# Cosmological Evolution of Supermassive Black Holes


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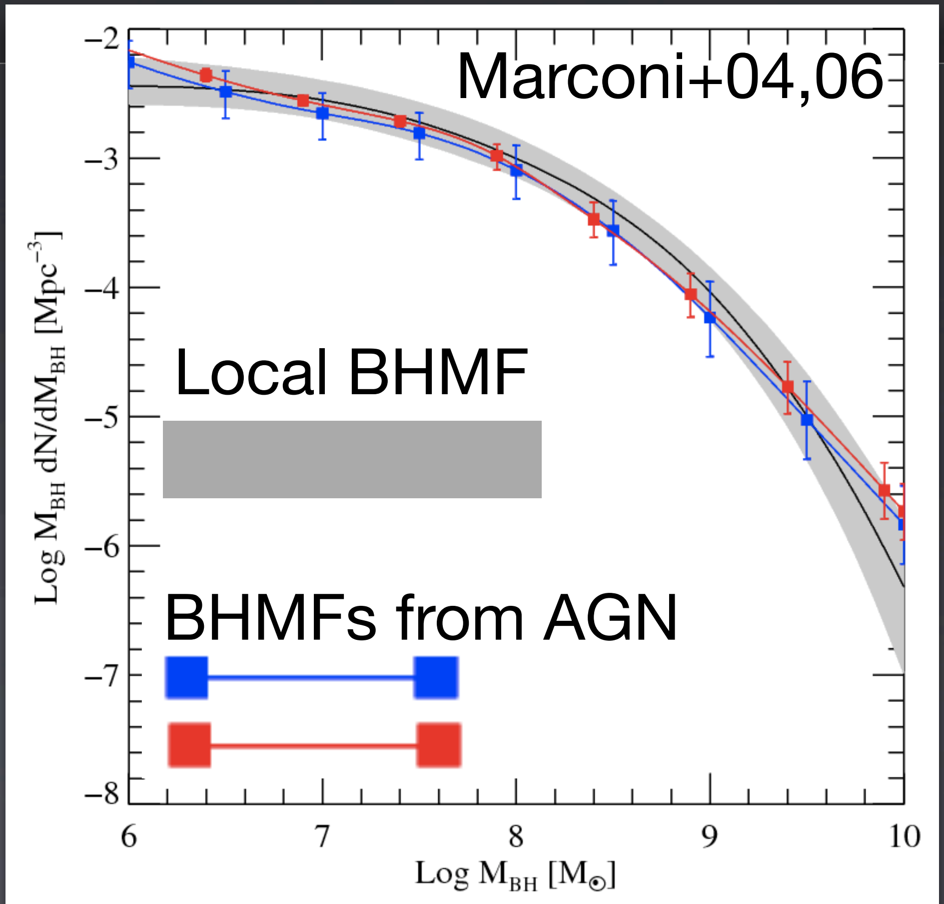
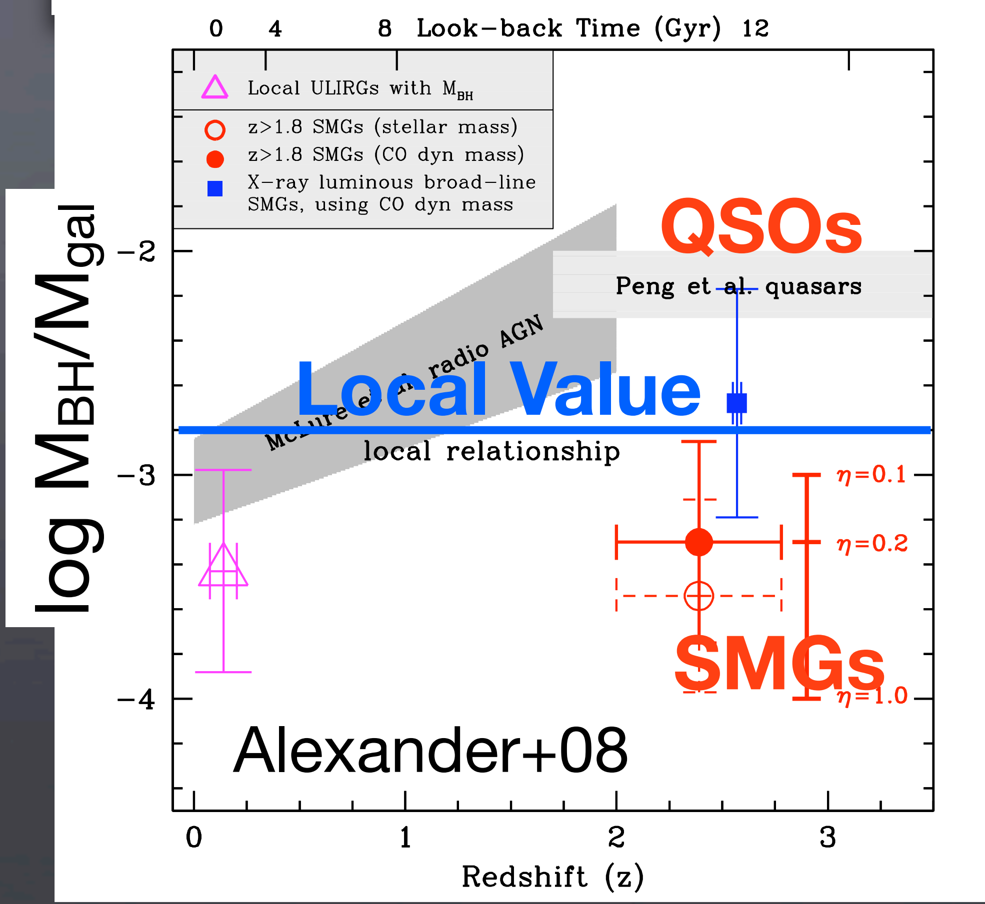
# BH evolution: what we know ...

