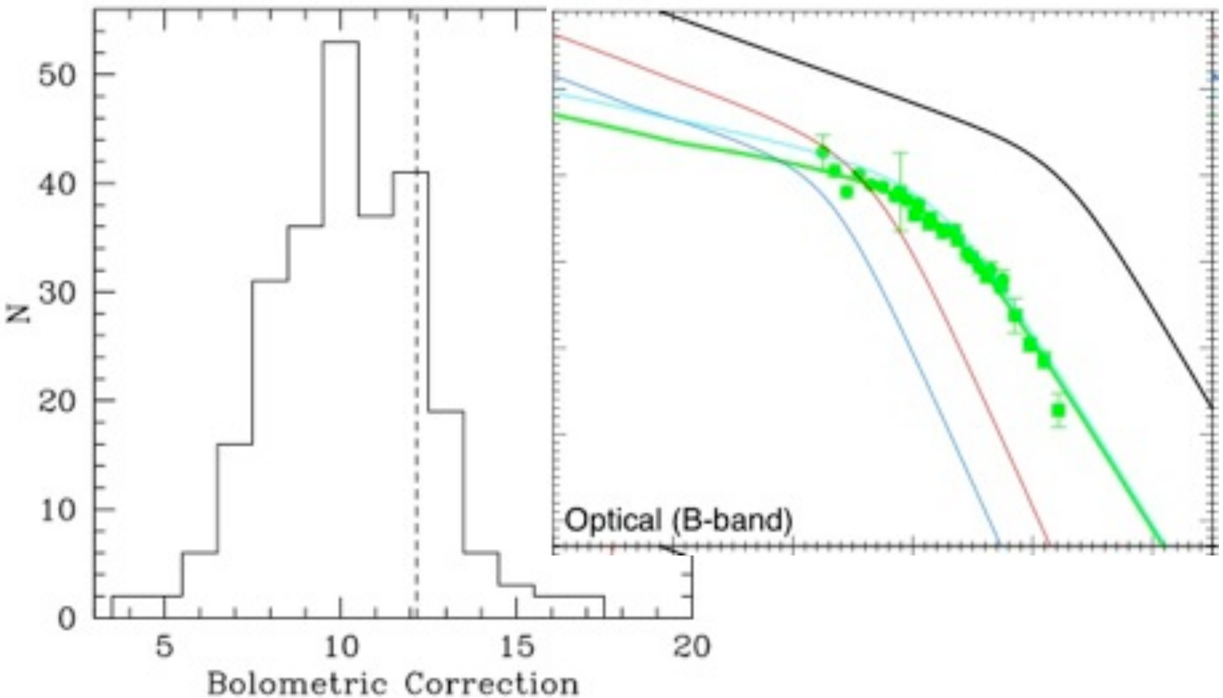
Richards+ 04, 06
see also Wyithe 04

What Do We Learn?

“SECOND ORDER”

- Bright End
  - Binning?
  - Lensing?
  - Effective bias? (distribution of bolometric corrections)
    - Unlikely in optical
    - Favored in *all bands*



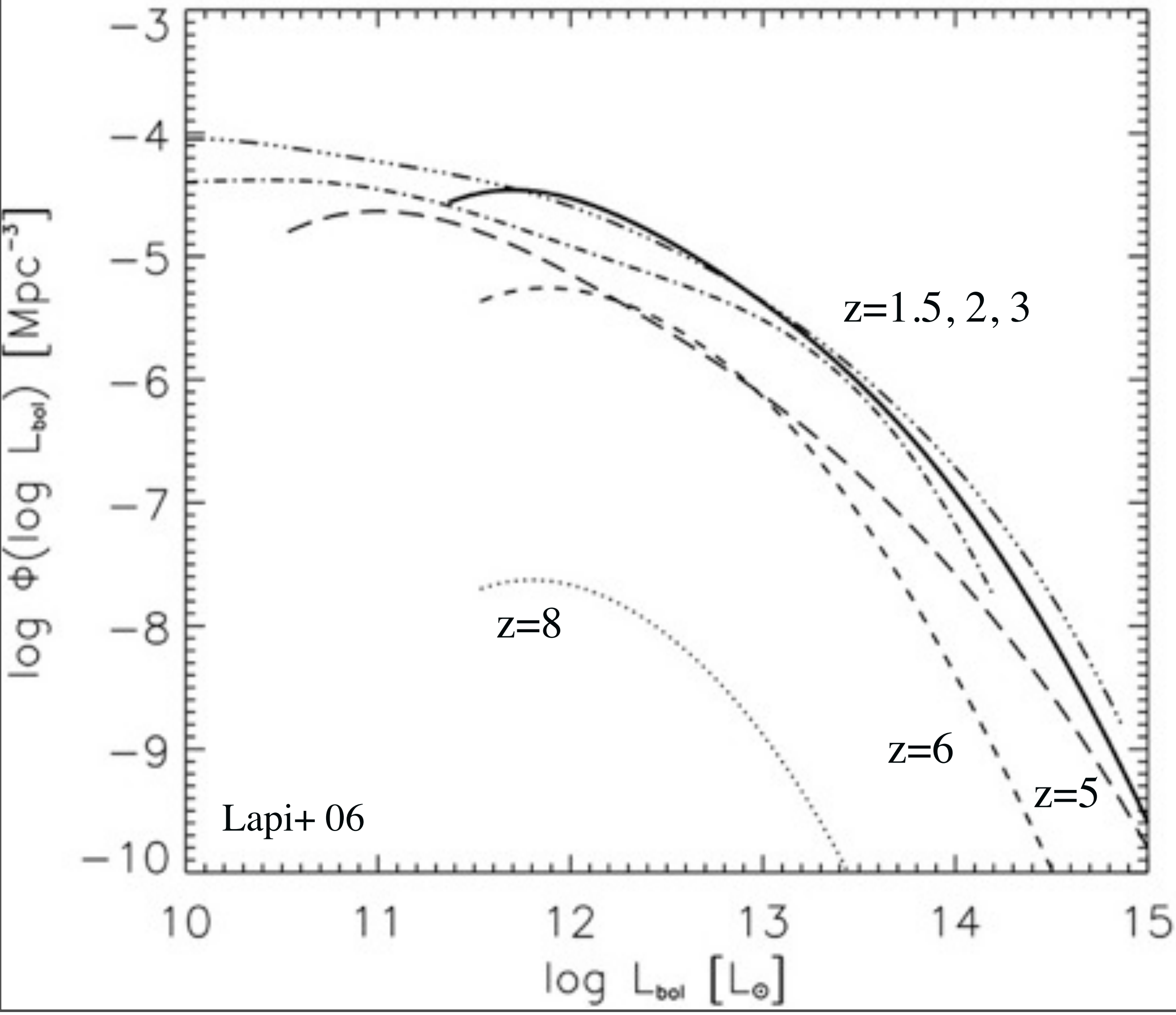


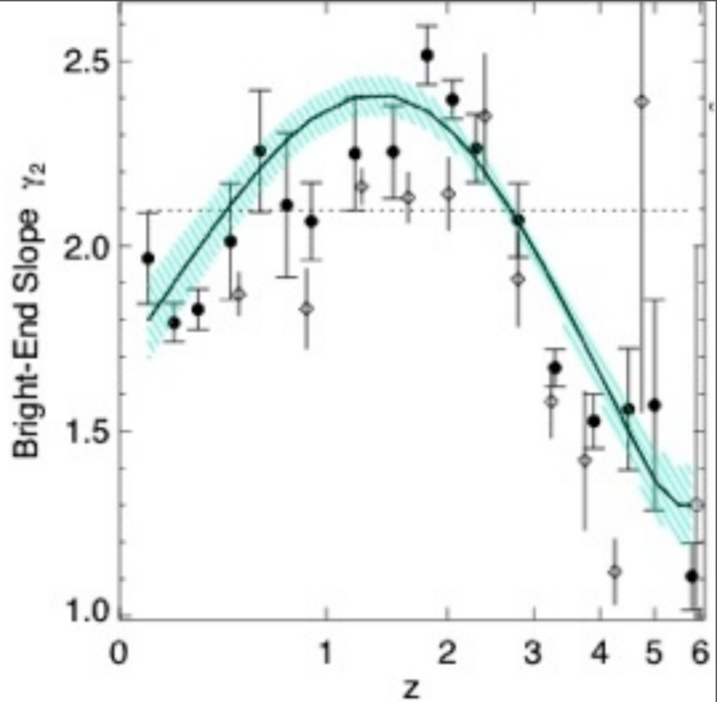
- Large, optical surveys still the best bet: hope for IR?

