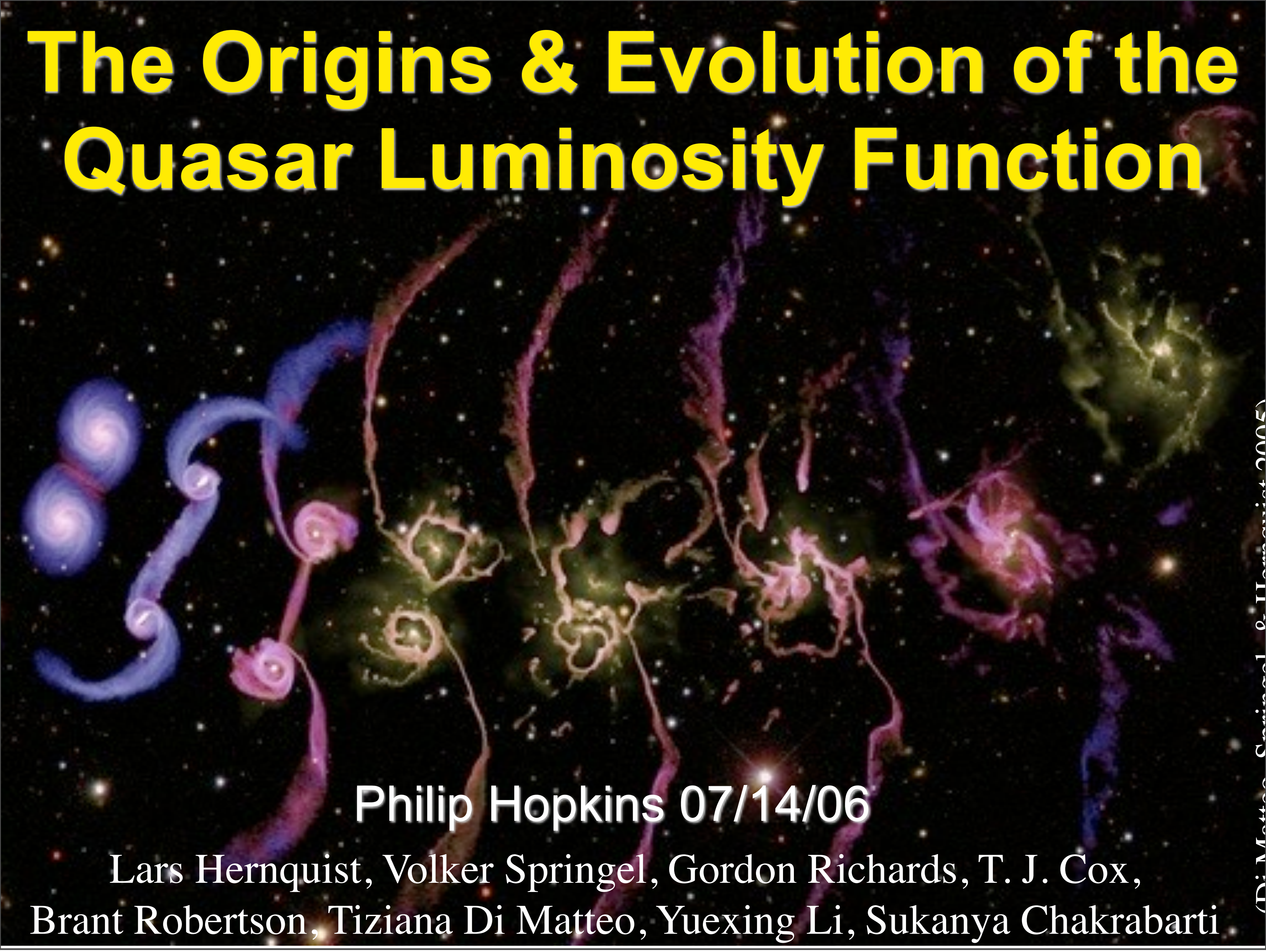
The Origins & Evolution of the Quasar Luminosity Function



Philip Hopkins 07/14/06

Lars Hernquist, Volker Springel, Gordon Richards, T. J. Cox,
Brant Robertson, Tiziana Di Matteo, Yuexing Li, Sukanya Chakrabarti

A subset of recent quasar samples...

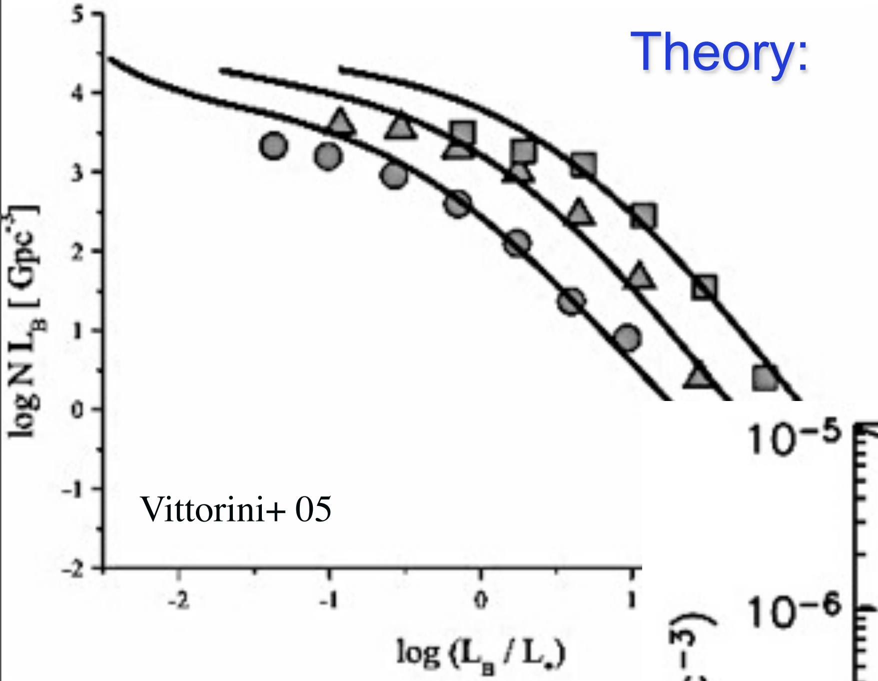
TABLE 1
MEASUREMENTS OF THE QLF

Reference	Survey/Field[a]	Rest Wavelength/Band	z Range[b]	Luminosity Range[b]	χ^2/ν[c]	$N_{\rm AGN}$	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	∼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	$0.015-4.8$	$10^{42} < L_{0.5-2} < 10^{48}\,{\rm erg\,s^{-1}}$	169/51	2,566	circles
Miyaji et al. (2000, 2001)	*ROSAT* (RASS+RDS)	$0.5-2$ keV	$0.015-4.8$	$10^{41} < L_{0.5-2} < 10^{47}\,{\rm erg\,s^{-1}}$	112/41	691	stars
Silverman et al. (2005b)	CHAMP+*ROSAT* (RASS)	$0.5-2$ keV	$0.1-5$	$10^{44.5} < L_{0.5-2} < 10^{46}\,{\rm erg\,s^{-1}}$	24.1/9	217	squares
Hard X-ray:							
Barger et al. (2003a,b)	CDF-N	$2-8$ keV	$\sim 5-6.5$	$10^{43} < L_{2-8} < 10^{45}\,{\rm erg\,s^{-1}}$	1.02/1	1	diamonds
Barger et al. (2005)	CDF-N/S + CLASXS + *ASCA*	$2-8$ keV	$\sim 0.1-1.2$	$10^{42} < L_{2-8} < 10^{46}\,{\rm erg\,s^{-1}}$	41.0/30	601	squares
...	CDF-N/S + CLASXS	$2-8$ keV	$\sim 1.5-5.0$	$10^{42} < L_{2-8} < 10^{46}\,{\rm erg\,s^{-1}}$	15.5/9	∼100	...
Barger & Cowie (2005)	CDF-N/GOODS-N	$2-8$ keV	$\sim 2-3$	$10^{43} < L_{2-8} < 10^{44.5}\,{\rm erg\,s^{-1}}$	1.73/1	136	...
La Franca et al. (2005)	HELLAS2XMM	$2-10$ keV	$0.0-4.0$	$10^{42} < L_{2-10} < 10^{46.5}\,{\rm erg\,s^{-1}}$	14.4/18	508	stars
Nandra et al. (2005)	GWS + HDF-N	$2-10$ keV	$2.7-3.2$	$10^{43} < L_{2-10} < 10^{44.5}\,{\rm erg\,s^{-1}}$	0.77/1	15	crosses
Sazonov & Revnivtsev (2004)	RXTE	$3-20$ keV	$0.0-0.1$	$10^{41} < L_{3-20} < 10^{46}\,{\rm erg\,s^{-1}}$	9.75/10	77	inverted triangles
Silverman et al. (2005a,c)	CHAMP	$0.3-8.0$ keV	$0.2-4.0$	$10^{42} < L_{0.3-8} < 10^{45.5}\,{\rm erg\,s^{-1}}$	26.3/15	368	triangles
Ueda et al. (2003)	*HEAO* 1 + AMSS-n/s + ALSS + *ASCA* + CDF-N	$2-10$ keV	$0.015-3.0$	$10^{41.5} < L_{2-10} < 10^{46.5}\,{\rm erg\,s^{-1}}$	26.5/35	247	circles
Mid-IR:							
Brown et al. (2006)	*Spitzer* Boötes (NDWFS)	8 μm	$\sim 1-5$	$10^{45} < L_{8\,\mu m} < 10^{47}\,{\rm erg\,s^{-1}}$	3.77/10	183	circles
Matute et al. (2006)	RMS + ELIAS + HDF-N/S	15 μm	$\sim 0.1-1.2$	$10^{42} < L_{15\,\mu m} < 10^{47}\,{\rm erg\,s^{-1}}$	23.4/18	148	squares
Emission Lines:							
Hao et al. (2005)	SDSS (main galaxy sample)	Hα	$0-0.33$	$10^5 < L_{\rm H\alpha} < 10^9\,L_\odot$	29.5/21	∼3000	pentagons
...	...	[OII]	...	$10^5 < L_{\rm O\,II} < 10^8\,L_\odot$	...	...	...
...	...	[OIII]	...	$10^5 < L_{\rm O\,III} < 10^9\,L_\odot$	...	...	...

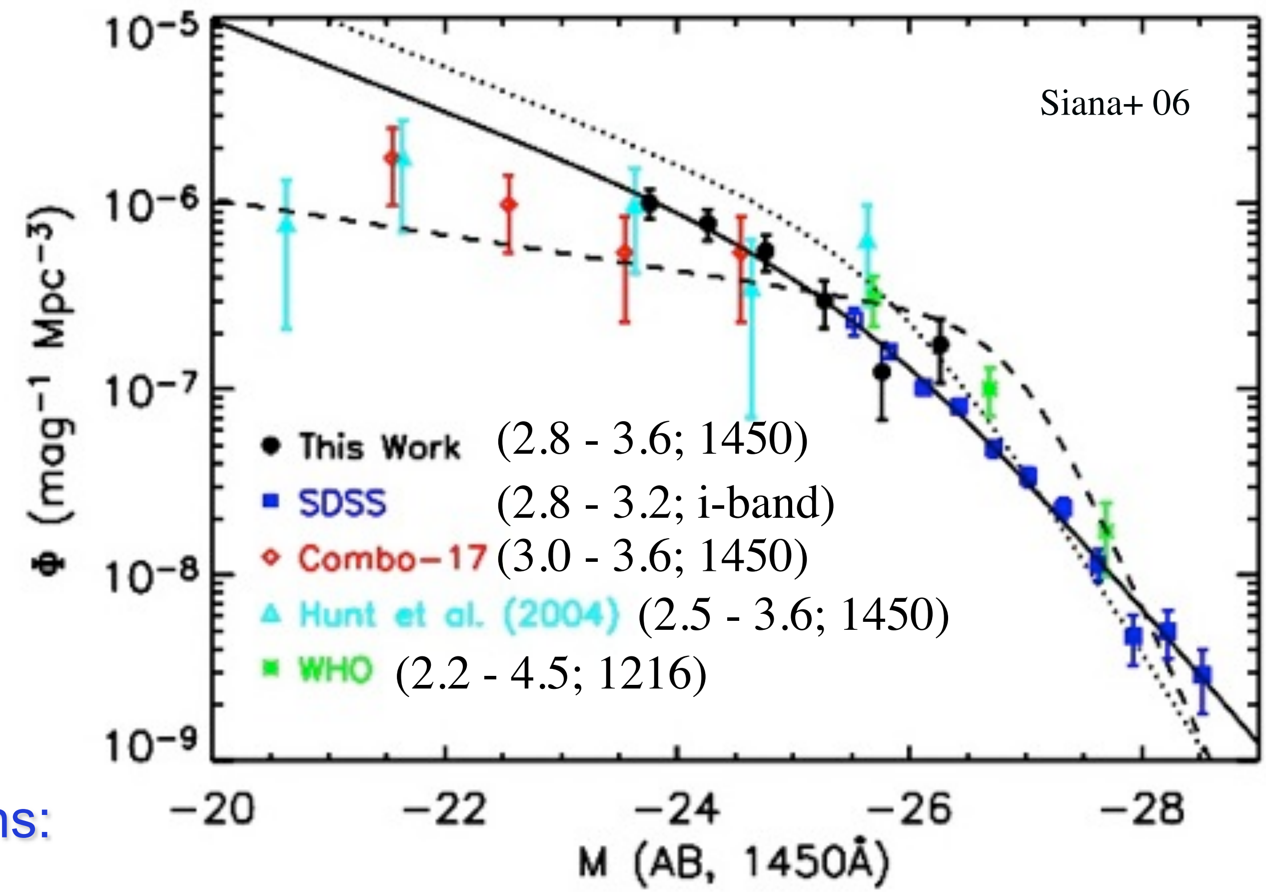
[a]For a detailed description of each sample, we direct the reader to the listed references (and references therein).
[b]Redshift and luminosity ranges listed are for the *entire* sample in each case, they should not be taken to imply that the observations simultaneously span both ranges.
[c]Reduced χ^2 of binned QLF with respect to our full best-fit.

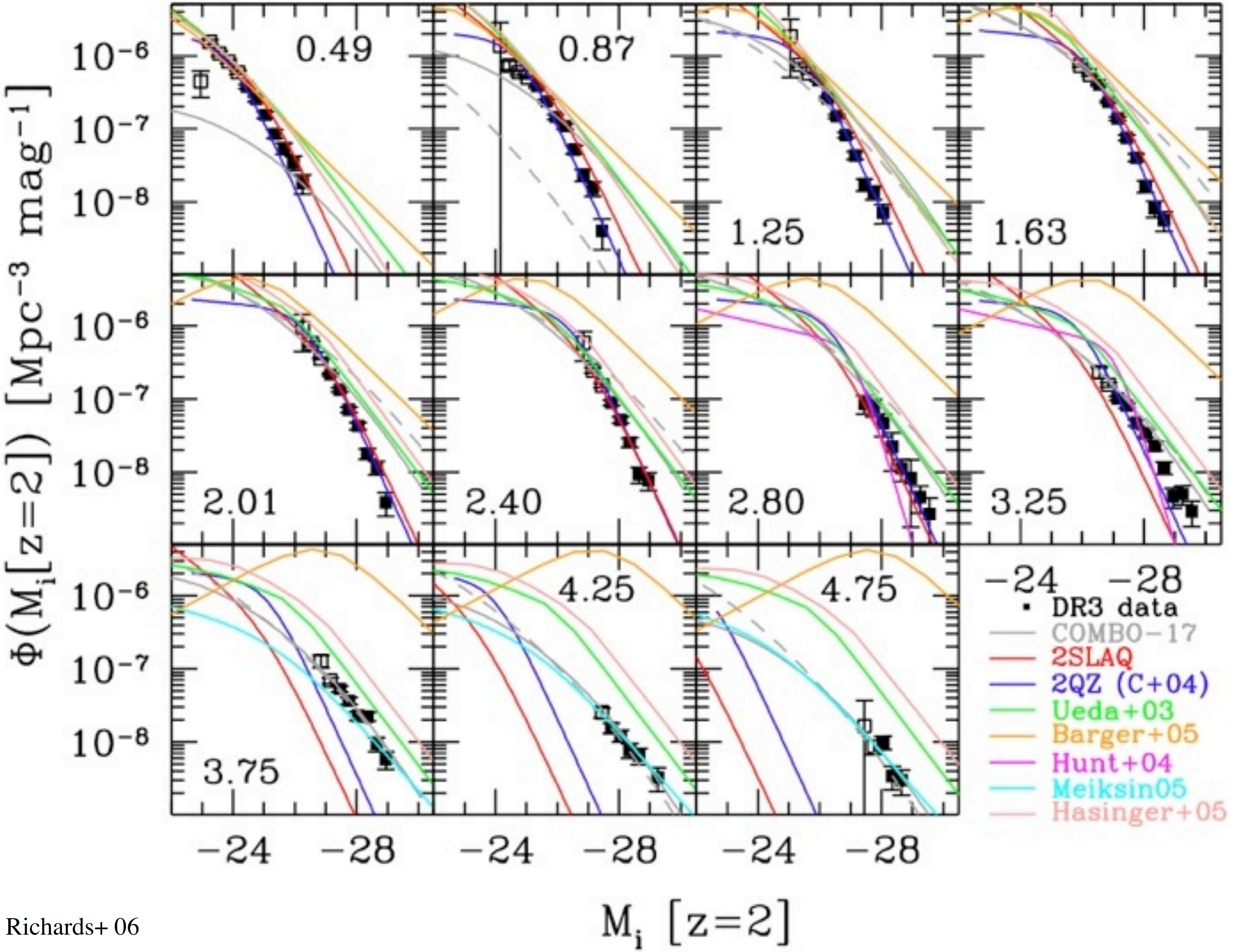
And yet...