- BHMF from AGN + BHMF of local BHs
  Local BHs ($\rho_{BH}$ ~ 3-6 ×$10^5$ $M_\odot$ $Mpc^{-3}$ ) mostly grown during luminous AGN activity with ε~0.1, $L/L_{Edd}$ ~ 0.2-0.5; anti-hierarchical BH growth.
  - *assume BHs in ALL local galaxies +* $M_{BH}$-$L_{sph}$;
  - *correction for missing obscured sources;*
  - *bolometric corrections;*
  - *single* $L/L_{Edd}$ *for all AGN.*
  (Yu & Tremaine 02, Marconi+04, Shankar+04, Hopkins+07, Merloni & Heinz 08, Shankar+09)




- Virial BH masses + host galaxy M and/or L
  BH growth appears to precede that of host spheroid: at z > 2 $M_{BH}/M_{gal}$~ 4-8 $M_{BH}/M_{gal}(z=0)$
  - *only type 1 AGN;*
  - *reliability of virial BH masses.*
  - *consistent with models* (Lamastra+09, in prep.)
  (Peng+06, McLure+06, Alexander+08, Walter+09, Merloni+09)



# The "differential" Sołtan argument

Apply continuity equation to BHMF (Cavaliere +71, Small & Bandford 92):

$$\frac{\partial f(M,t)}{\partial t} + \frac{\partial}{\partial M}\left[\langle \dot{M} \rangle f(M,t)\right] = 0$$

Assuming
- no "source" term (no merging of BHs)
- $L = \varepsilon \dot{M} c^2$
- $L = \lambda L_{Edd} = \lambda \frac{M c^2}{t_E}$

✱ single $L/L_{Edd}$ value for all AGN

BH Mass Function (AGN relics) AGN Luminosity Function

$$\frac{\partial f(M,t)}{\partial t} + \frac{(1-\varepsilon)\lambda^2 c^2}{\varepsilon t_E^2}\left(\frac{\partial \phi(L,t)}{\partial L}\right) = 0$$