What Do We Learn?

"SECOND ORDER"

- Bright End
  - (Systematics)
  - Reflects shape of halo MF/buildup?



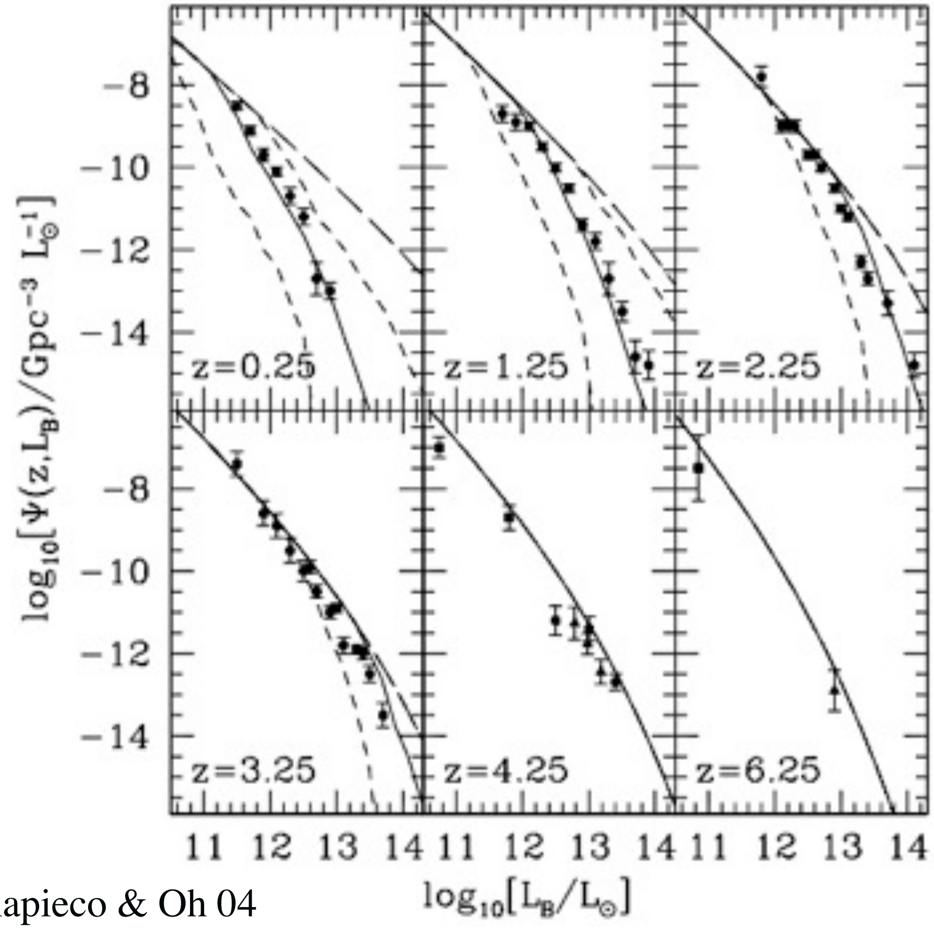


Shape ~
Sheth-Torman time
derivative?

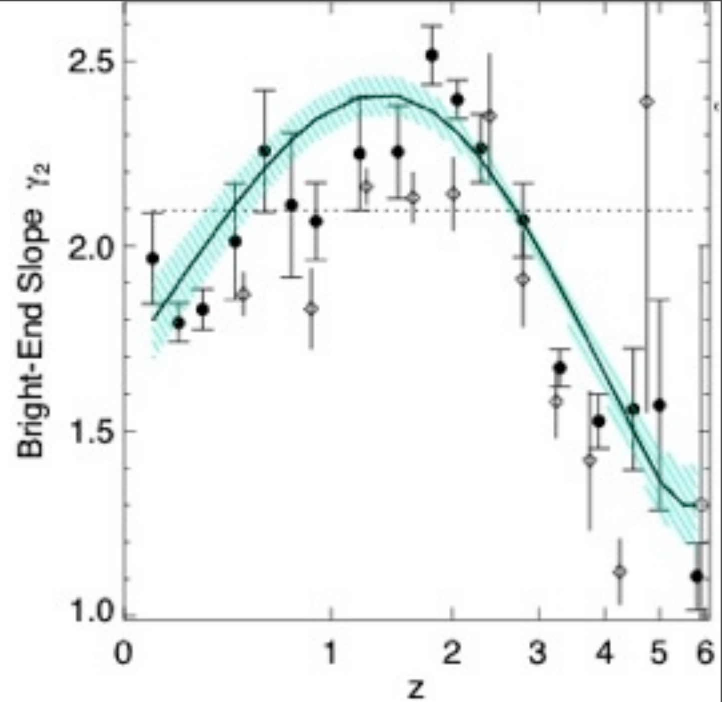
What Do We Learn?

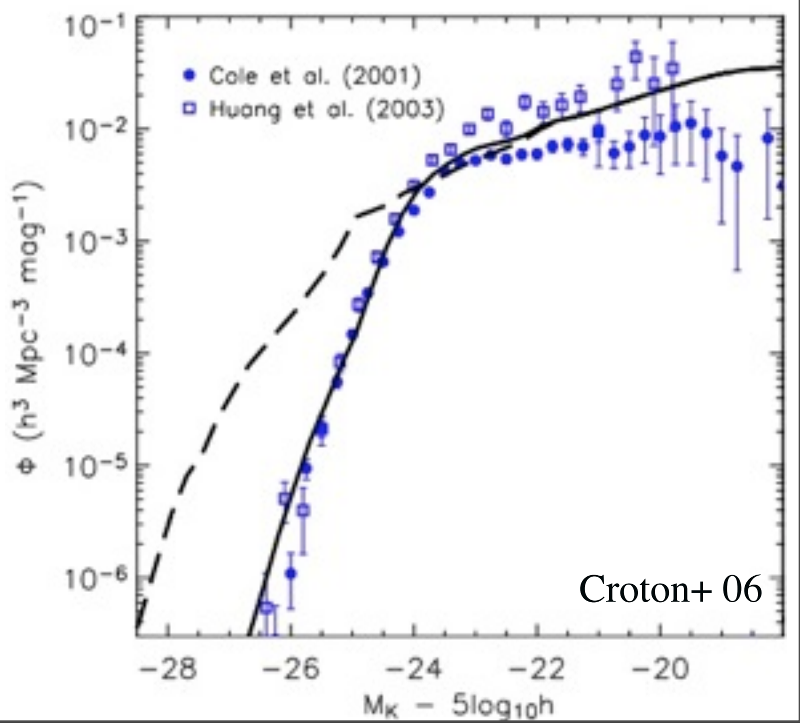
“SECOND ORDER”

- Bright End
    - (Systematics)
    - Reflects shape of halo MF/buildup?
    - Feedback again?