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
Φ(Mi[z=2]) [Mpc−3 mag−1]
Mi [z=2]
DR3 data
COMBO-17
2SLAQ
2QZ (C+04)
Ueda+03
Barger+05
Hunt+04
Meiksin05
Hasinger+05

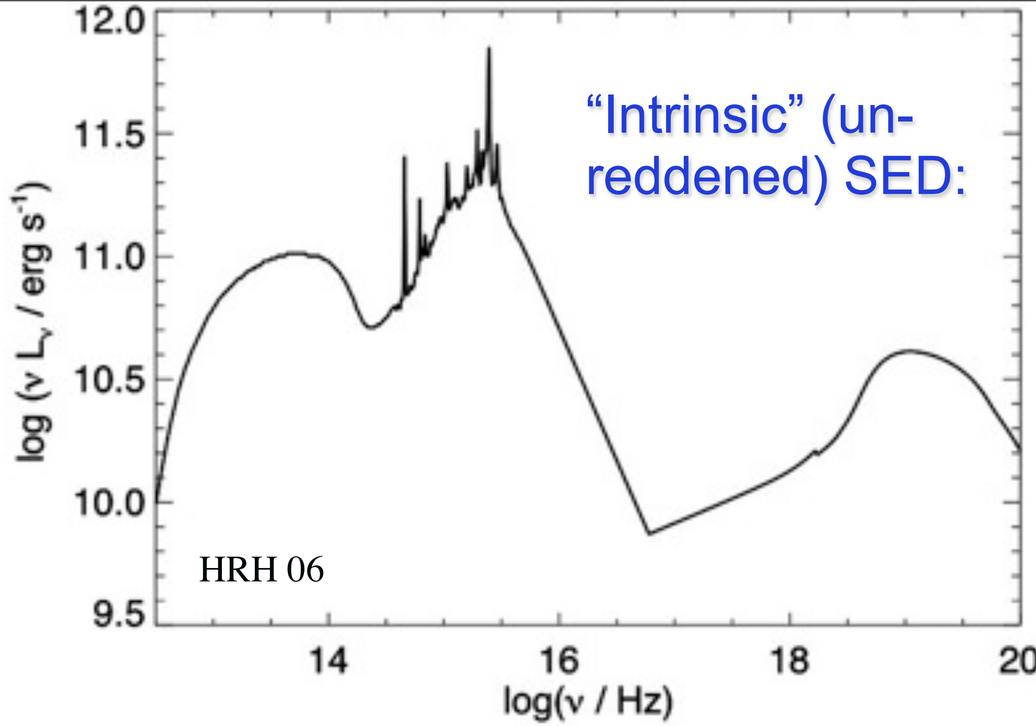
Richards+ 06

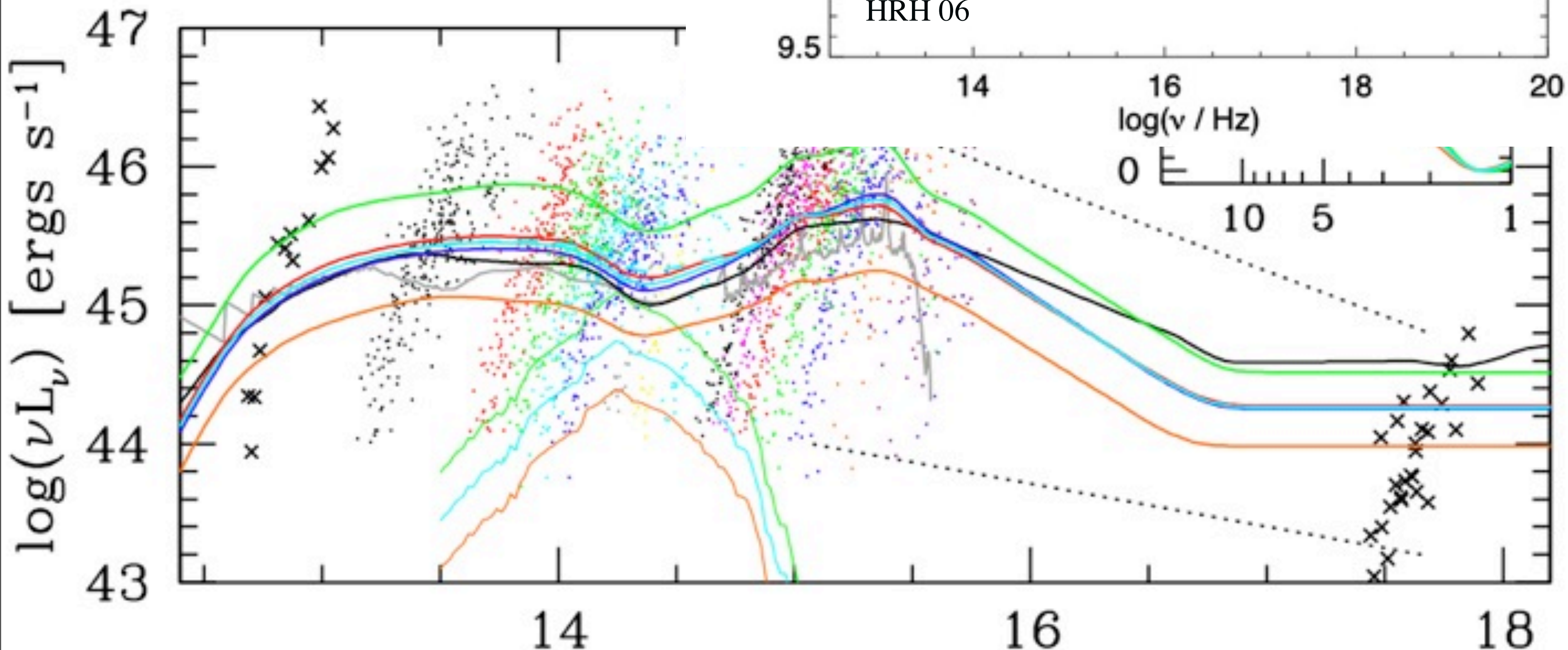
How to Address This?

METHODOLOGY

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

“Intrinsic” (un-reddened) SED:



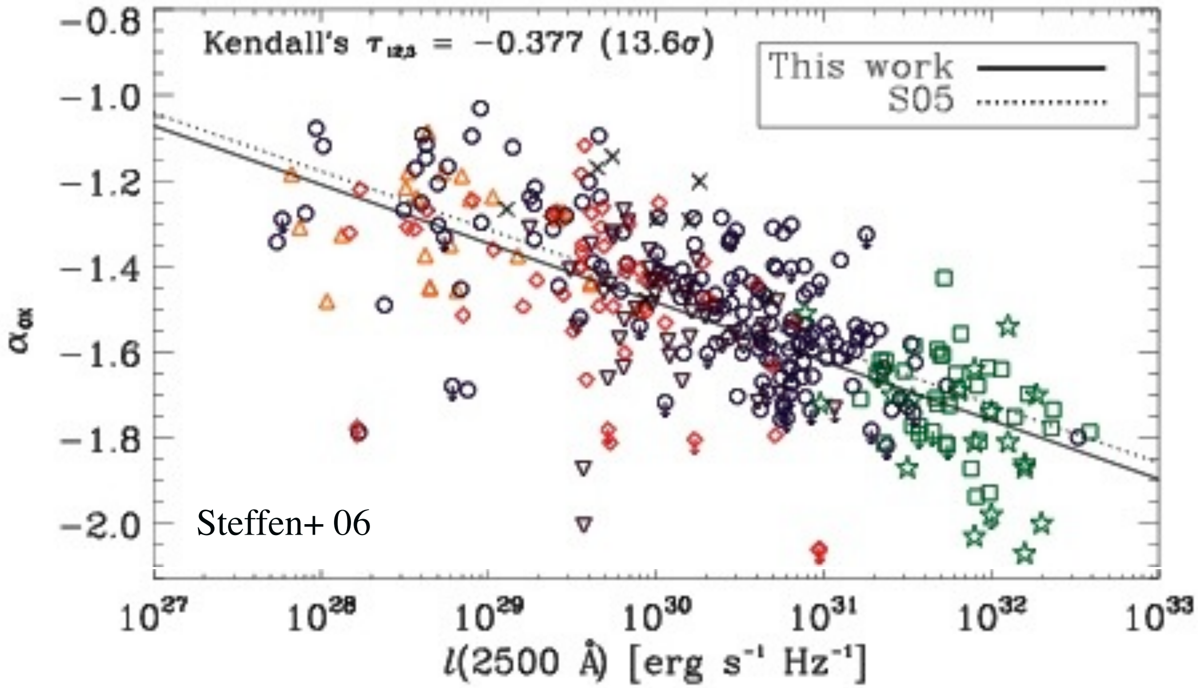


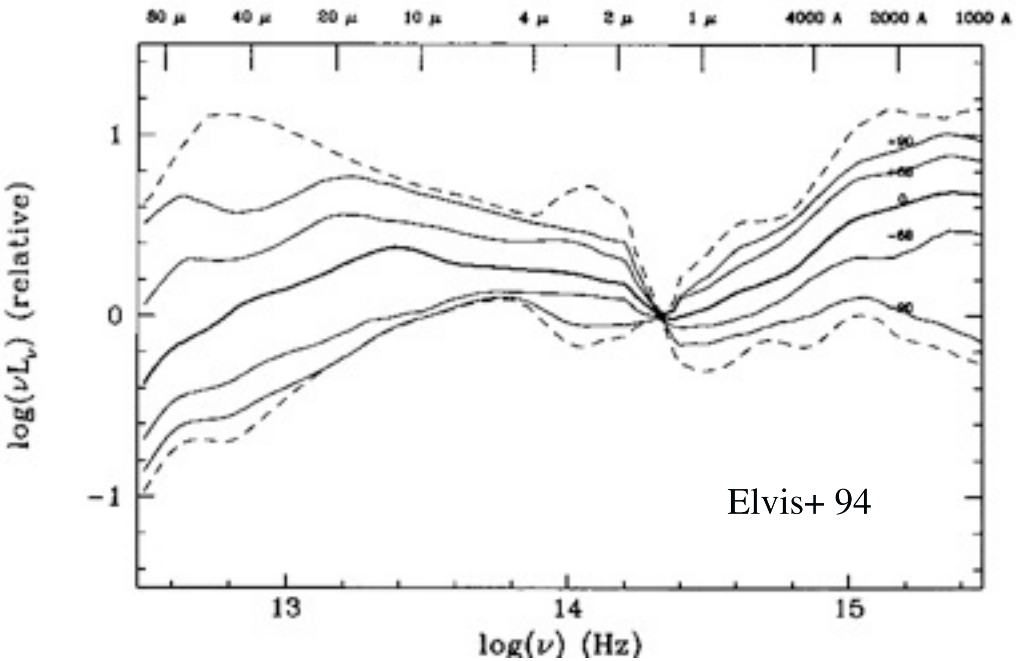
Elvis+ 94; Vanden Berk+ 01; Telfer+ 01;
Ueda+ 03; Hatziminaoglou+ 05; Richards+ 06;

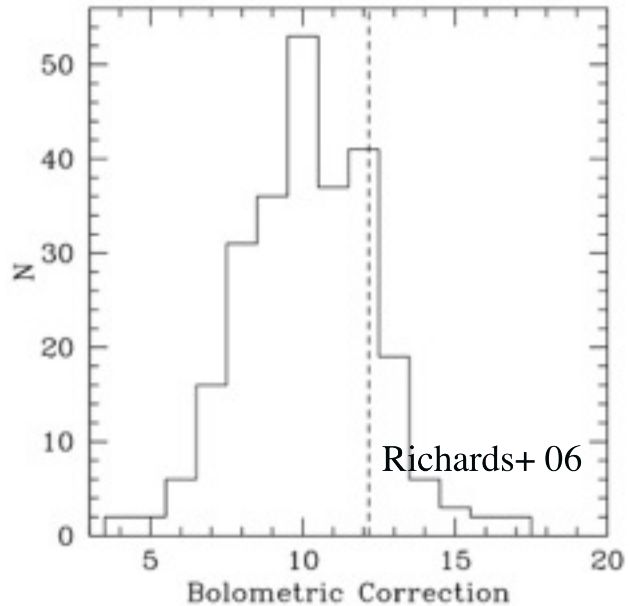
How to Address This?

METHODOLOGY

- Dependence on L
- Distribution of SED shapes



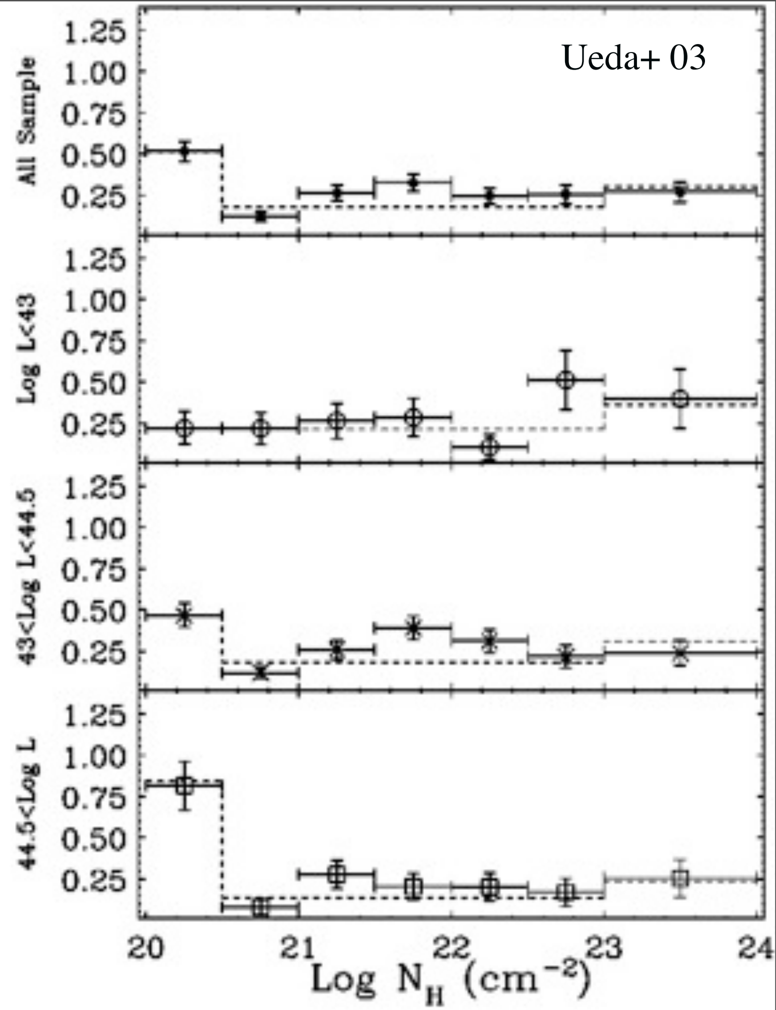


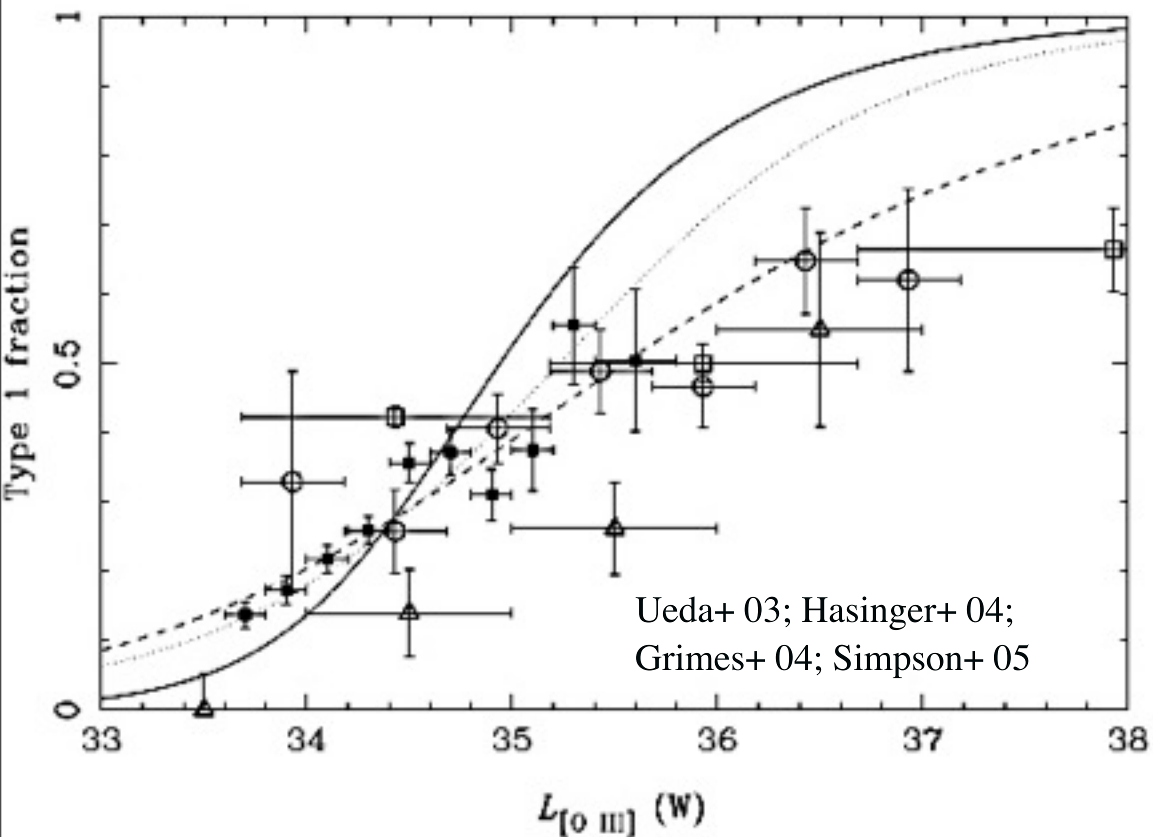


How to Address This?

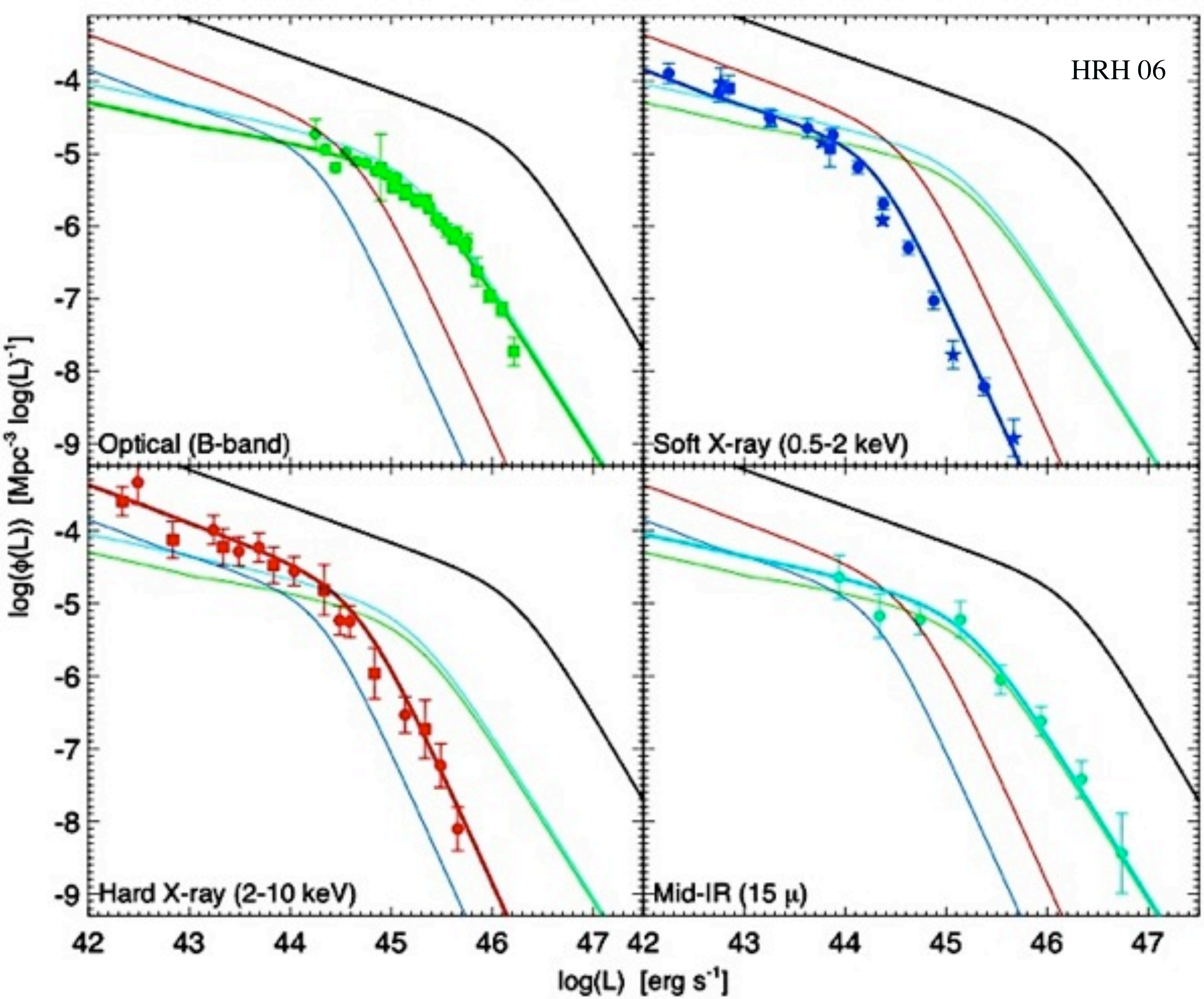
METHODOLOGY

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



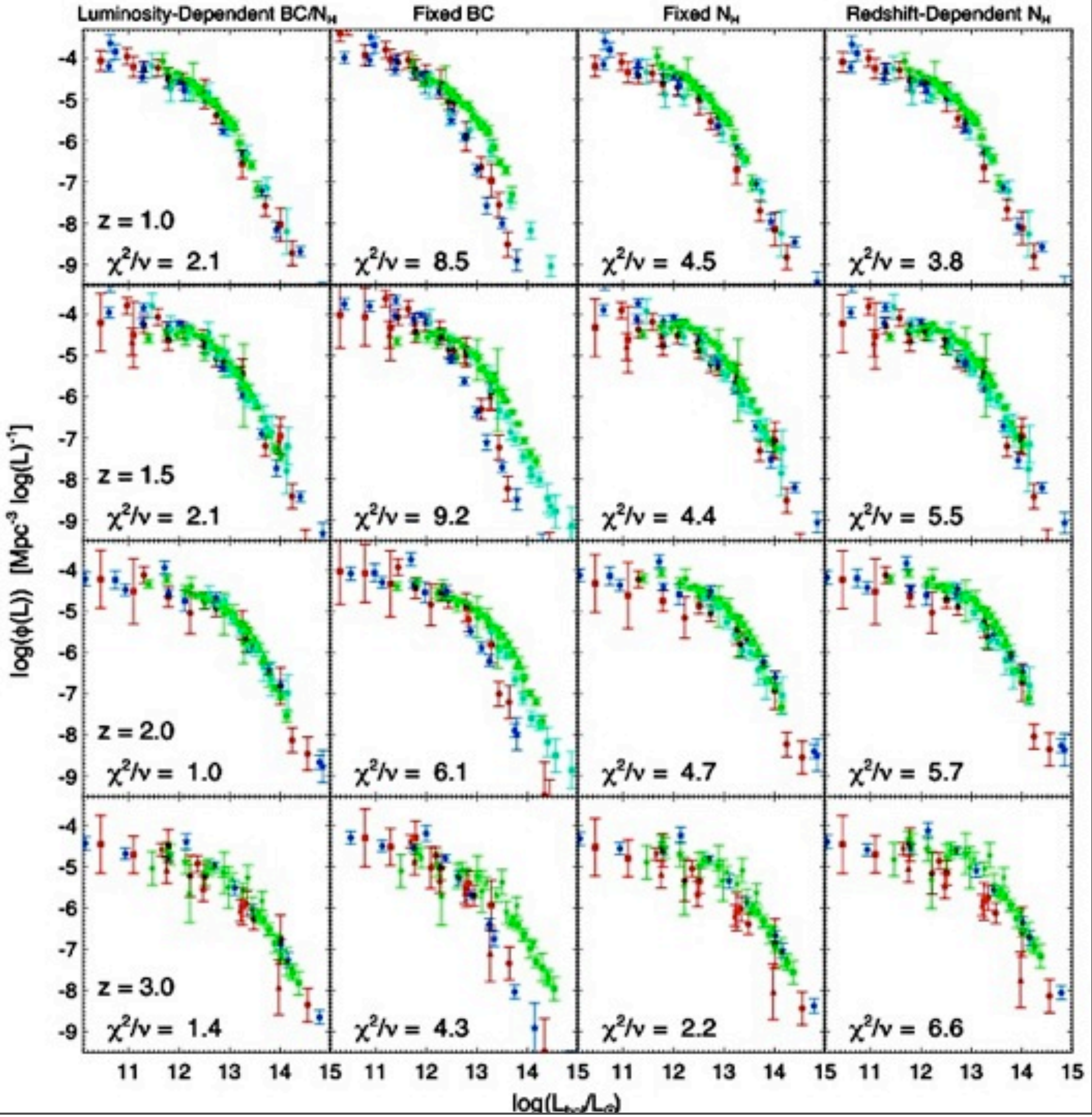


Obtain Phi(L) specific to observed band, L_obs, and redshift:



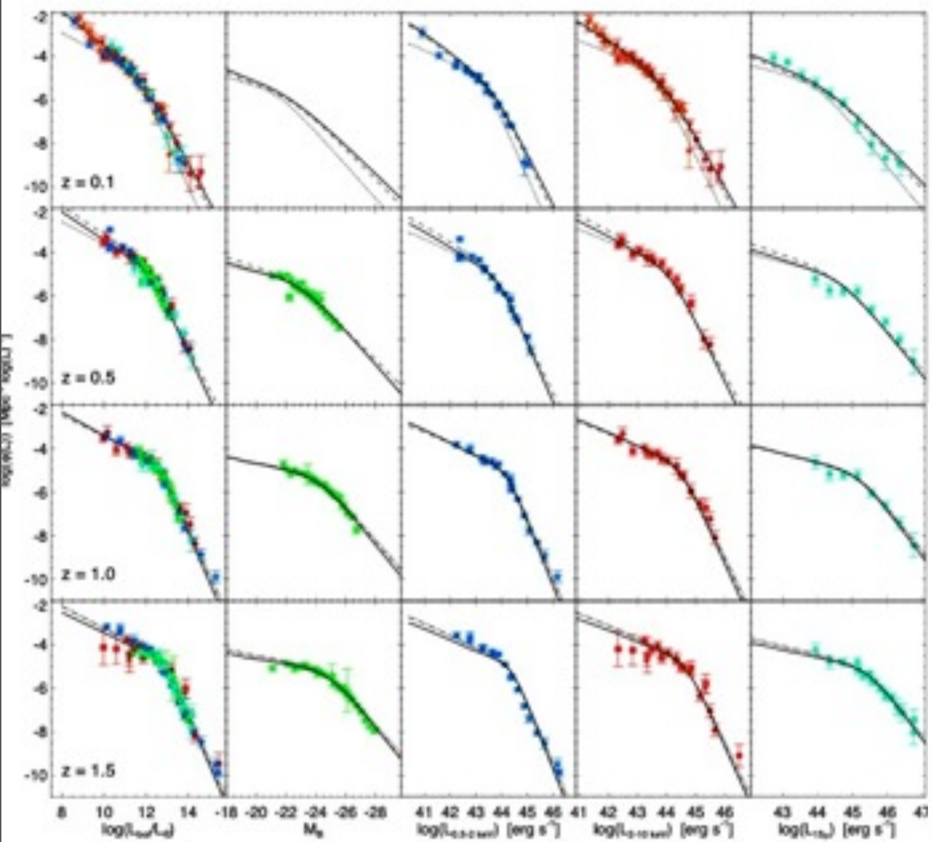
Luminosity-Dependence

TEST DIFFERENT BOLOMETRIC CORRECTIONS, ETC.

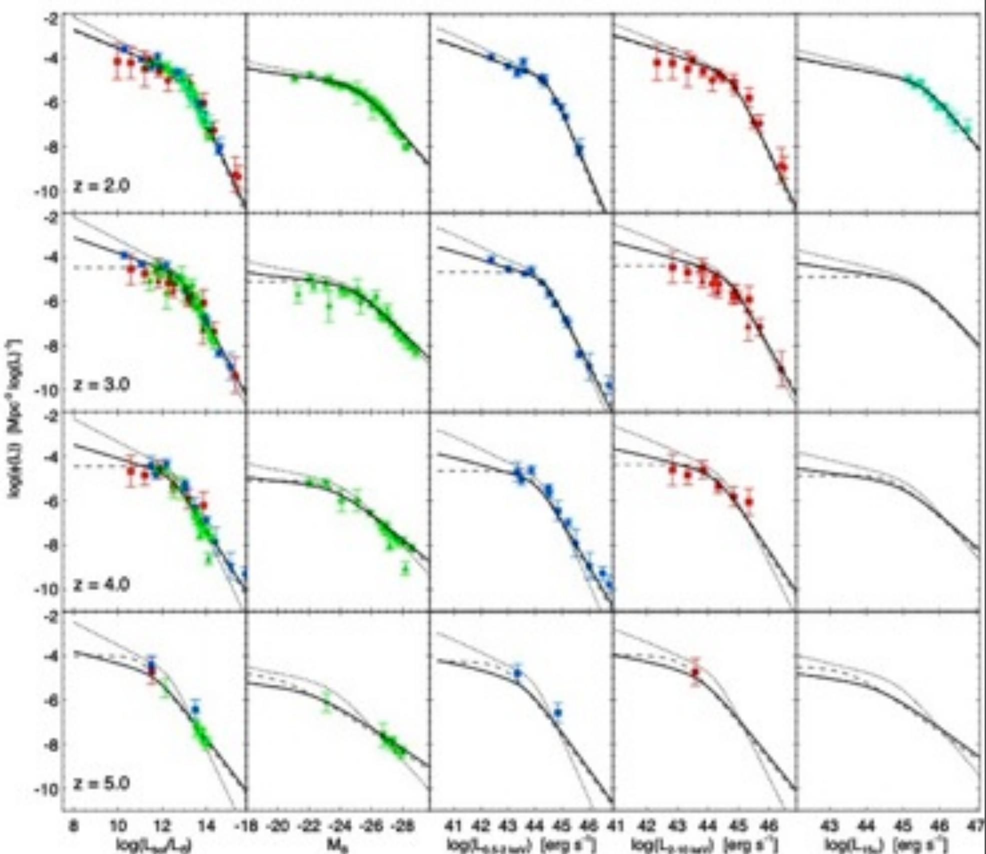


LF vs. Redshift

UV THROUGH IR

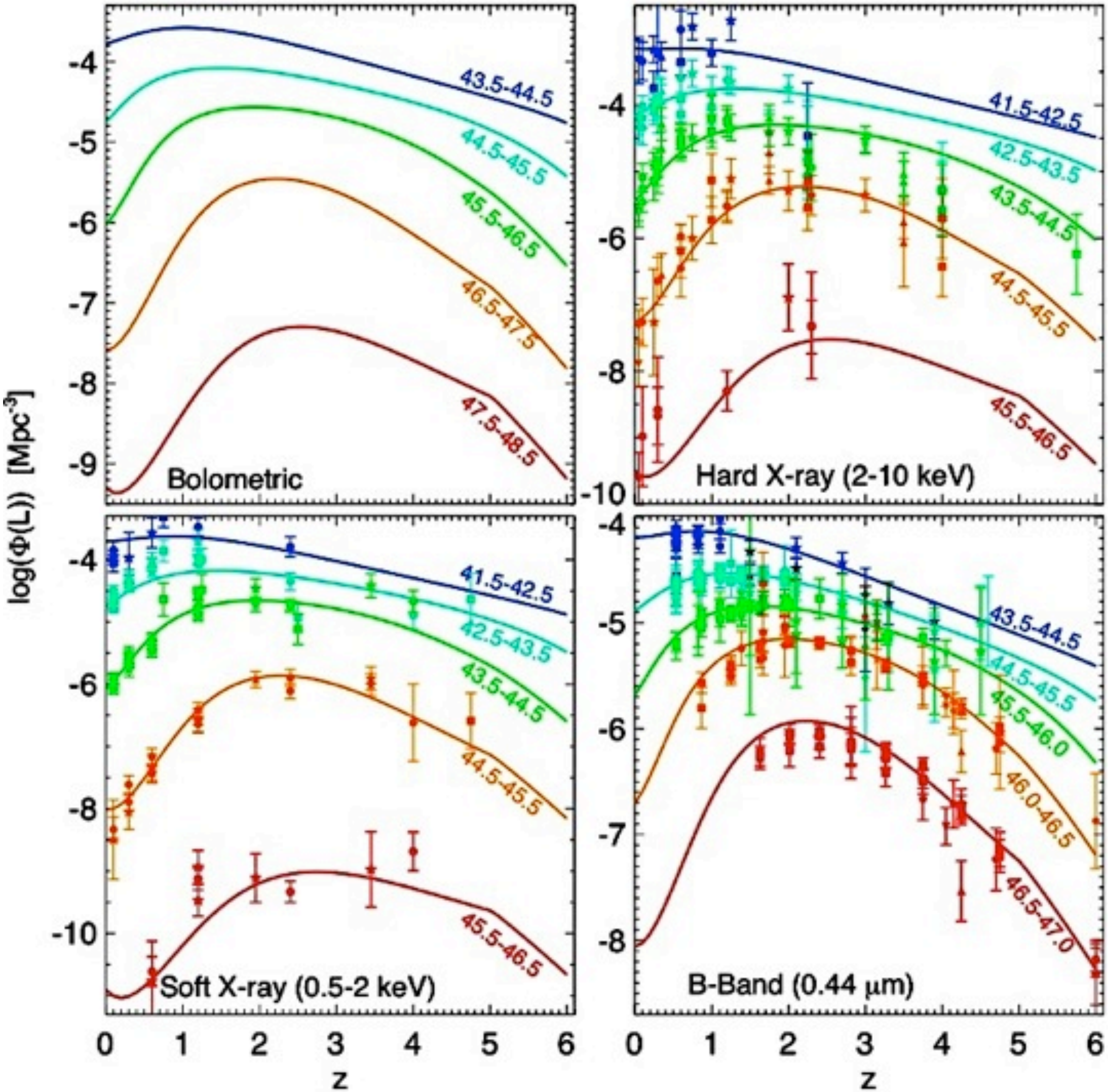


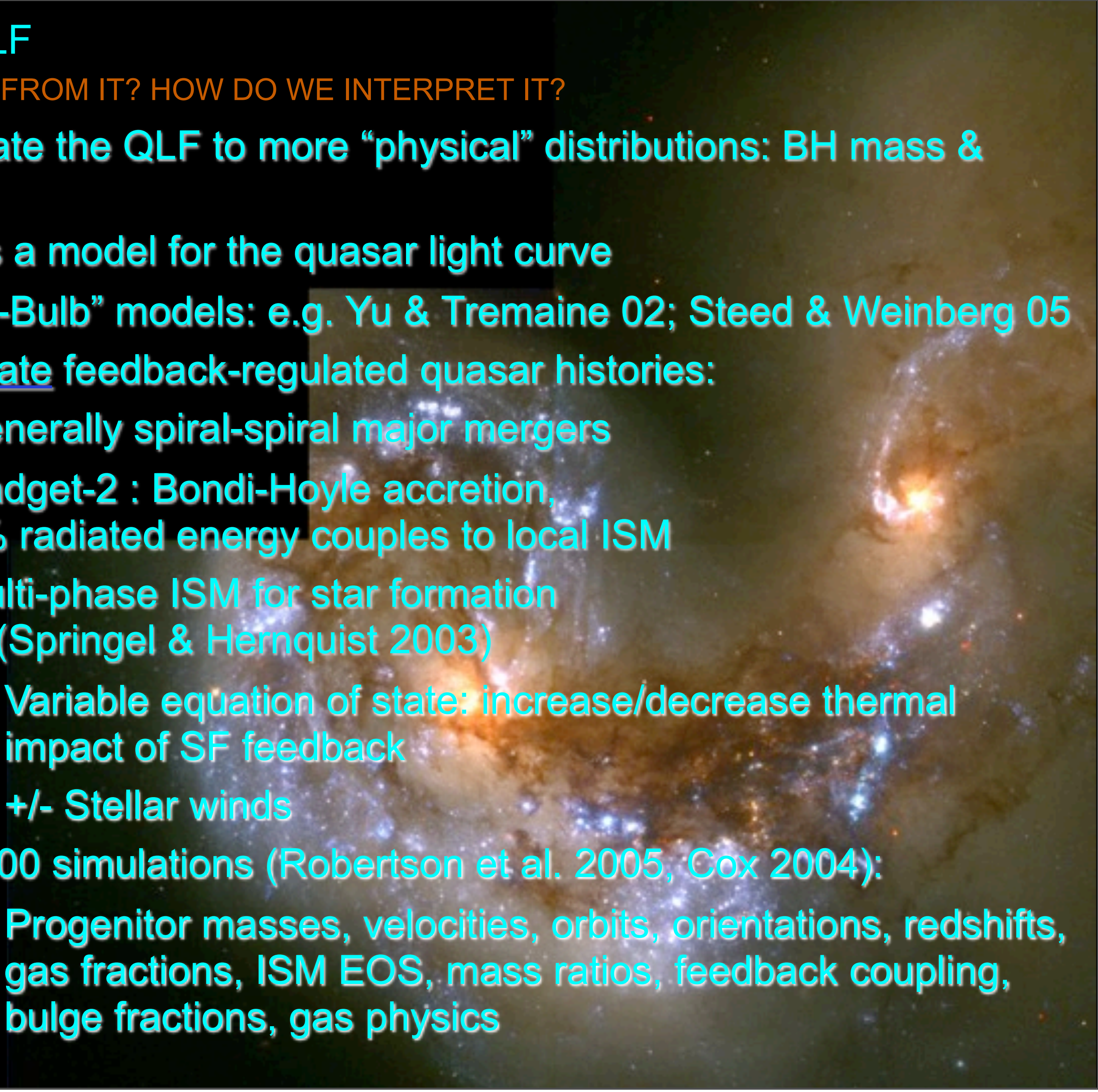
- Significant (>6 sigma) shape change:
  - Faint & Bright end slopes shallower with z