Scannapieco & Oh 04

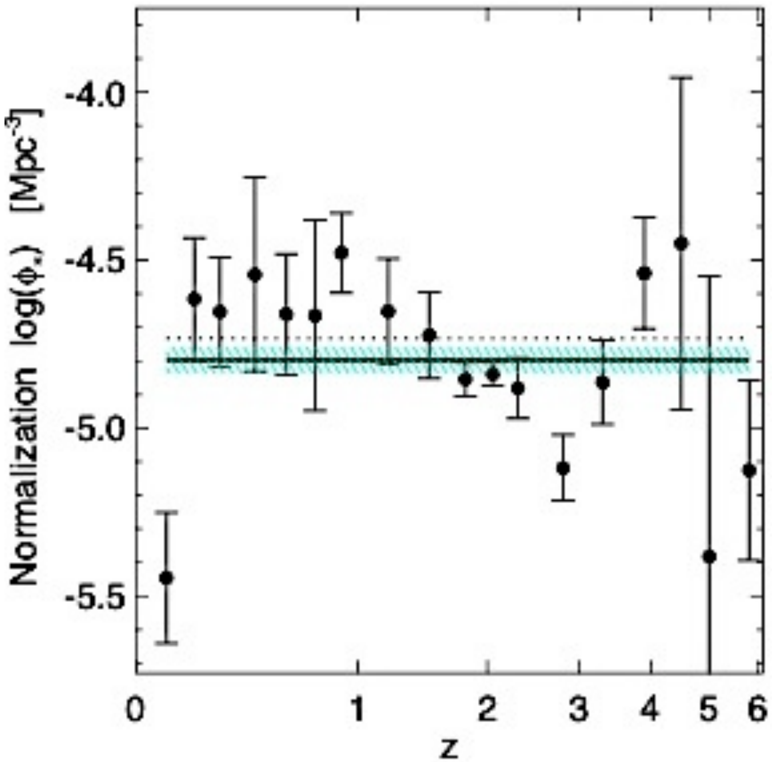


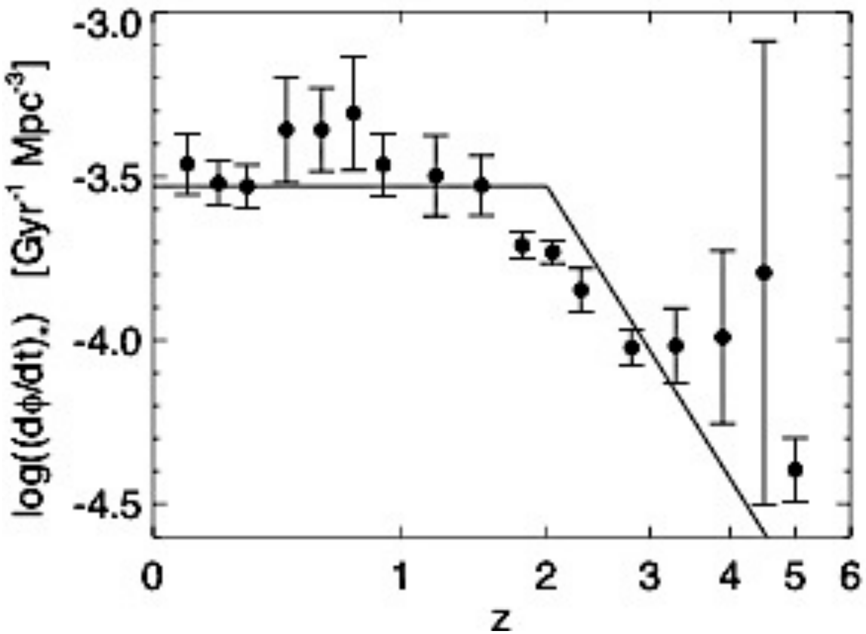


Croton+ 06

What Do We Not Know How to Interpret?

- Phi_star: what does it mean?
  - Number of active systems?
  - Duty cycles / lifetimes?





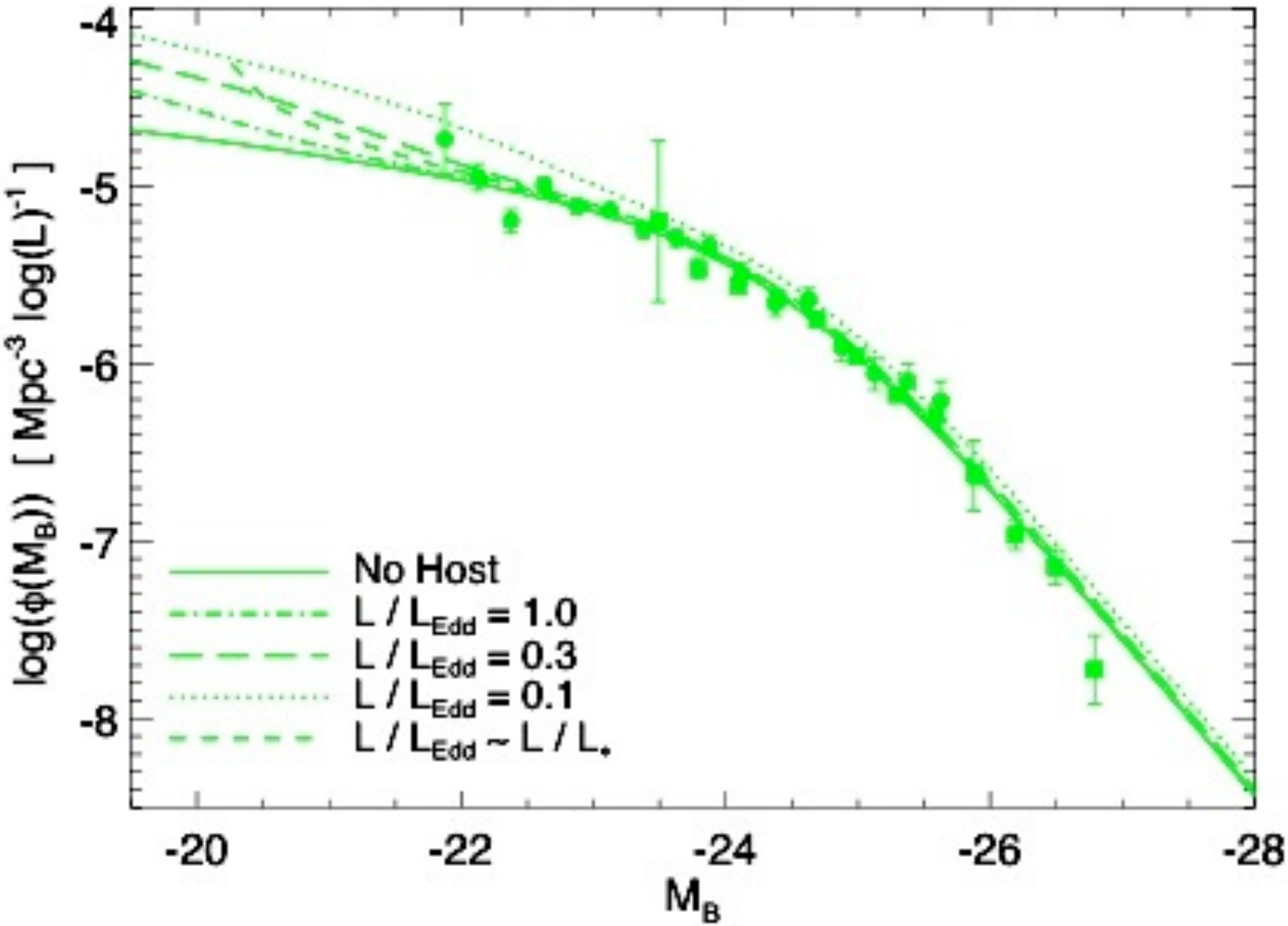
Summary

- The combined set of quasar observations has enormous constraining power that should be exploited
  - $-11 < \phi < -2$; $8 < L < 16$; $z = 0.0 - 6.4$
  - Need to be careful about combining observations
  - Systematics now the dominant uncertainty at $z<4$

- Constrains AGN physics:
  - SEDs & NH depend on L, not z
  - Break, luminosity density, shape change well-measured

- Encodes information about population buildup & feedback
  - "Cosmic Downsizing" as manifest in QSOs
  - Complex shape evolution
  - Quasar lifetime not one number:
    Luminosity-dependent lifetimes