Luminosity-Dependent Density Evolution

UV THROUGH IR

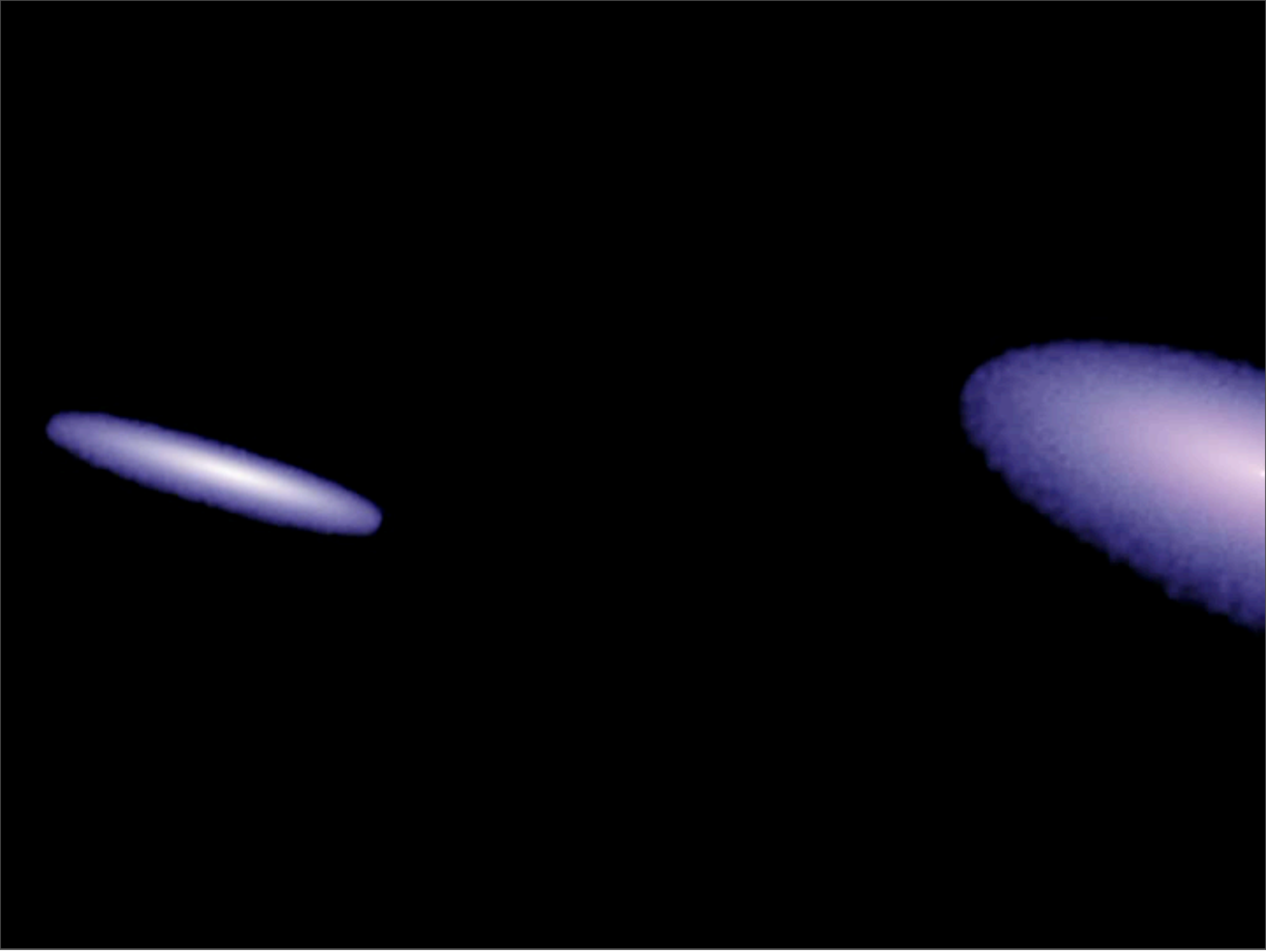




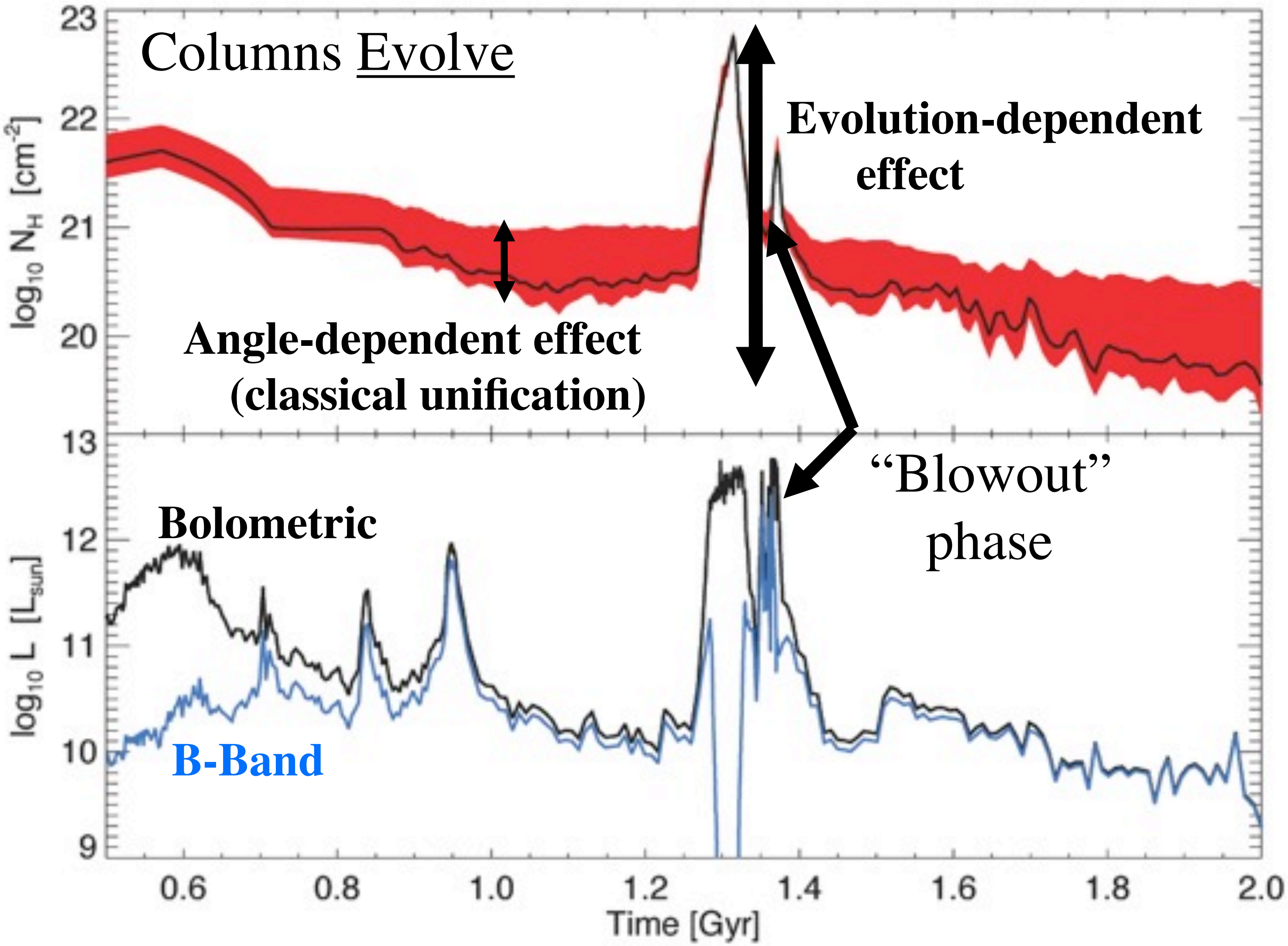
Evolution in the QLF

WHAT CAN WE LEARN FROM IT? HOW DO WE INTERPRET IT?

- Want to translate the QLF to more “physical” distributions: BH mass & accretion rate
    - Requires a model for the quasar light curve
        - “Light-Bulb” models: e.g. Yu & Tremaine 02; Steed & Weinberg 05
        - Simulate feedback-regulated quasar histories:
            - Generally spiral-spiral major mergers
            - Gadget-2 : Bondi-Hoyle accretion,
              5% radiated energy couples to local ISM
            - Multi-phase ISM for star formation
              (Springel & Hernquist 2003)
                - Variable equation of state: increase/decrease thermal impact of SF feedback
                - +/- Stellar winds
            - ~500 simulations (Robertson et al. 2005, Cox 2004):
                - Progenitor masses, velocities, orbits, orientations, redshifts, gas fractions, ISM EOS, mass ratios, feedback coupling, bulge fractions, gas physics



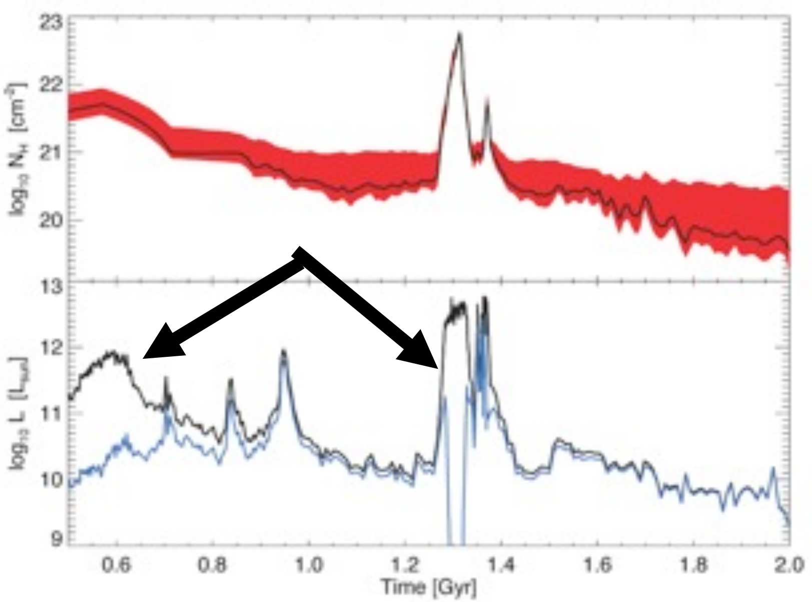
Quasar Lightcurves:



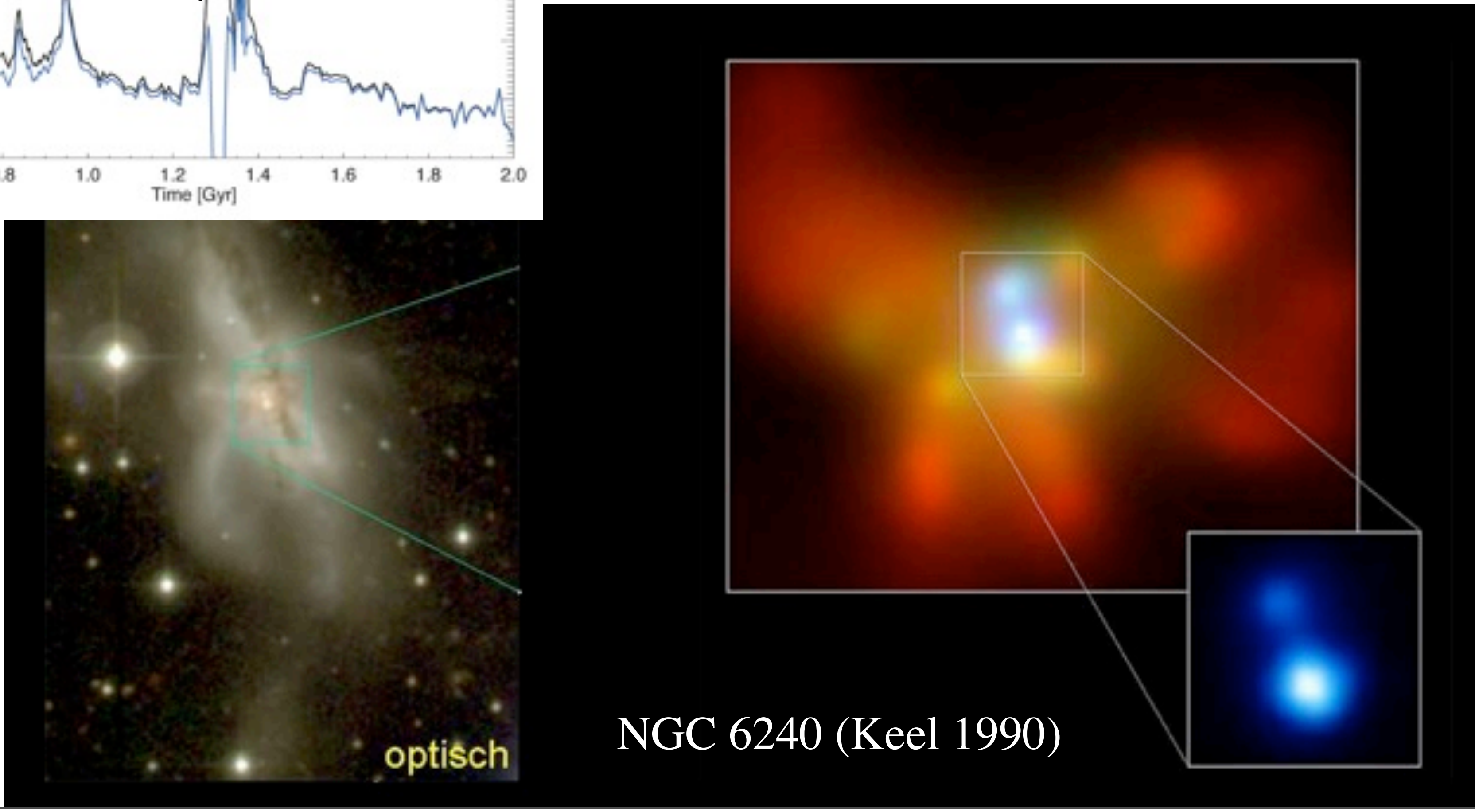
- Multi-phase ISM decomposition: gas+dust+metal columns

Mergers Drive Strong Gas Inflows, Fueling Starbursts and BH Growth

GAS DENSITIES, COLUMNS, STAR FORMATION RATES CHANGE RAPIDLY

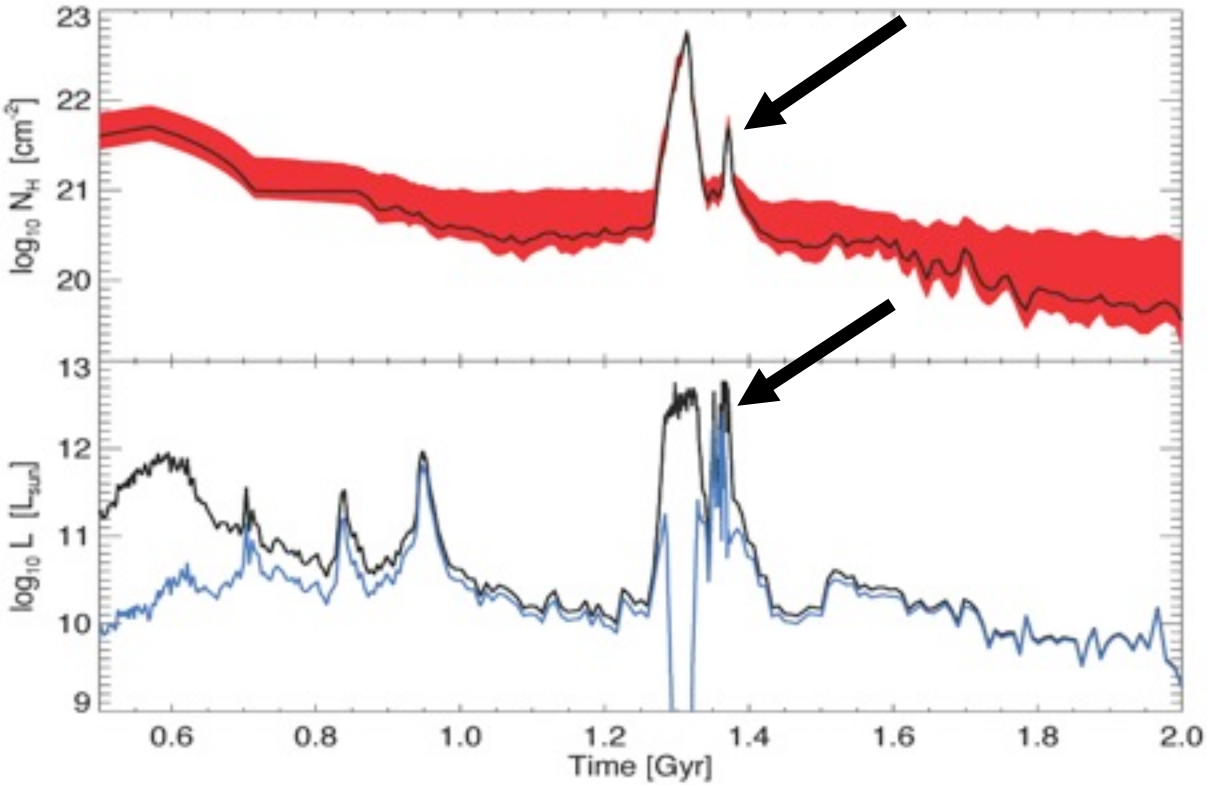


- Obscured growth associated w. starburst
  (e.g. Sanders; Fabian; Alexander,Chapman,Borys et al.)



Feedback Is Necessary to Reveal the Brightest Quasars

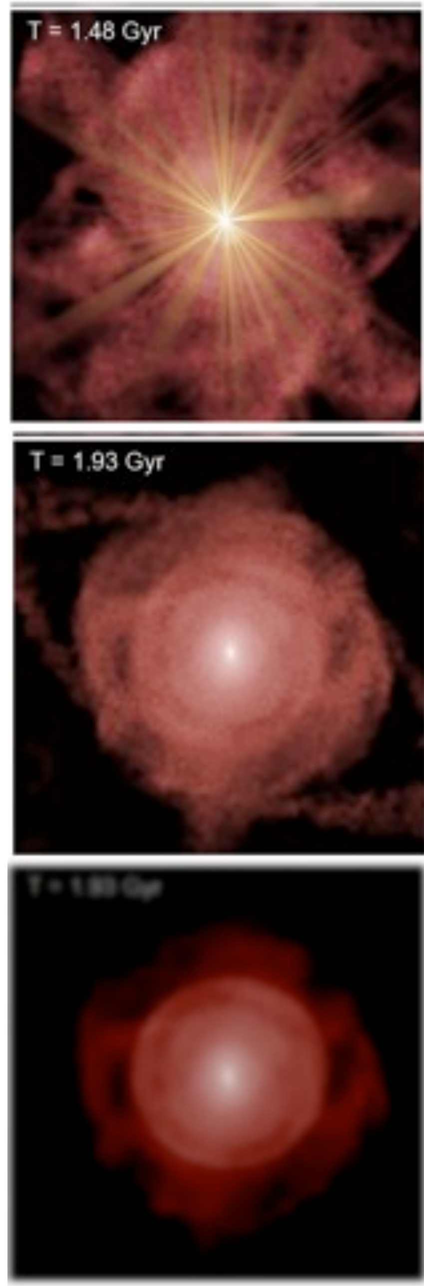
GAS IS HEATED AND EXPELLED IN BLOWOUT, REVEALING A BRIEF, BRIGHT QUASAR



QSO = 1000xHost

QSO = Host

QSO = 0.1xHost



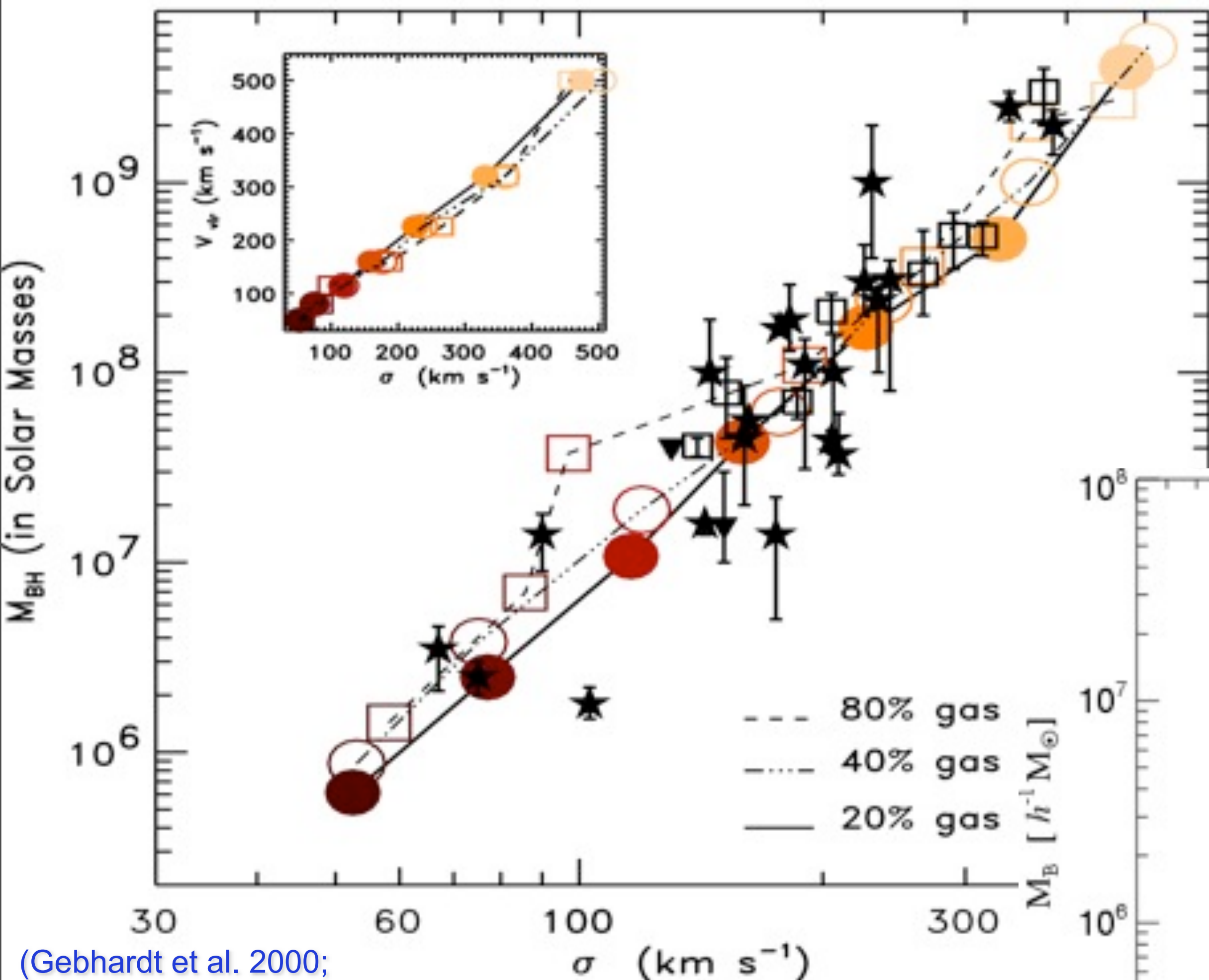
- Evolutionary Processes : NOT necessarily physical to “extrapolate” the local, quiescent torus
- Eddington ratios vs. host properties (size, luminosity, morphology, redshift)
- Active BH mass functions

Hopkins et al. 2005e

Feedback-driven "Blowout" Gives M-sigma Relation

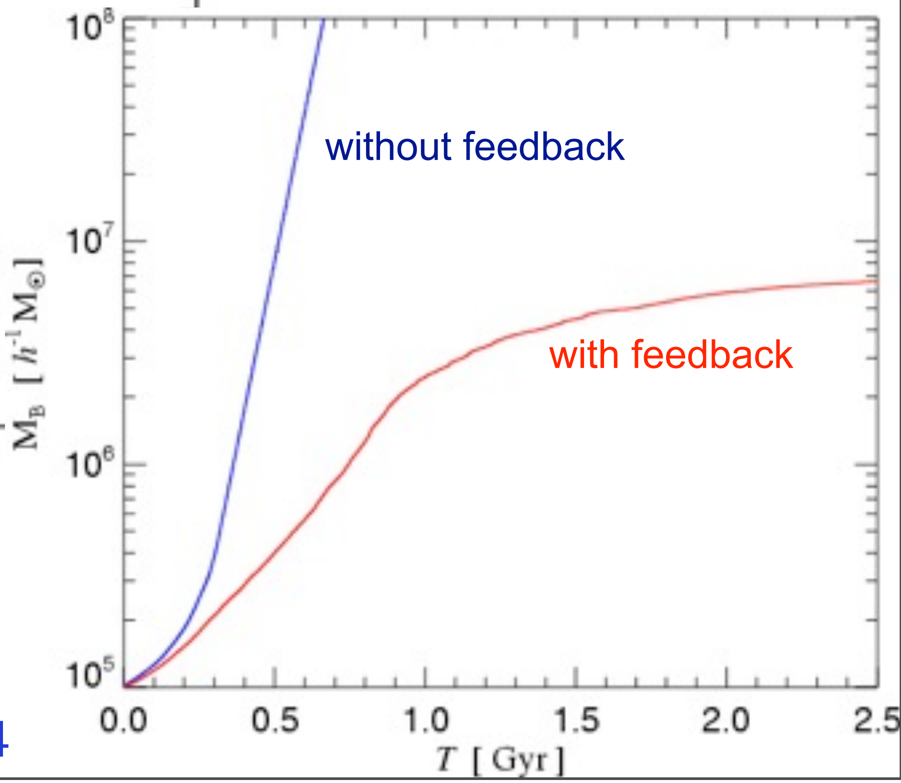
PREVENTS RUNAWAY BLACK HOLE GROWTH

Di Matteo et al. 2005



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

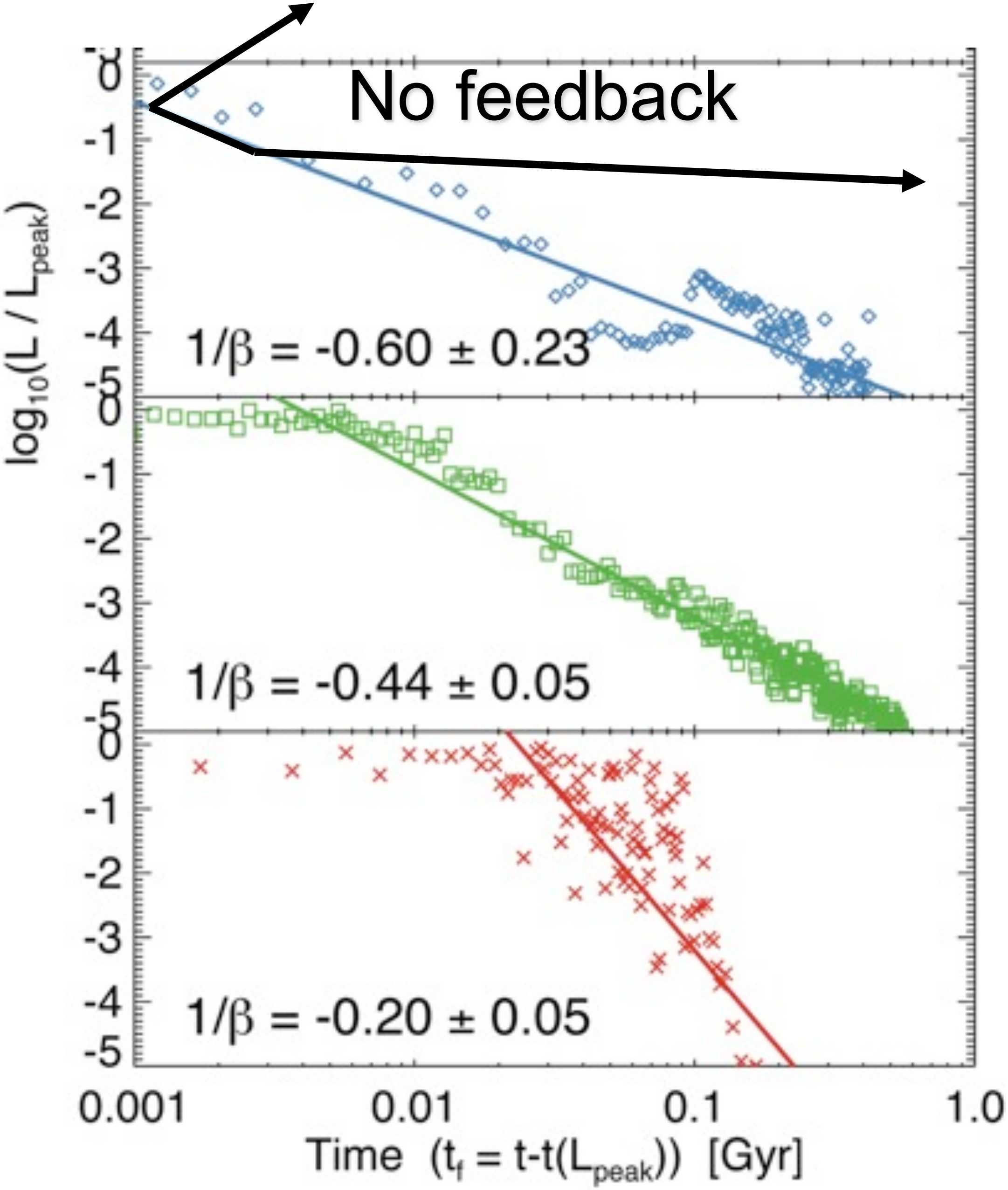
Black hole growth



Springel et al. 2004

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME

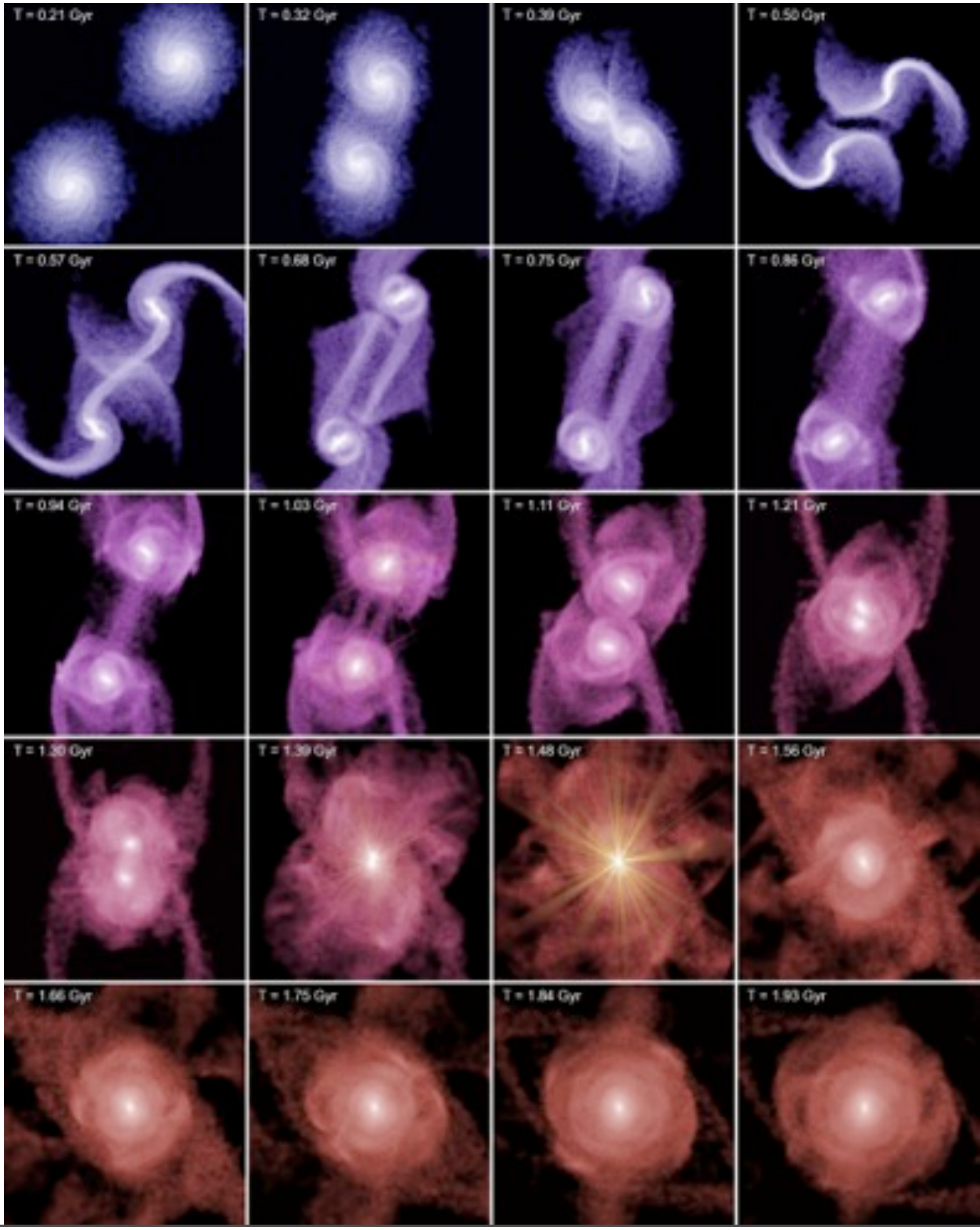


- Simulation: Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)

Hopkins et al. 2006a

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME

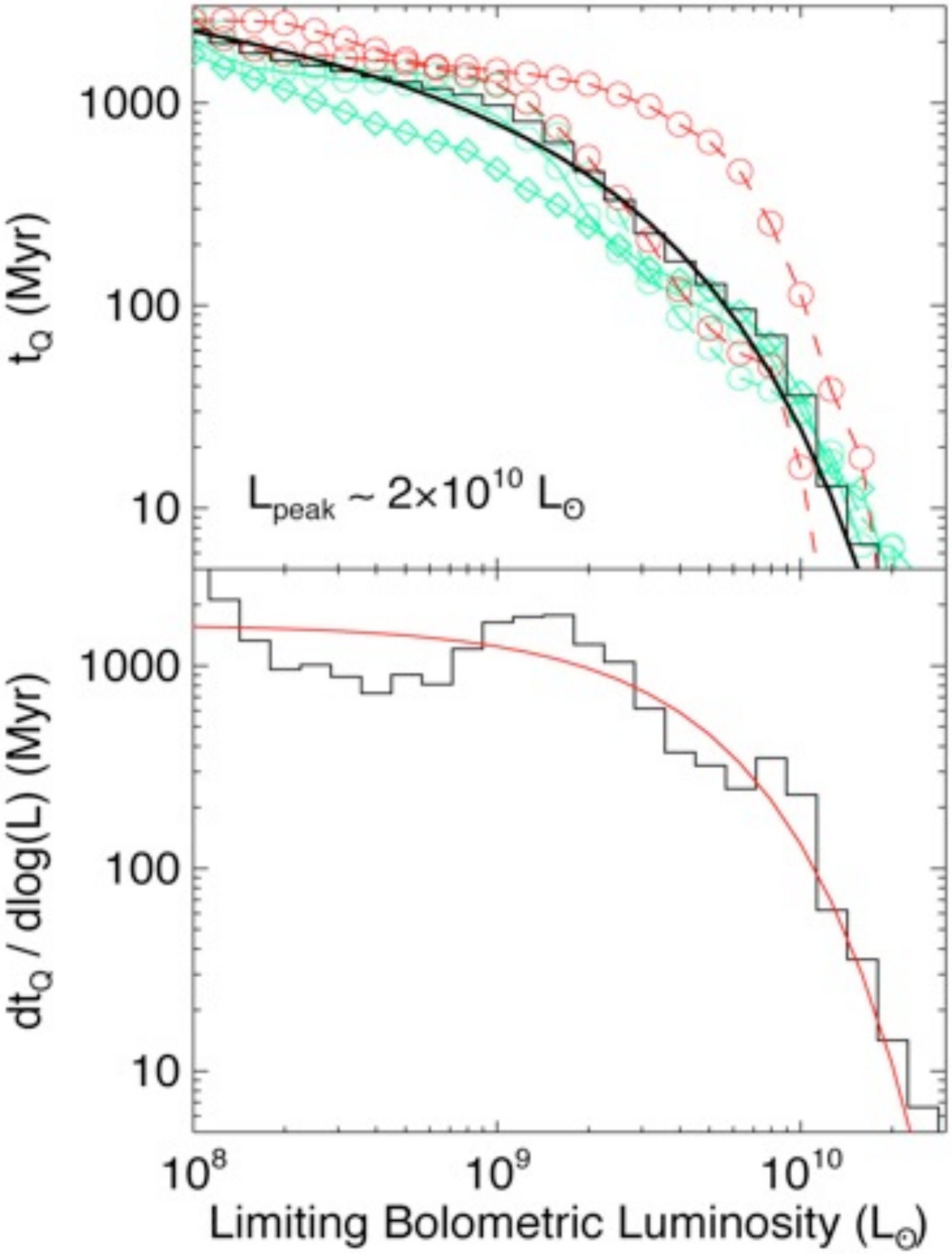


- "Quasar Lifetime" : a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity
  - General solution depends just on energy injection

Hopkins et al. 2006b

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME



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Hopkins et al. 2006b

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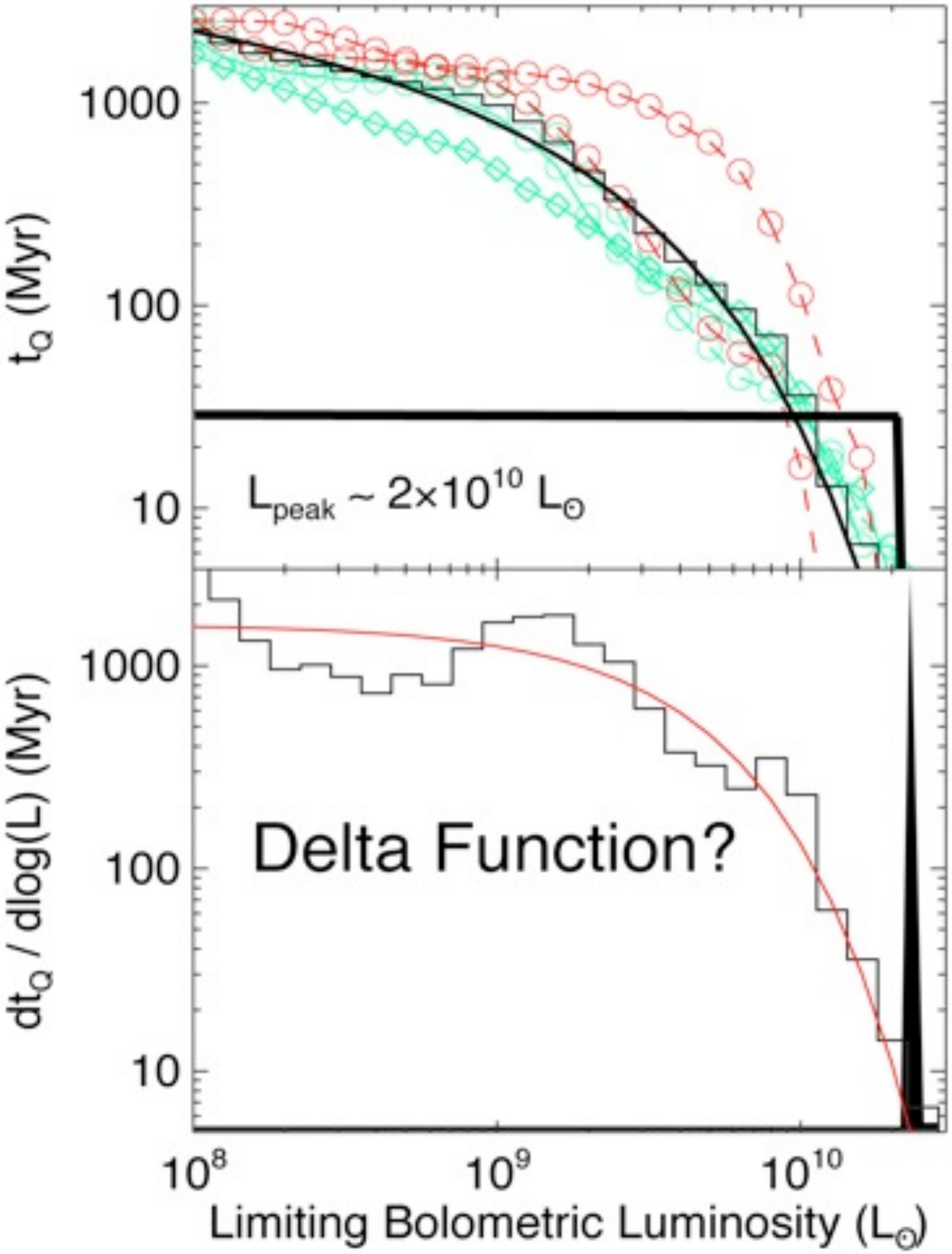

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Hopkins et al. 2006b

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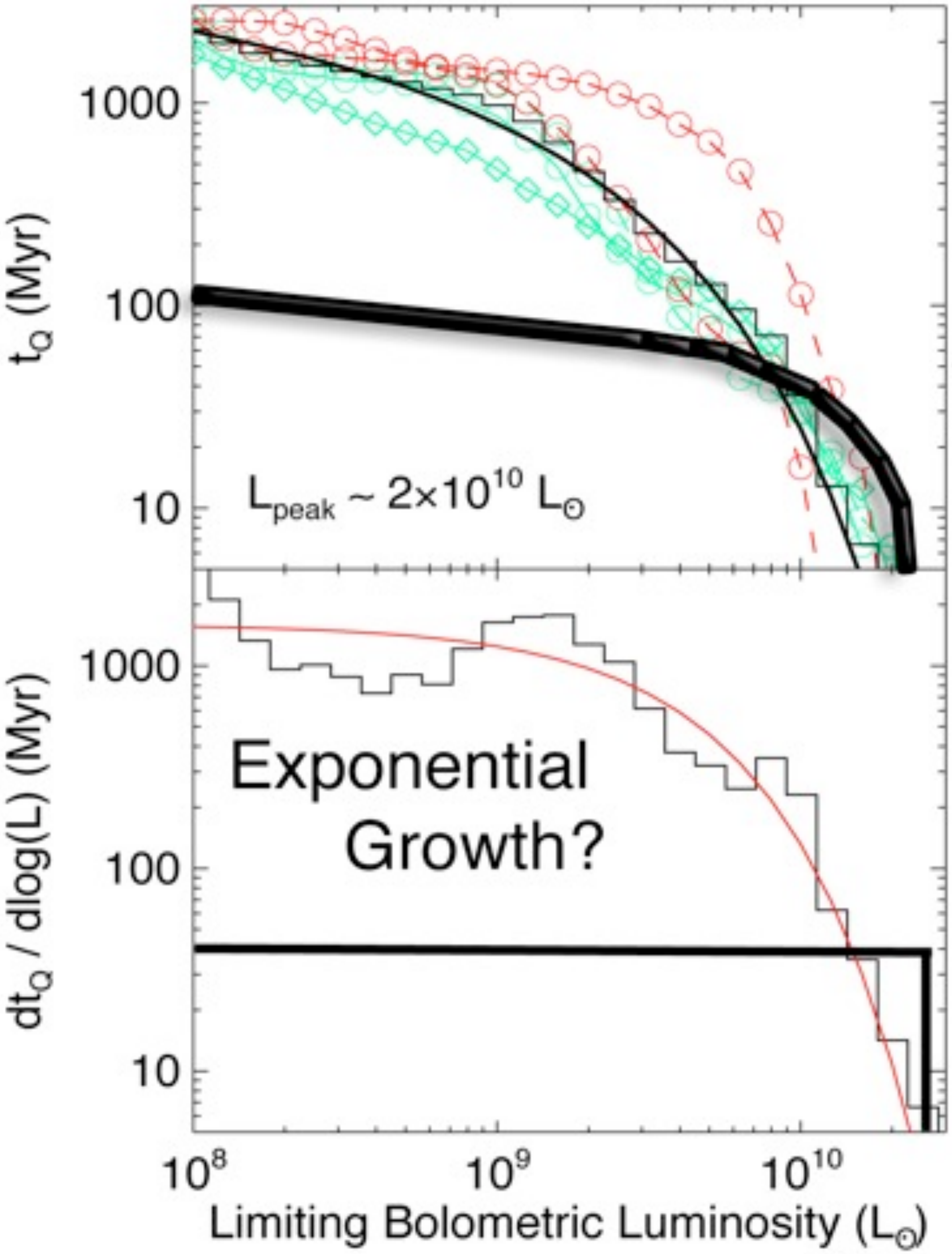