Host Light

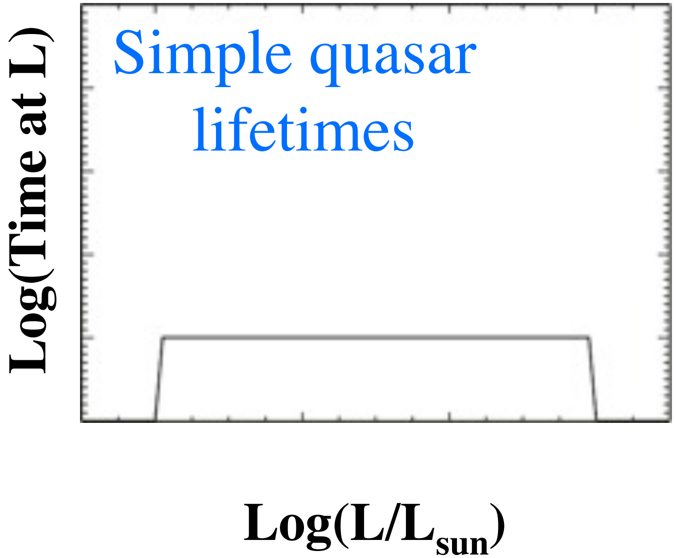


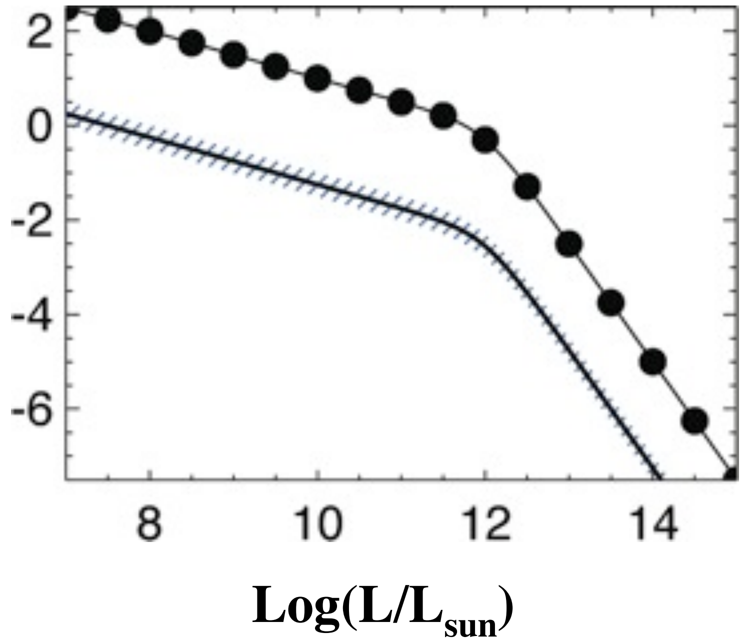
-4
-5
-6
-7
-8
-20
-22
-24
-26
-28
M_B
$\log(\phi(M_B))$ [Mpc^{-3} $\log(L)^{-1}$]
No Host
$L / L_{Edd} = 1.0$
$L / L_{Edd} = 0.3$
$L / L_{Edd} = 0.1$
$L / L_{Edd} \sim L / L_*$

Given the Conditional Quasar Lifetime, De-Convolve the QLF

QUANTIFIED IN THIS MANNER, UNIQUELY DETERMINES THE RATE OF “TRIGGERING”

$$\phi(L) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\log L}(L) = \int \frac{\mathrm{d}t(L, L_{\mathrm{peak}})}{\mathrm{d}\log(L)}\, \dot{n}(L_{\mathrm{peak}})\, \mathrm{d}\log(L_{\mathrm{peak}}).$$





- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF

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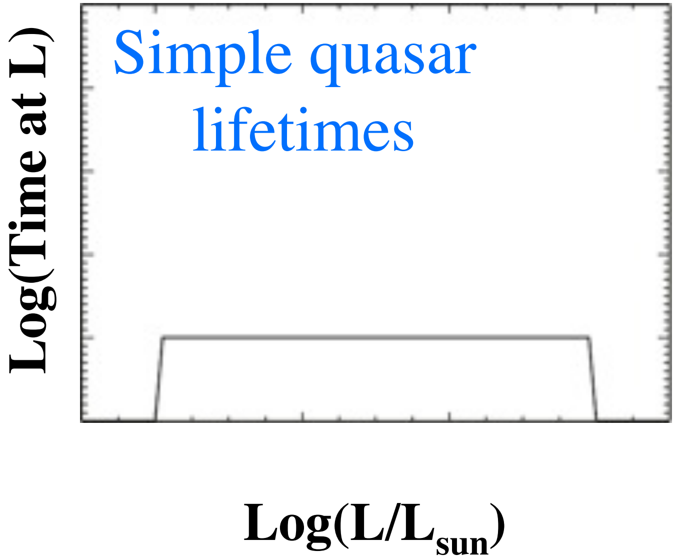

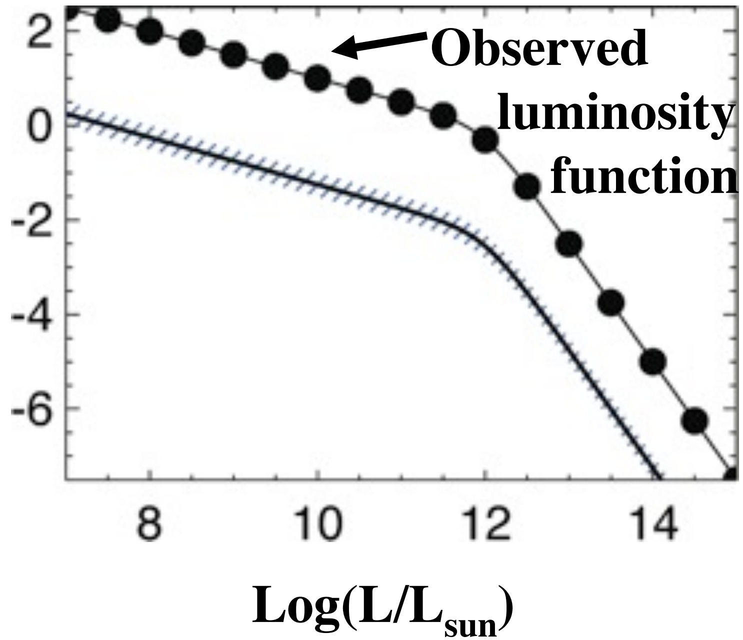

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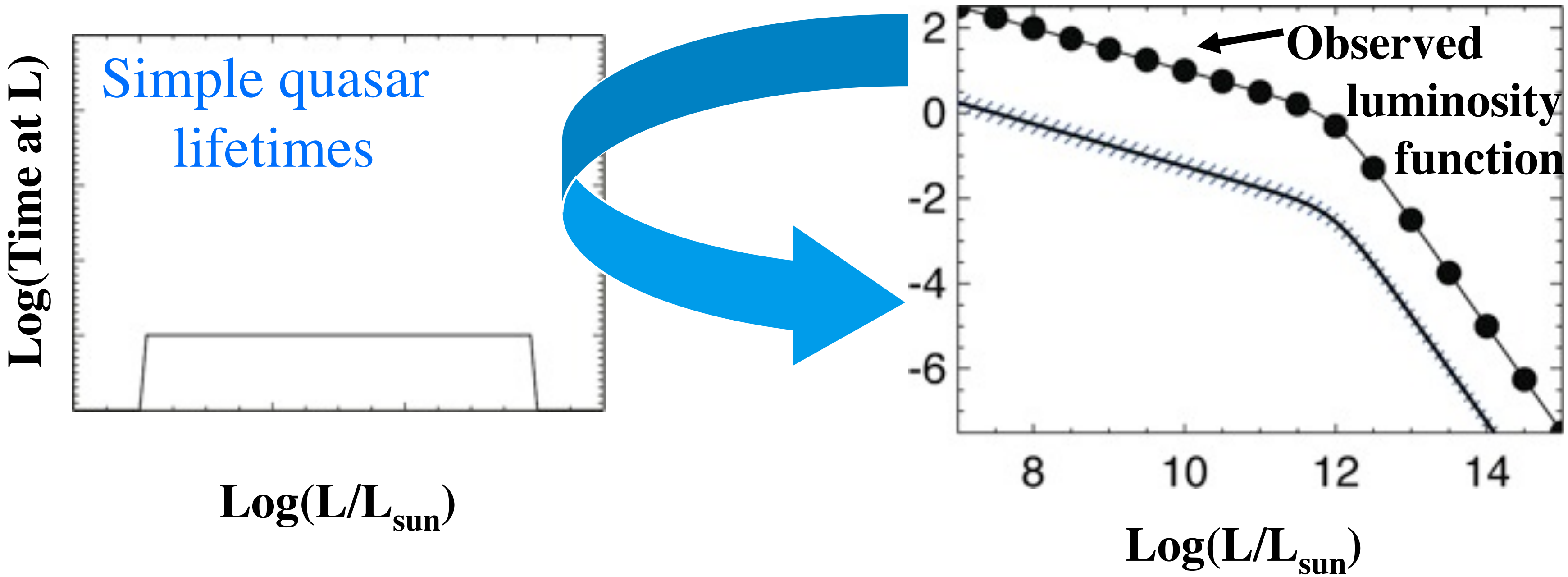