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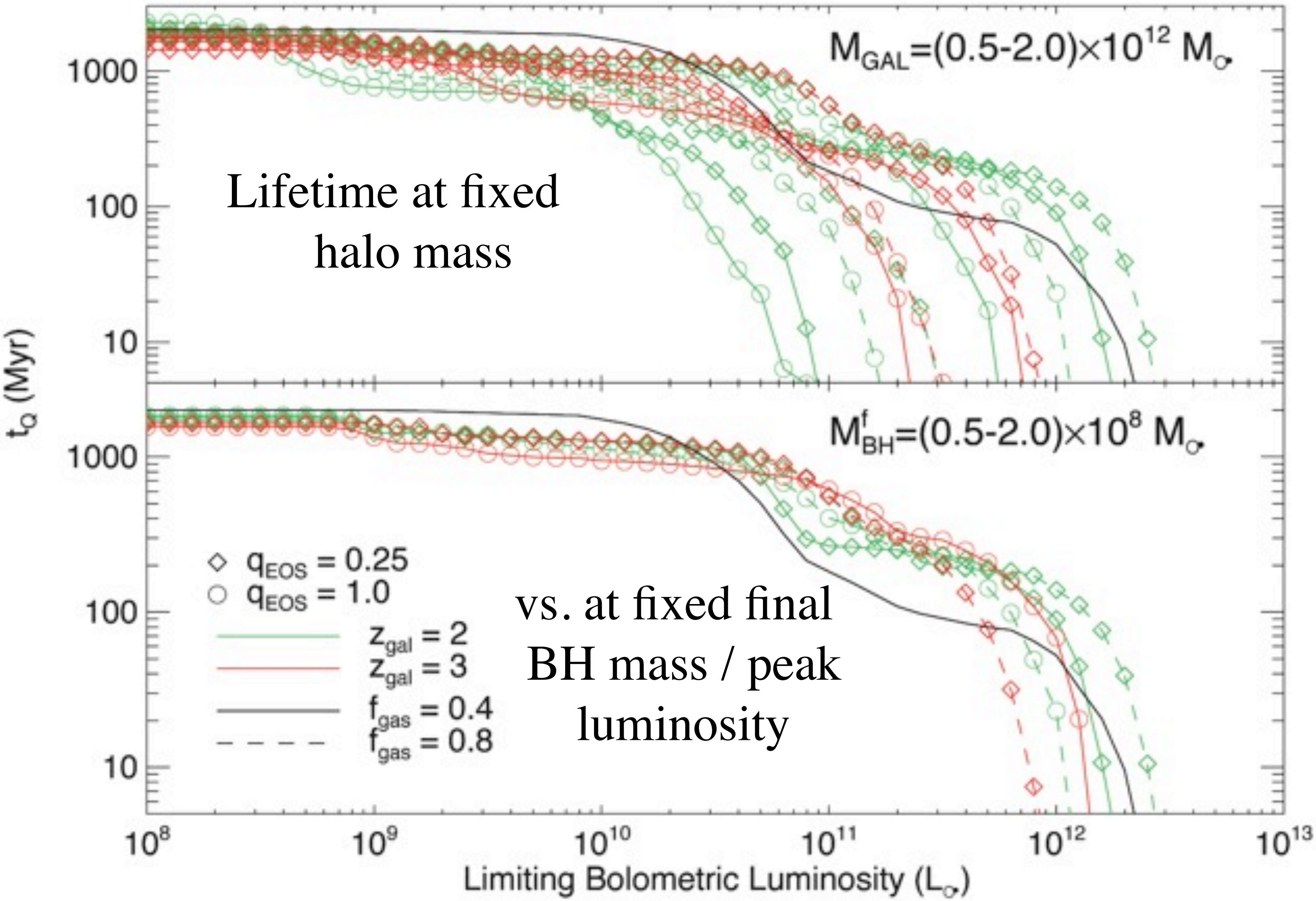
Hopkins et al. 2006b

Robustness of Quasar Lifetimes

LIFETIME DISTRIBUTION IS A FUNCTION OF JUST THE FINAL MASS/PEAK LUMINOSITY

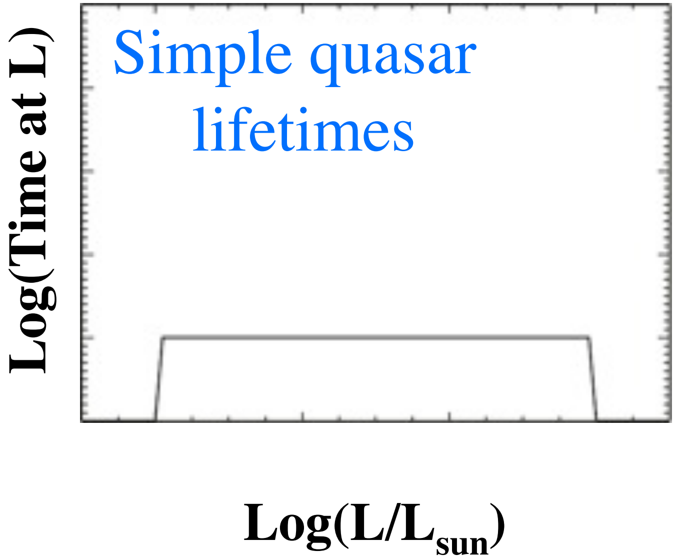


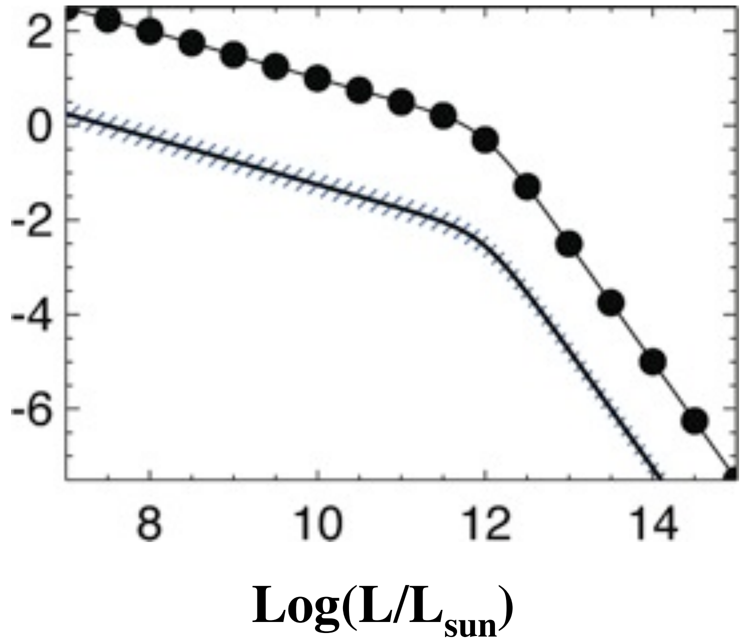
Hopkins et al. 2006b

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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

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





- 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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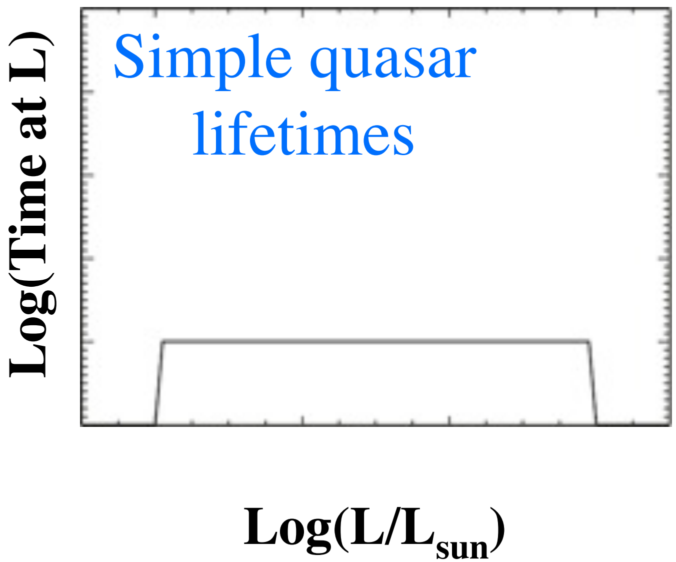

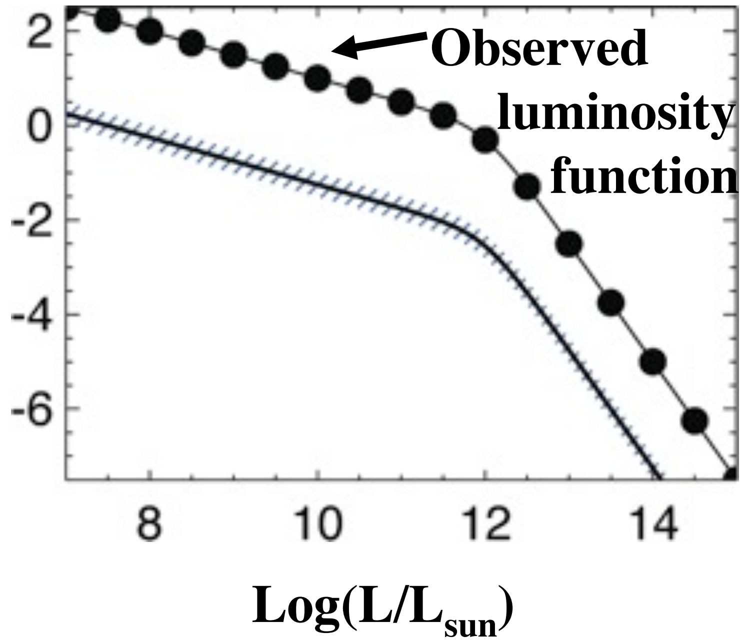

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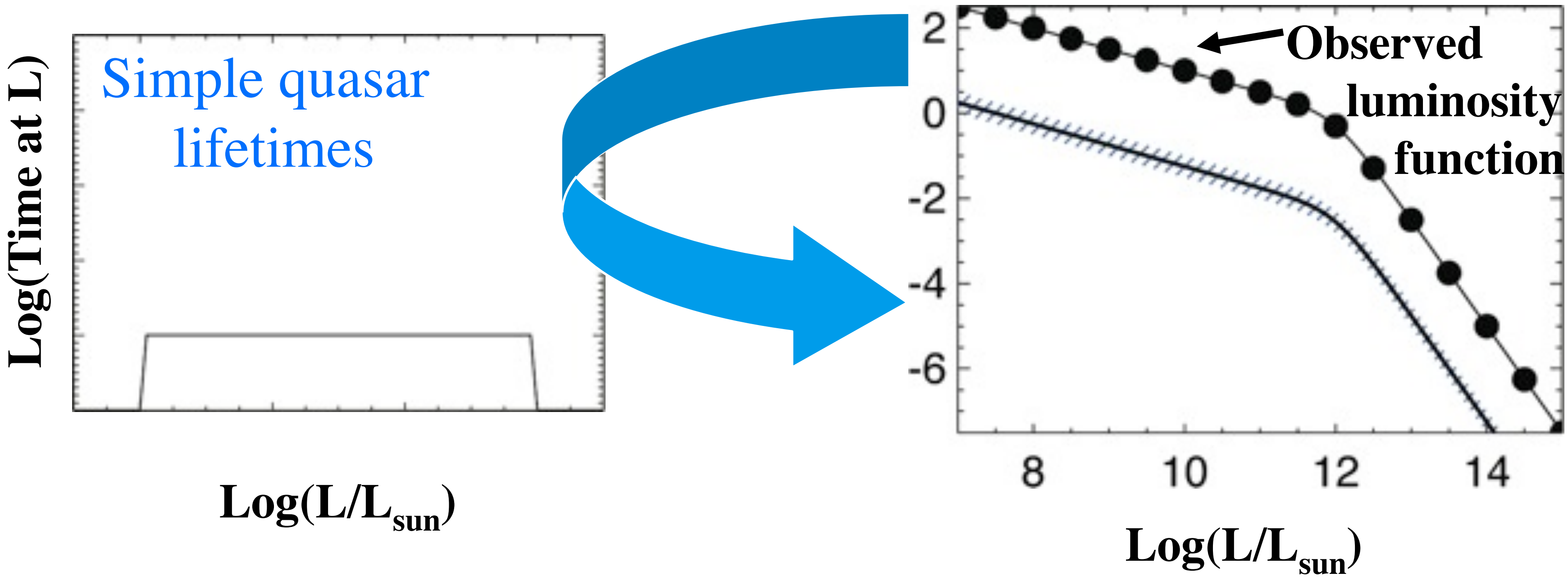

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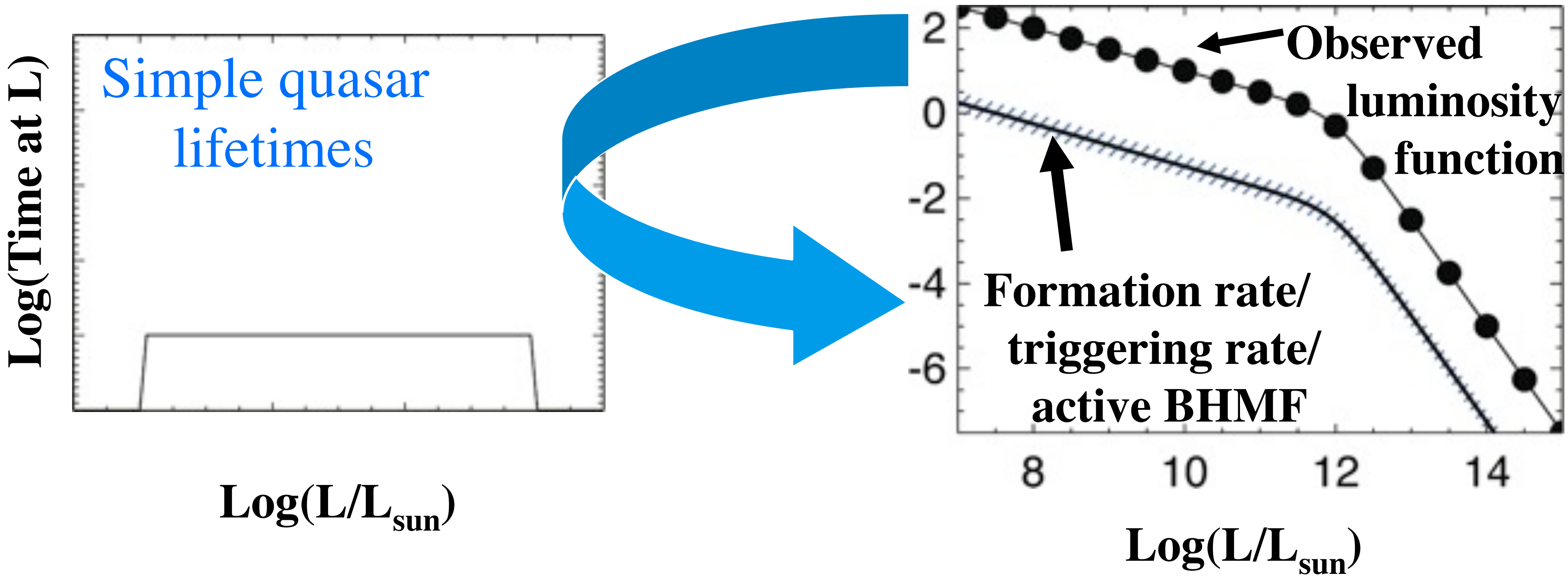
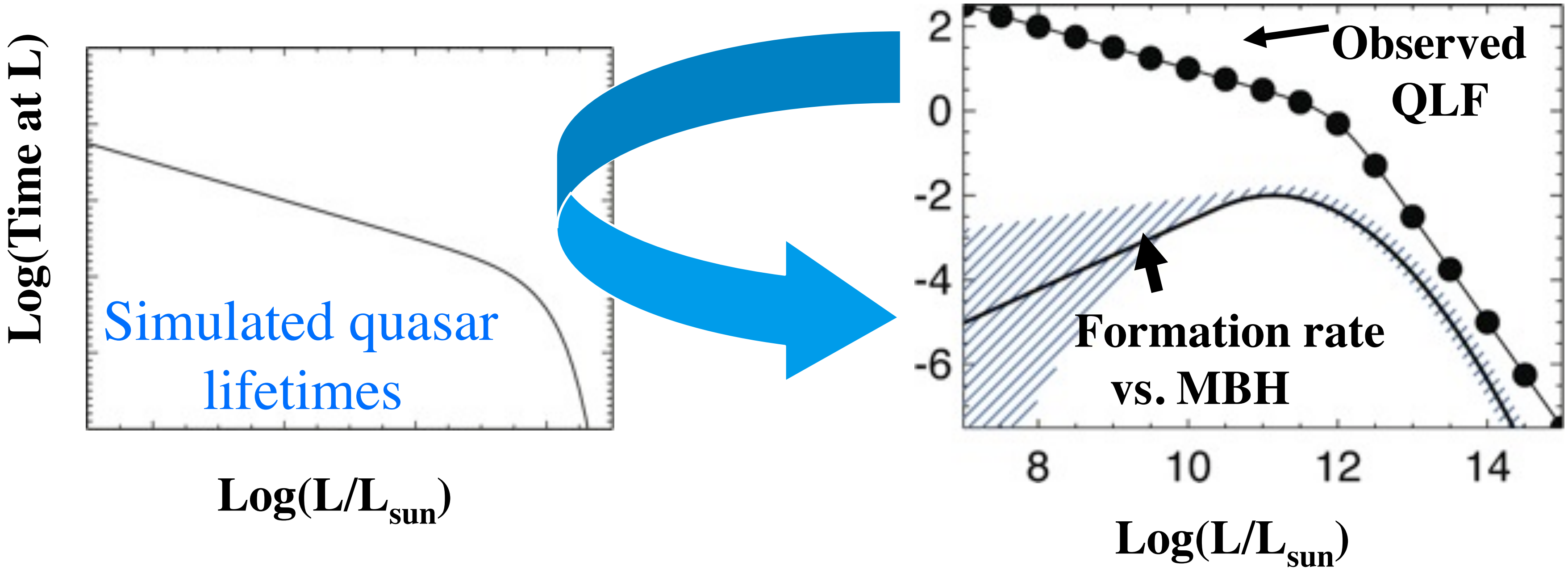
$$\phi(L) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\log L}(L) = \int \frac{\mathrm{d}t(L, L_{\rm peak})}{\mathrm{d}\log(L)}\, \dot{n}(L_{\rm peak})\,\mathrm{d}\log(L_{\rm peak}).$$