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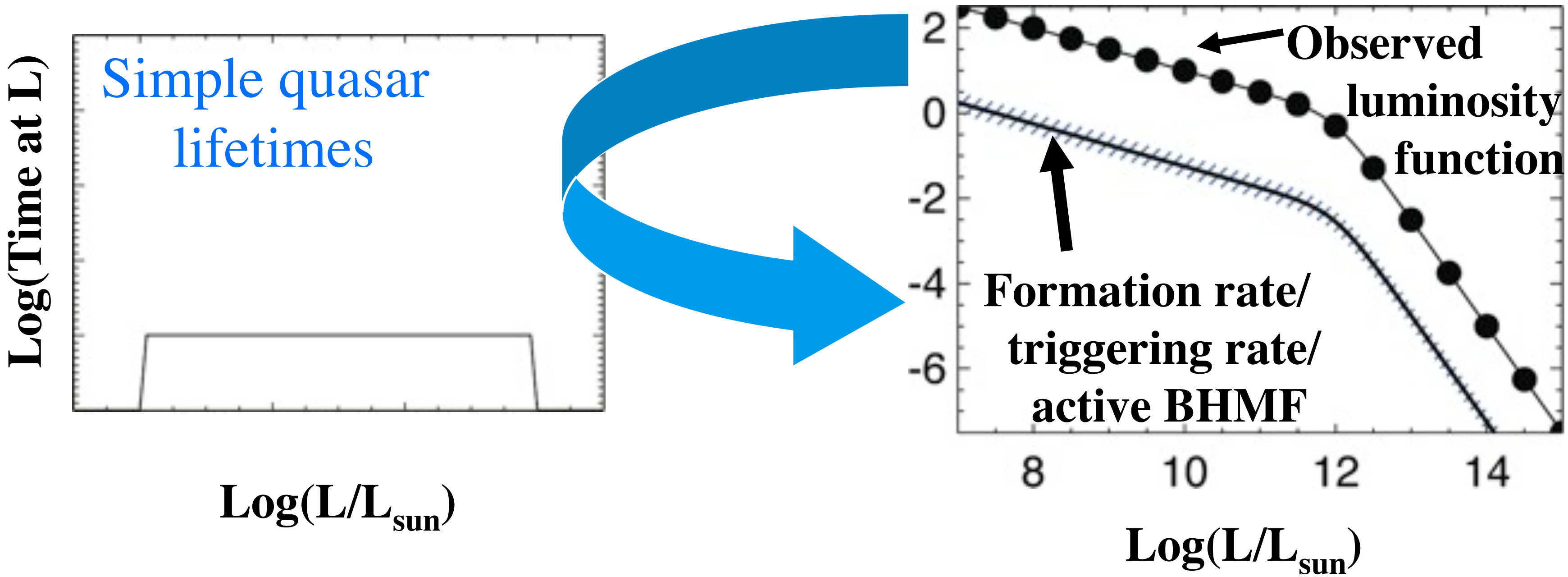

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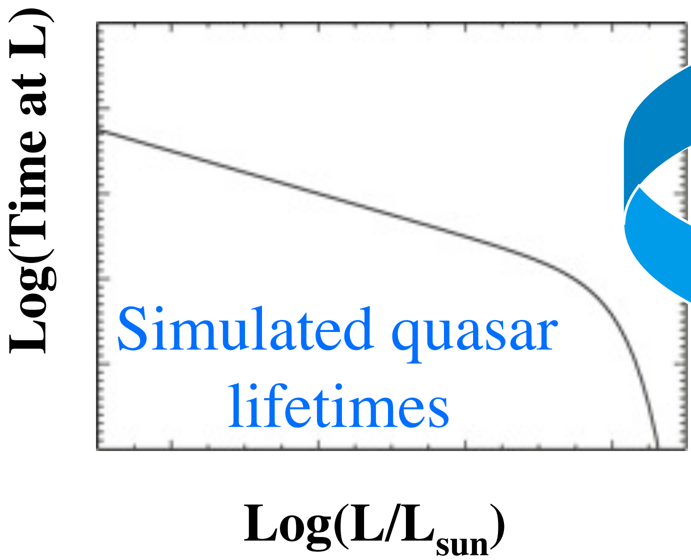
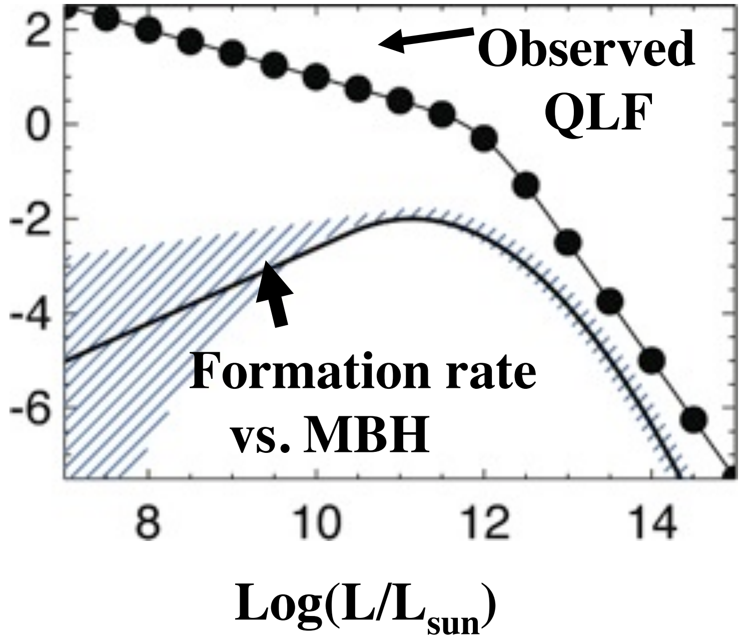


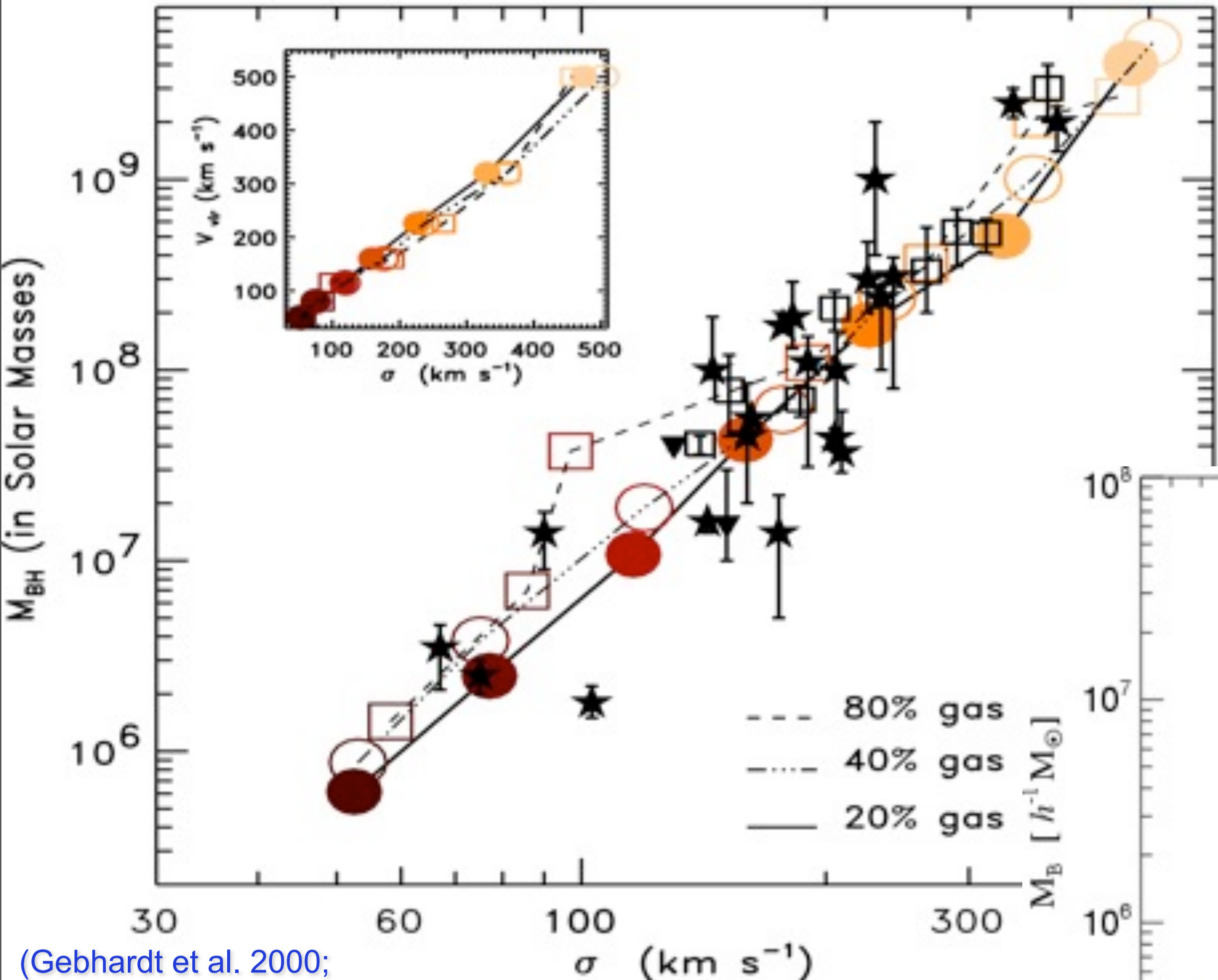


- Feedback-regulated lifetime drives a given QSO to lower L after blowout, and spends more time at low-L
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts

Feedback-driven "Blowout" Gives M-sigma Relation

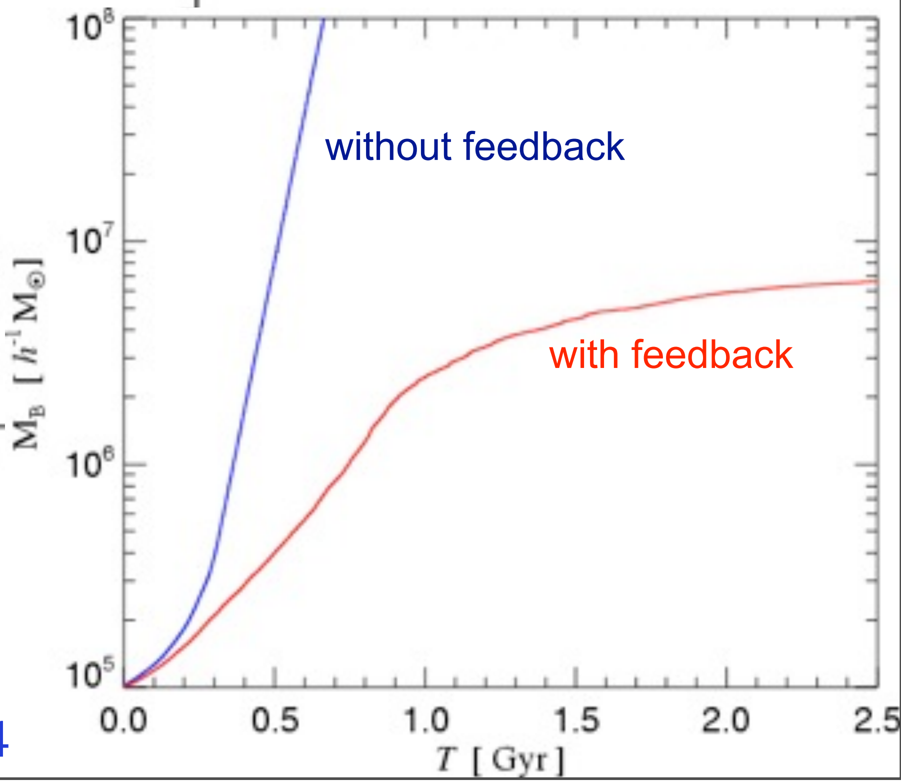
PREVENTS RUNAWAY BLACK HOLE GROWTH

Di Matteo et al. 2005



(Gebhardt et al. 2000;
Ferrarese & Merritt 2000;
Tremaine et al. 2002)

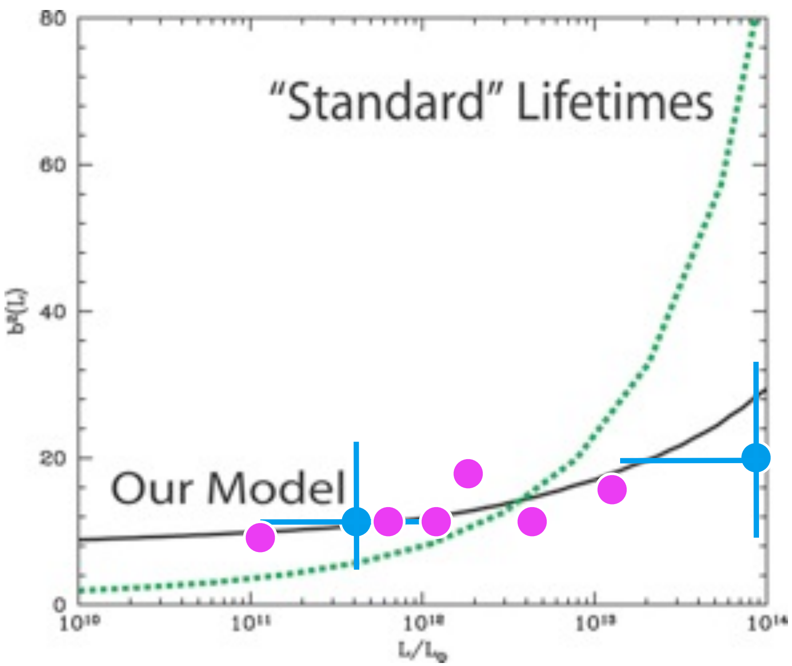
Black hole growth



Springel et al. 2004

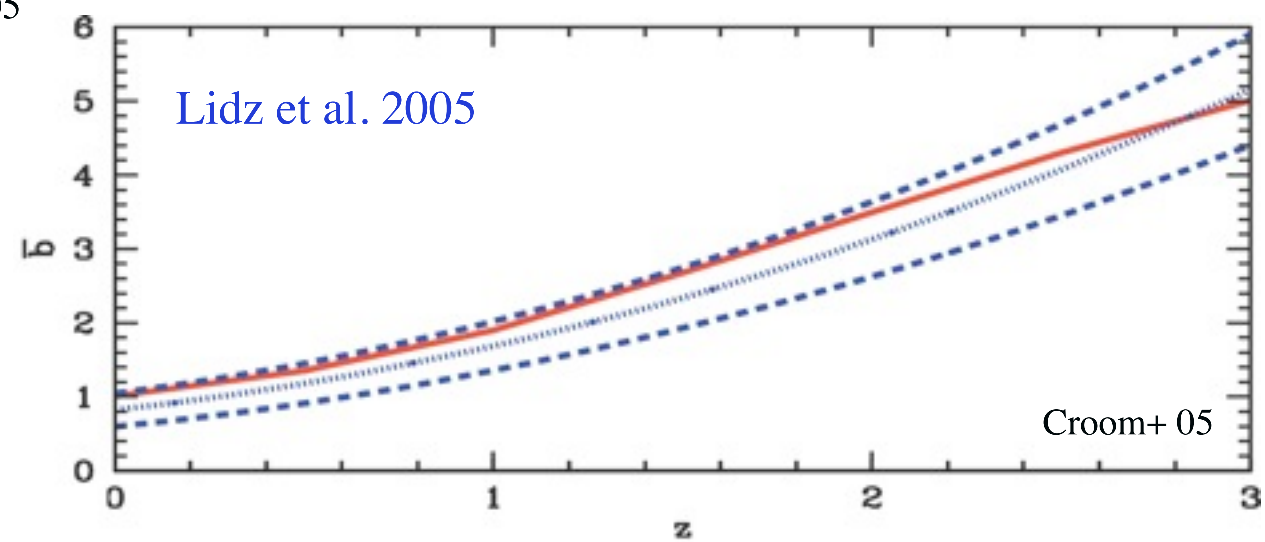
Quasar Clustering is a Strong Test of this Model

MOST FAINT QSOS ARE DECAYING BRIGHT QSOS - SHOULD BE IN SIMILAR HOSTS



- Weak dependence of clustering on observed luminosity
  - (Croom et al. 2005, Adelberger & Steidel 2005, Myers et al. 2005)
- Observed trends with redshift
  - (M_halo ~ 10^13 M_sun)