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

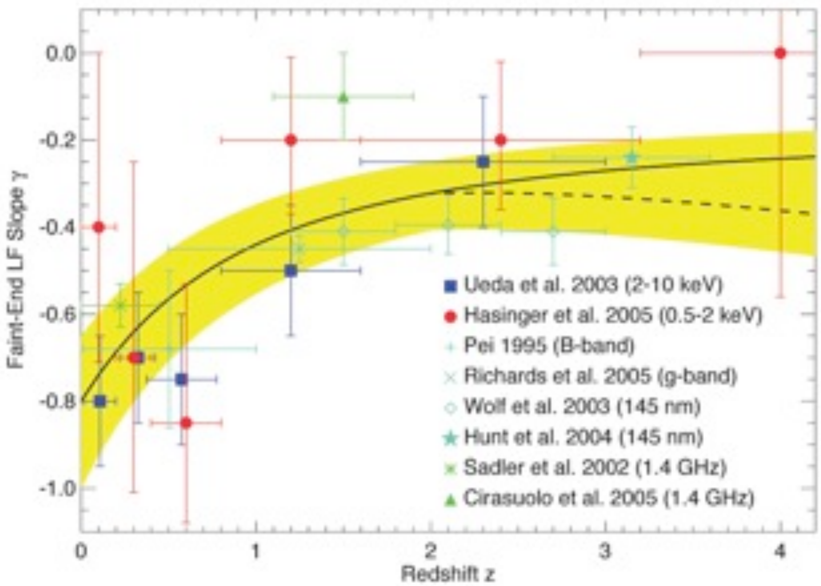
$$\phi(L) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\log L}(L) = \int \frac{\mathrm{d}t(L, L_{\mathrm{peak}})}{\mathrm{d}\log(L)}\, \dot{n}(L_{\mathrm{peak}})\, \mathrm{d}\log(L_{\mathrm{peak}}).$$



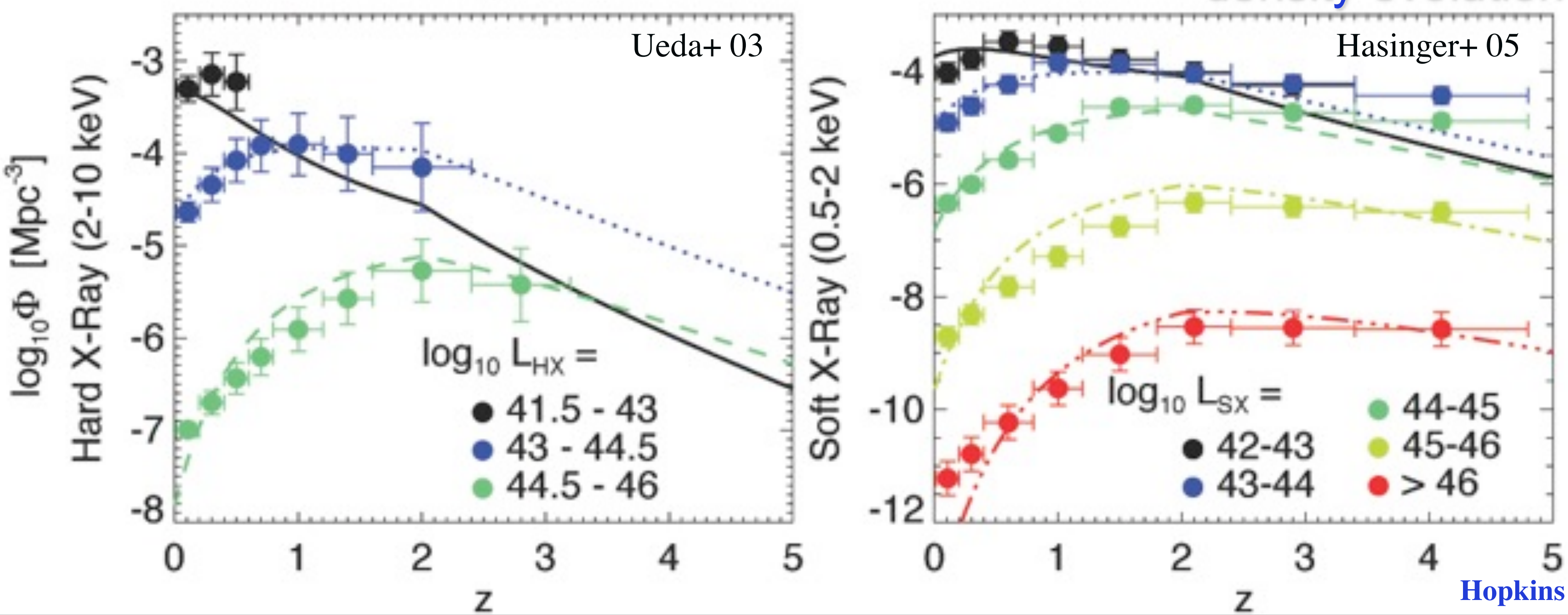
- Feedback-regulated lifetime drives a given QSO to lower L after blowout, and spends more time at low-L
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts

Faint-End Slope of QLF is Determined by Faint-End Quasar Lifetime

FAINT QSOs ARE DECAYING - LIFETIME DETERMINES HOW MANY SEEN



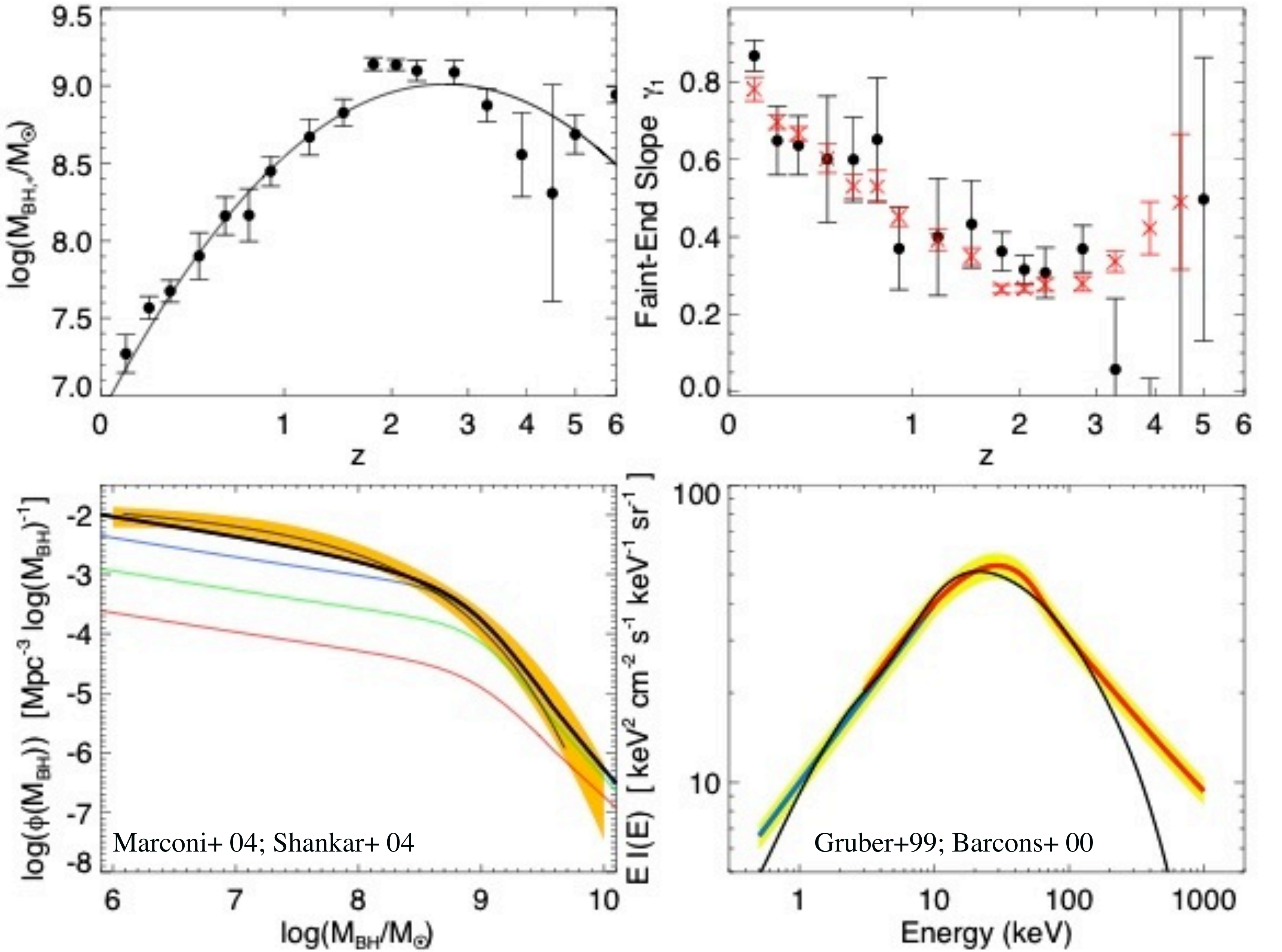
- Dependence on peak luminosity gives dependence on z
- Values inform feedback: e.g. steady wind vs. injection vs. steady "unfueled" disk
- Luminosity-dependent density evolution



Hopkins et al. 2006a

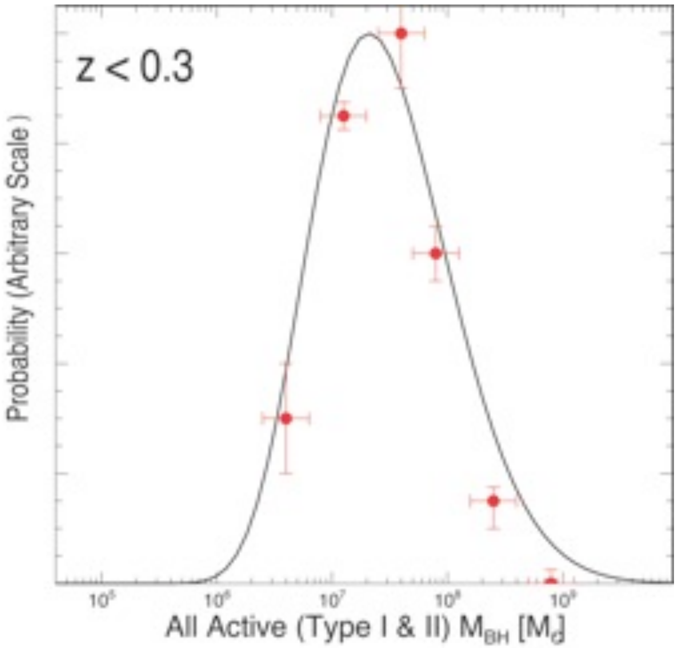
Trace the BH Formation History & Relic Properties

DOWNSIZING OF QSOs AND GALAXIES CAN NOW BE COMPARED QUANTITATIVELY

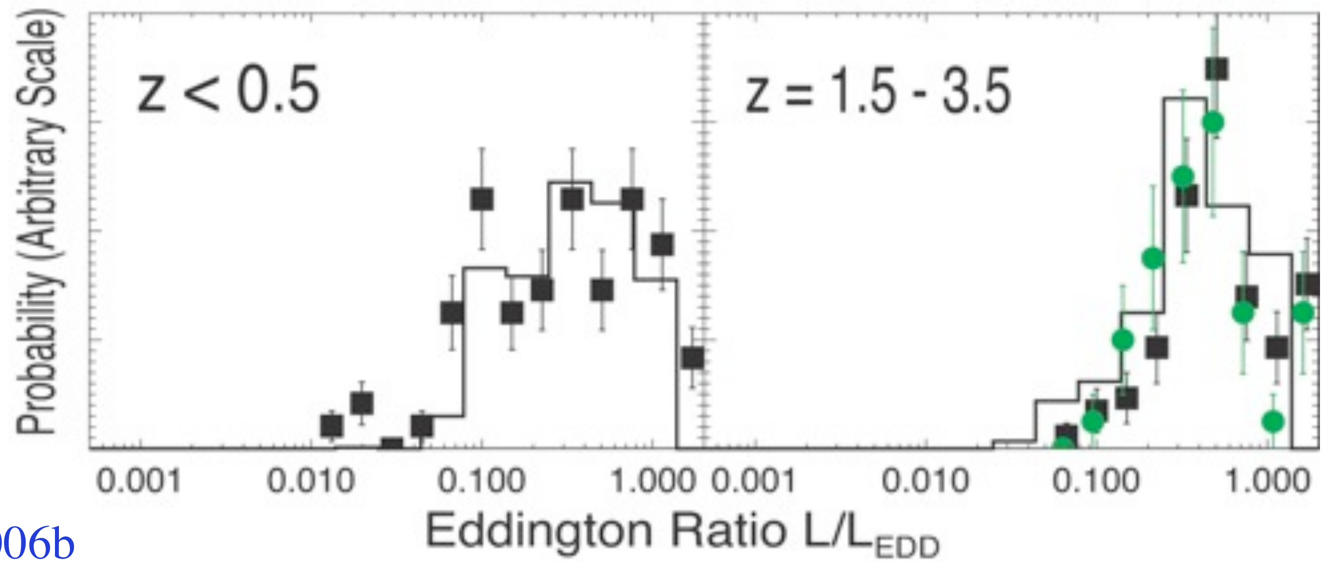


Eddington Ratio Distributions and Active Black Hole Mass Functions

REFLECT TURNOVER IN FORMATION/MERGER RATE



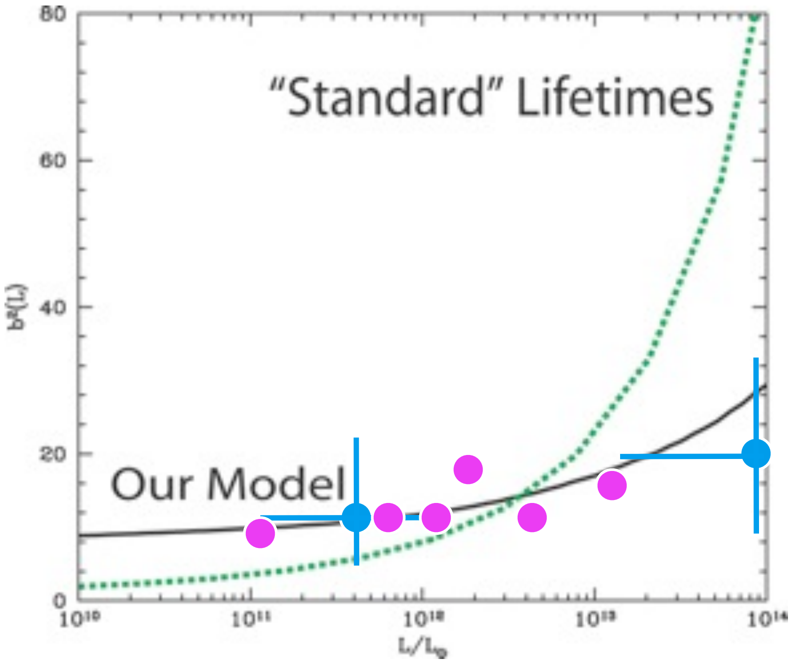
- QLF below break as Eddington ratio sequence
  - (Vestergaard+, Marchesini+, Woo & Urry, Hao+)
- Active BHMF similar in shape to formation rate
  - (Heckman+,Ho+, McLure & Dunlop)



Hopkins et al. 2006b

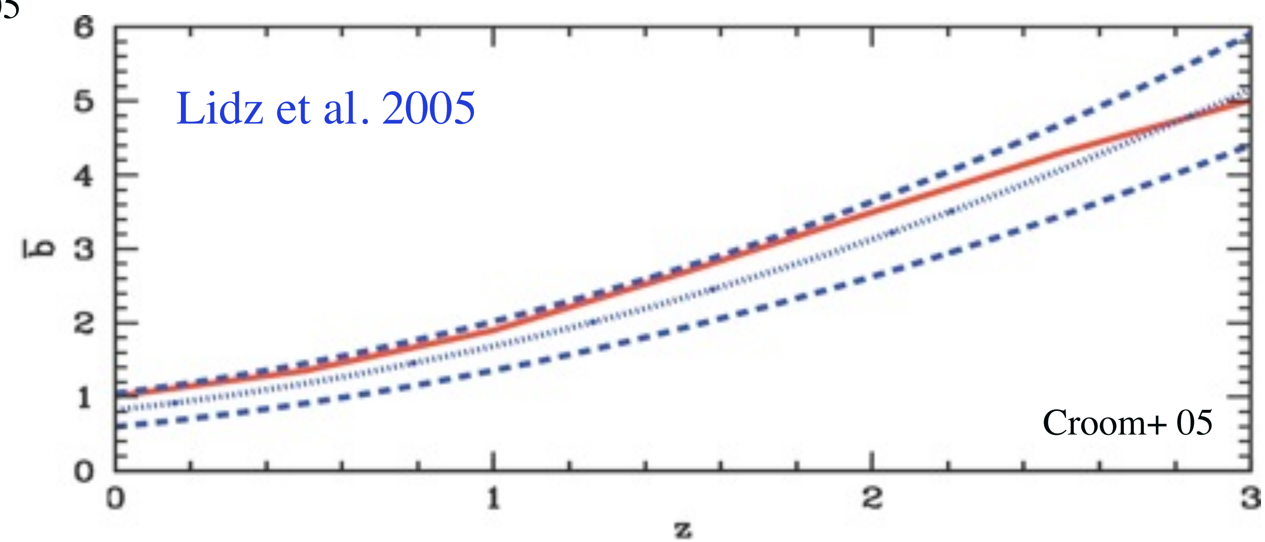
Quasar Clustering is a Strong Test of this Model

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



- Adelberger & Steidel 05
- Myers et al. 05

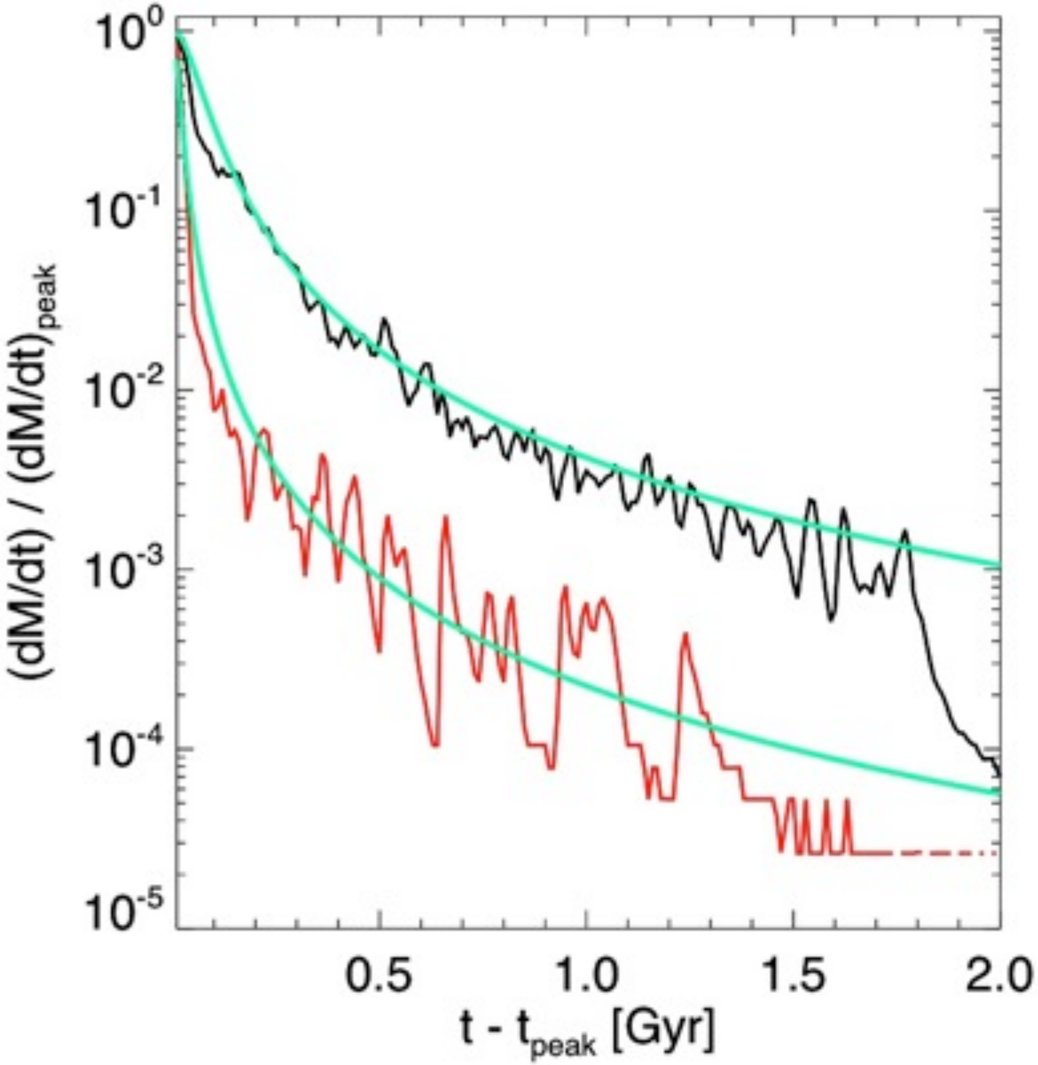
- Weak dependence of clustering on observed luminosity
  - (Croom et al. 2005, Adelberger & Steidel 2005, Myers et al. 2005)
- Observed trends with redshift
  - (M_halo ~ 10^13 M_sun)



Generalizing the Model

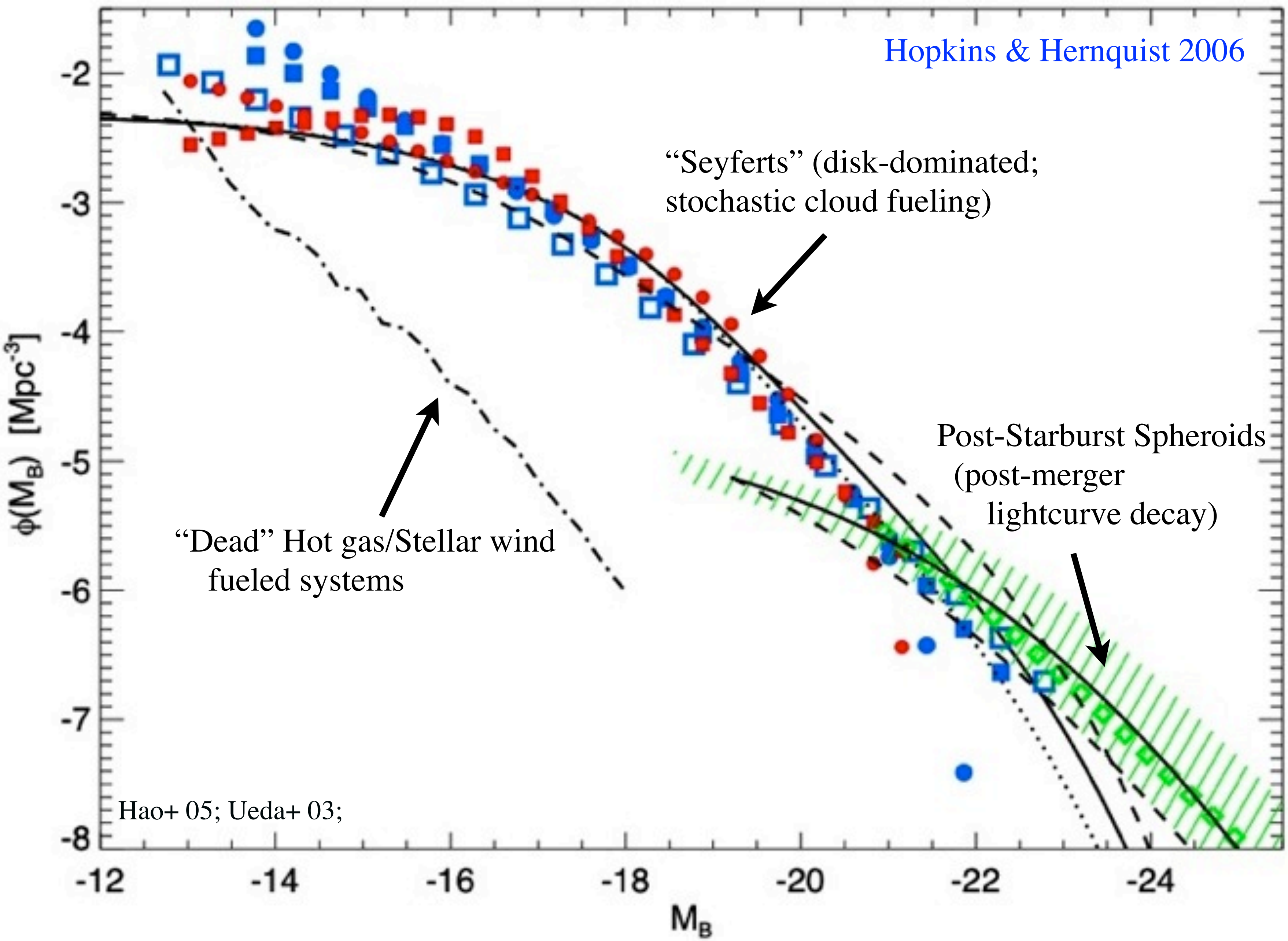
NOT ALL AGN ARE MERGER-DRIVEN

- 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



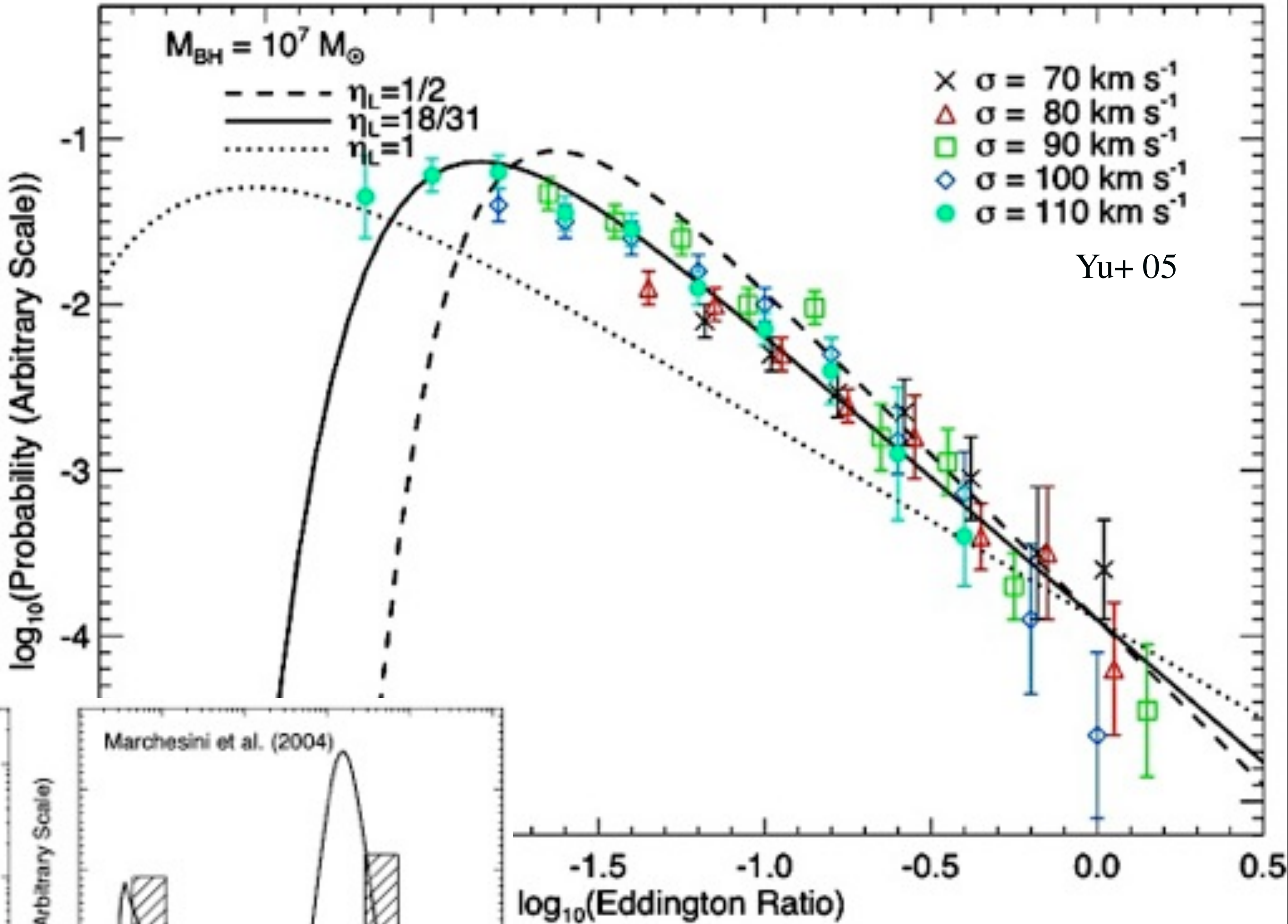
The Seyfert Luminosity Function

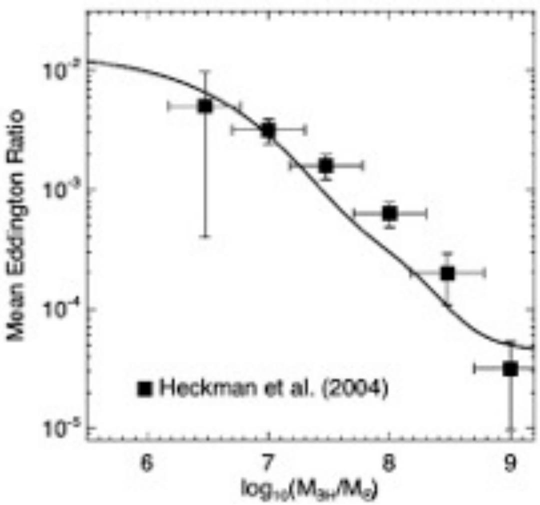
A STOCHASTIC BUT FEEDBACK-REGULATED MODEL

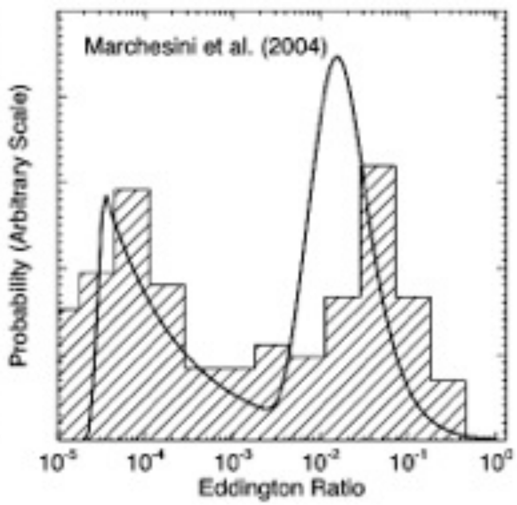


The Seyfert Luminosity Function

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

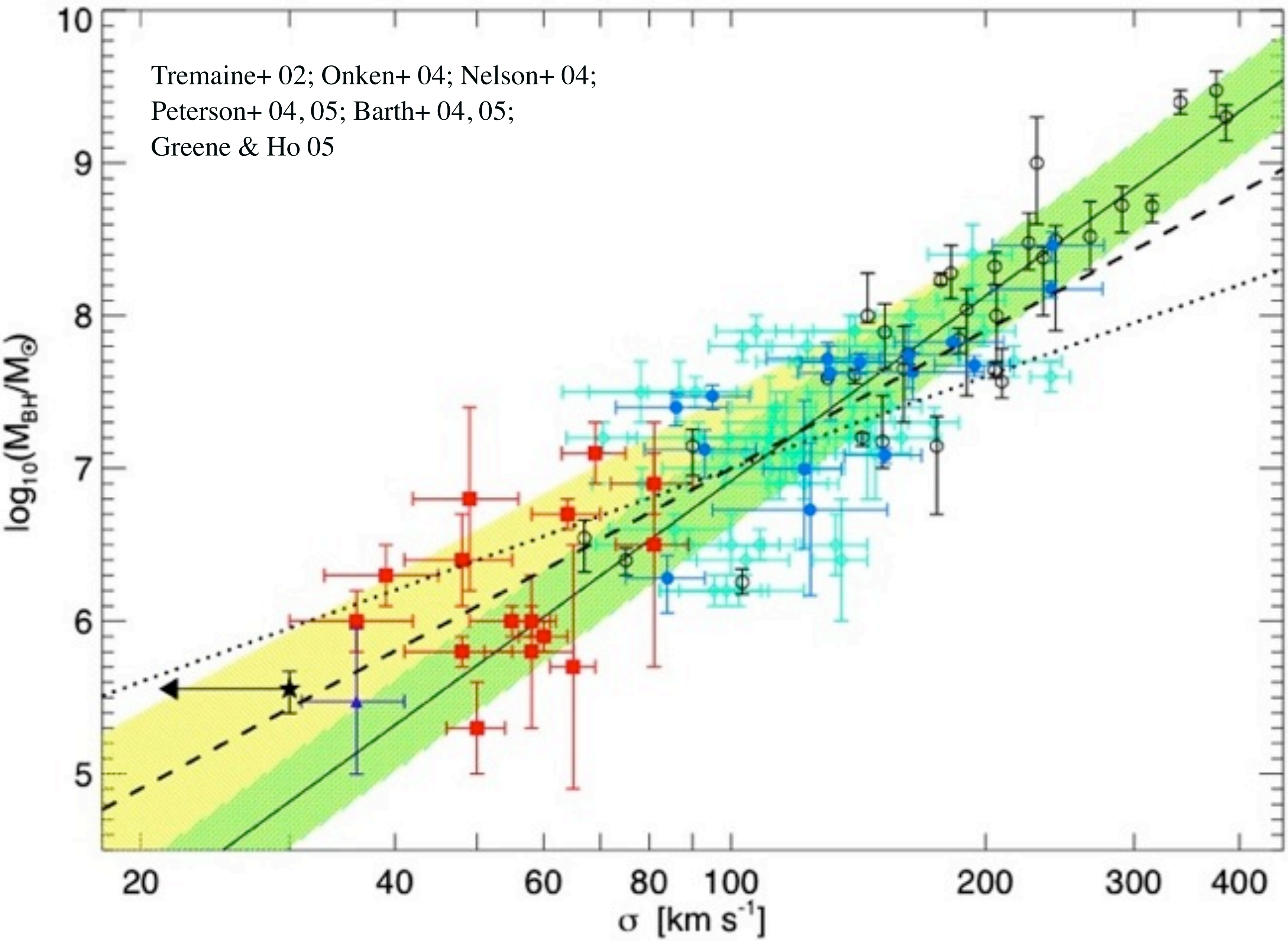






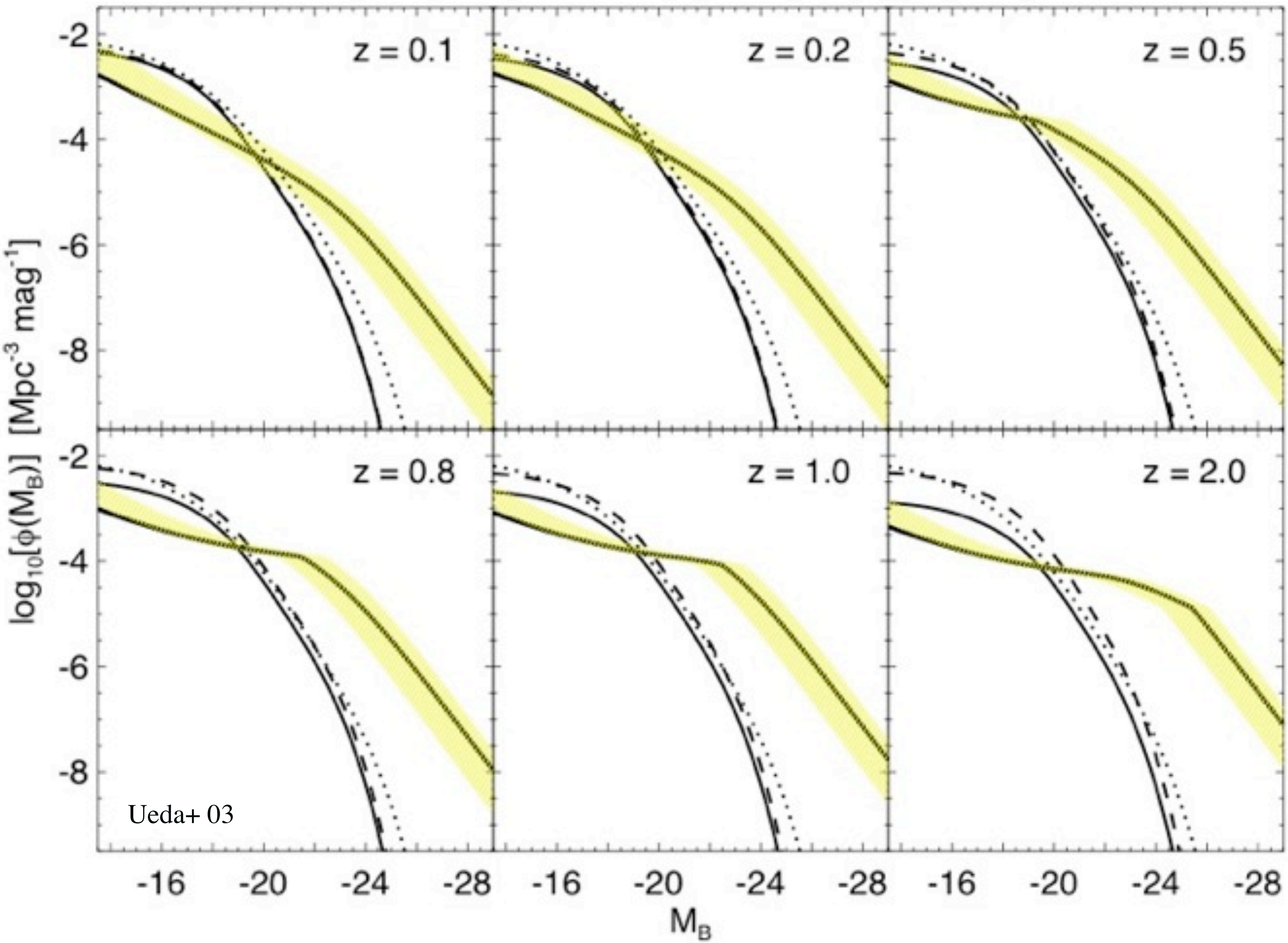
The Seyfert Luminosity Function

CORRECTIONS TO THE M_BH-SIGMA RELATION



The Seyfert Luminosity Function

CONTRIBUTION AS A FUNCTION OF REDSHIFT



Summary

- There is a lot of information in the observed QLF
  - Complex shape evolution vs. redshift
  - Need to be careful about combining observations
  - Systematics now the dominant uncertainty at z<4
- Feedback has dramatic effects on the shape & interpretation of the QLF:
  - Quasar lifetime not one number:
    Luminosity-dependent lifetimes
    Increases at lower L
  - Evolution of slopes & LDDE
  - "Cosmic Downsizing" as manifest in QSOs
- Feedback models : can consider differential contributions of quiescent & merger-triggered fueling
  - Tests: improved Eddington ratio distributions
  - Morphology along the QLF, especially vs. z
  - Improved m-sigma, clustering measurements