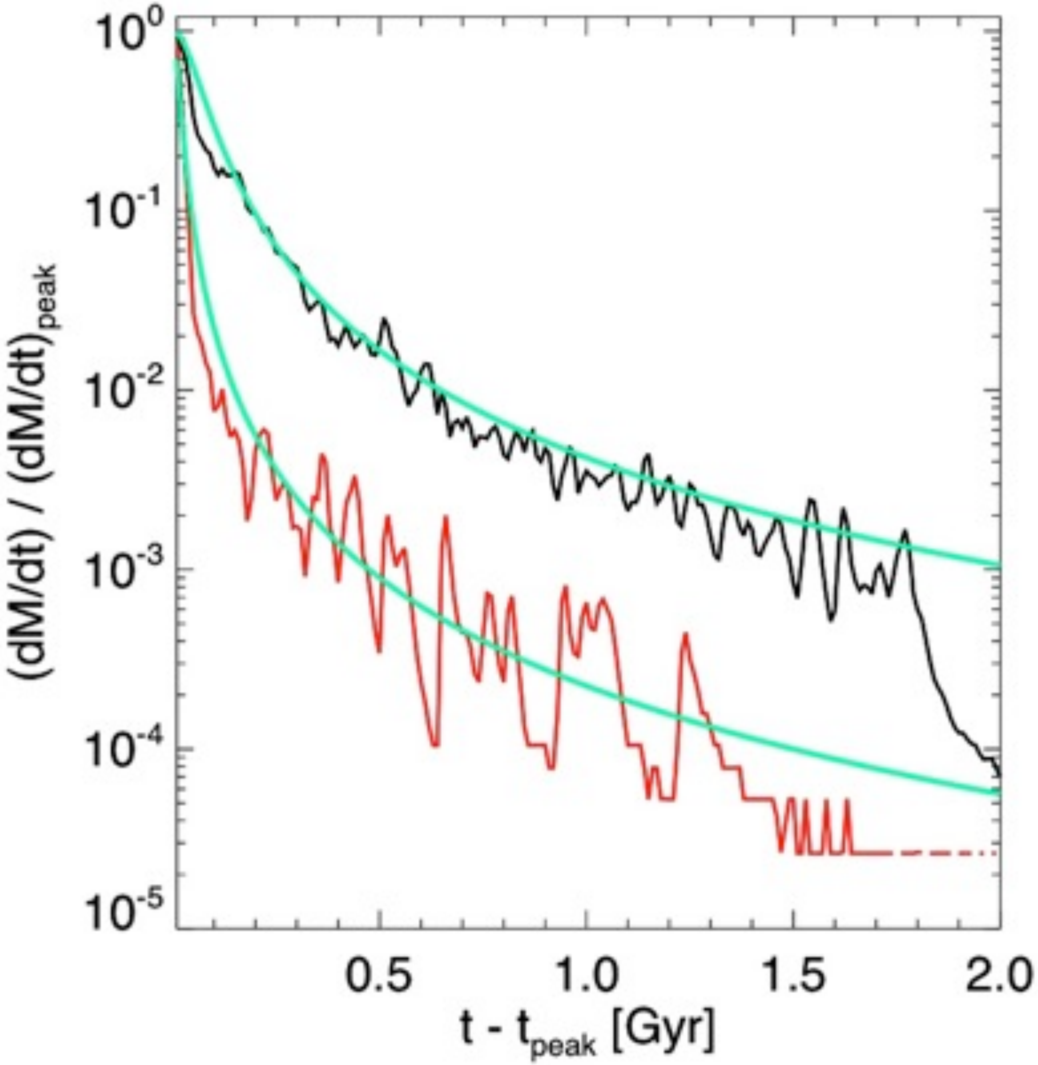
- Adelberger & Steidel 05
- Myers et al. 05



Generalizing the Model

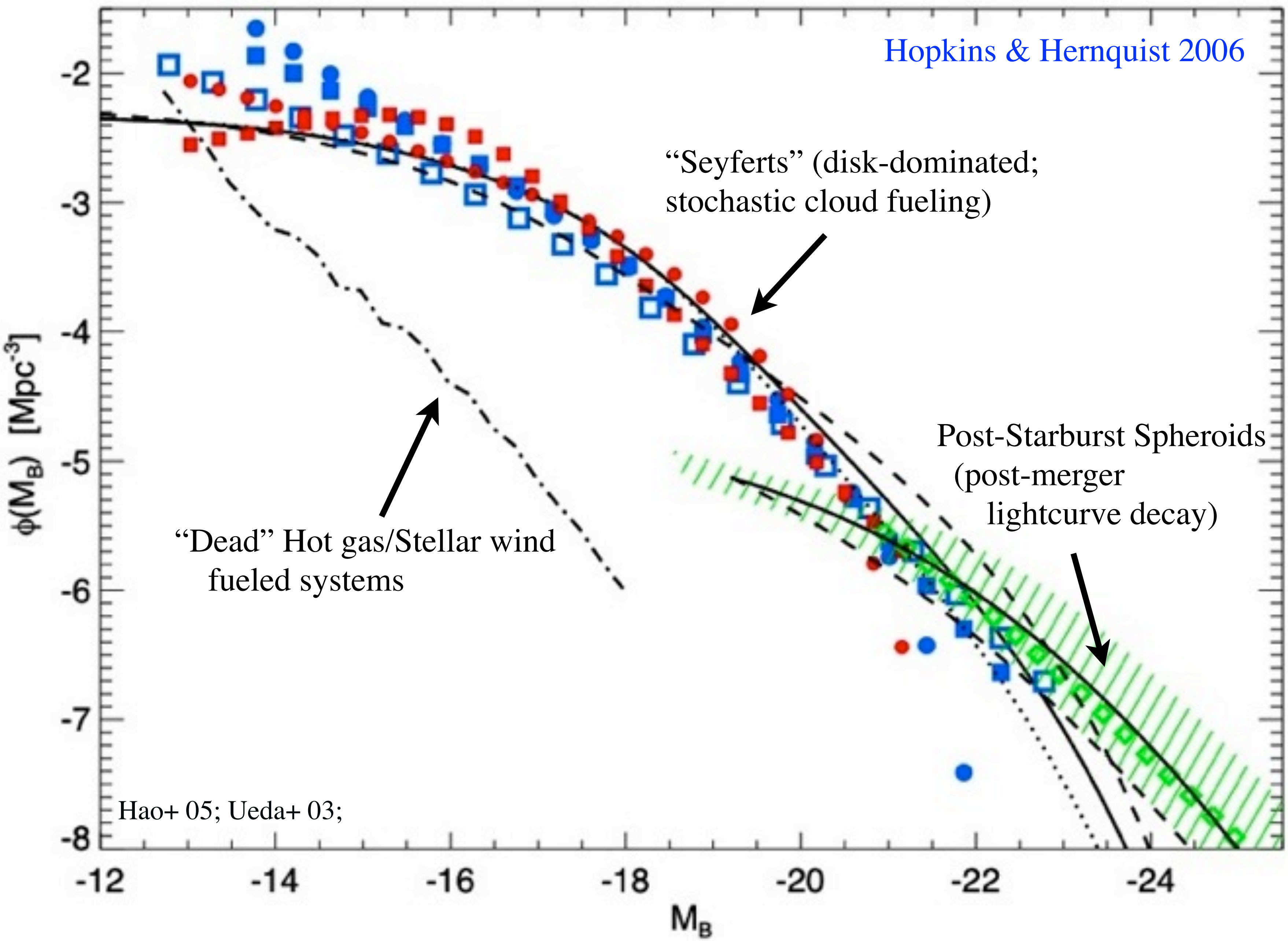
NOT ALL AGN ARE MERGER-DRIVEN

- Almost any (ex. radio) AGN feedback will share key properties:
  - Point-like
  - Short input (~ t_Salpeter)
  - E~E_binding (defines when the feedback is important)
- Suggests analytical solutions for decay of accretion rates in feedback-driven winds or blastwaves
  - Agrees well with simulations!
- Generalize to “Seyferts”
  - Disk-dominated galaxy, central molecular clouds
  - Calculate accretion rate(time) when a cloud “collides” with the BH



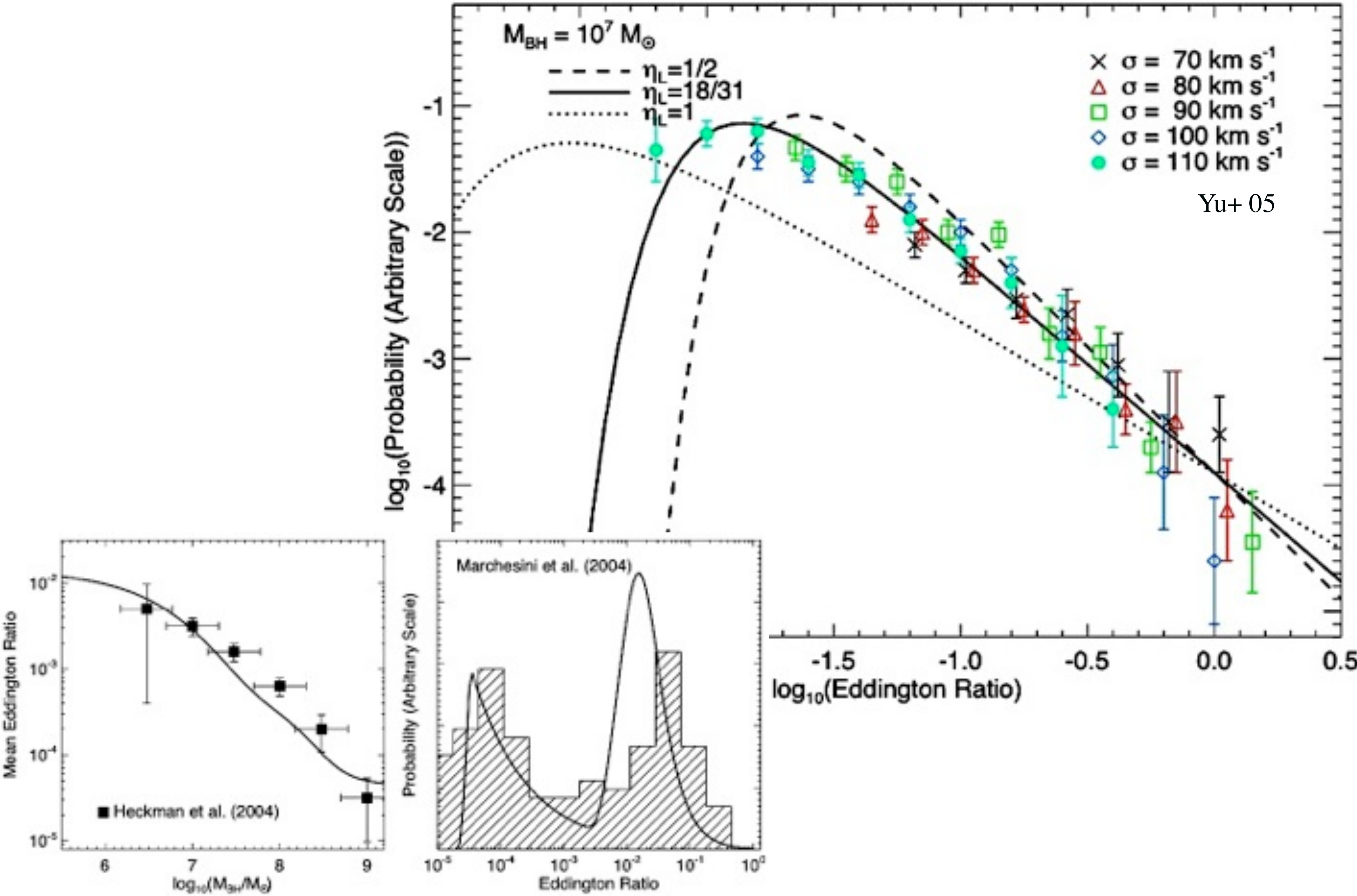
The Seyfert Luminosity Function

A STOCHASTIC BUT FEEDBACK-REGULATED MODEL



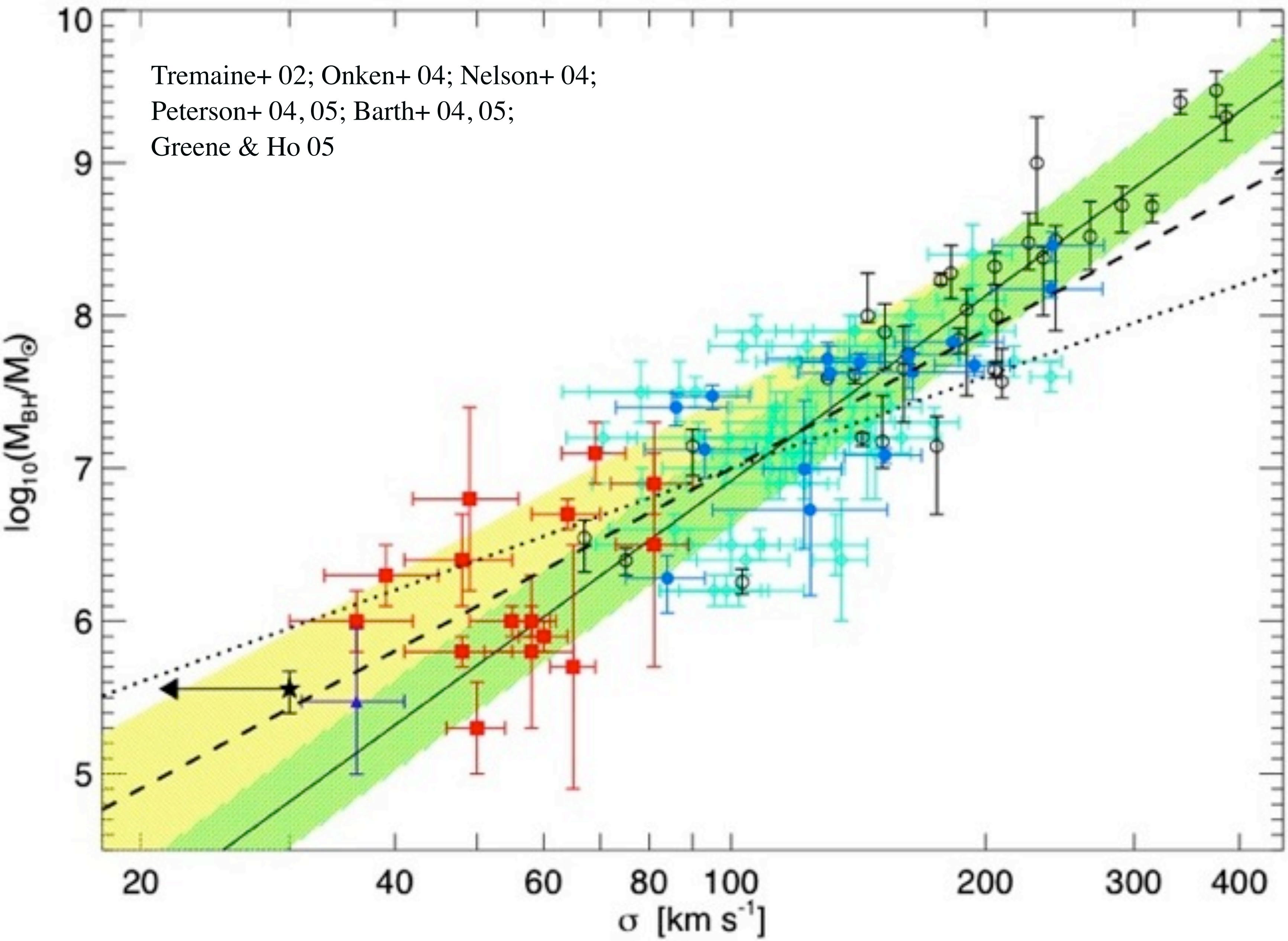
The Seyfert Luminosity Function

PREDICT THE EDDINGTON RATIO DISTRIBUTIONS FROM THIS FUELING MODE, AS BEFORE



The Seyfert Luminosity Function

CORRECTIONS TO THE M_BH-SIGMA RELATION



The Seyfert Luminosity Function
CONTRIBUTION AS A FUNCTION OF REDSHIFT