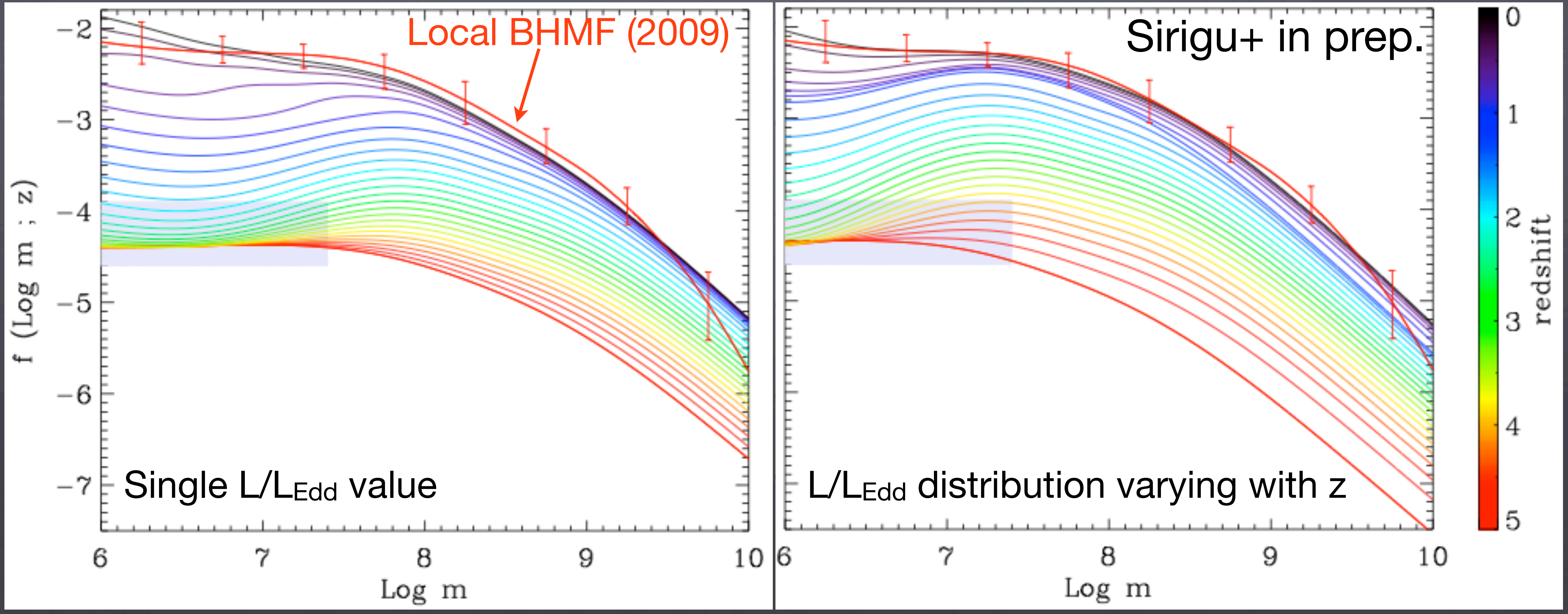
✱ L is total (bolometric) accretion luminosity (usually from $L_X$ after applying bolometric correction)

✱ ϕ(L,t) is the luminosity function of the whole AGN population (usually derived from X-ray LF after correcting for obscured sources)

# Allowing for a L/L$_{Edd}$ distribution

$$\frac{\partial f(M,t)}{\partial t} + \frac{1-\varepsilon}{\varepsilon c^2}\frac{\partial}{\partial M}\left(\int L\,\mathcal{P}(M|L,t)\,\phi(L,t)\,dL\right) = 0$$

- The single L/L$_{Edd}$ for all L, z still provides the best match of local BH MF.
- Need to take into account z, L dependence of L/L$_{Edd}$ distributions for improvement but small changes on final results.
- Too many free parameters, need observational constraints on L/L$_{Edd}$ distr.
- Only possibility is to measure virial M$_{BH}$ in type 1 AGN at all z.



# Virial BH masses

Direct measurements from spatially resolved kinematics (gas or stars) limited to local universe (D < 250 Mpc).

At larger distances assume BLR clouds gravitationally bound and apply virial theorem:

$$M_{\rm BH} = f \frac{V^2 \, R_{BLR}}{G}$$

Reverberation Mapping (RM) based virial masses

V from line width (FWHM)

$R_{BLR}$ from reverberation mapping

Extremely time consuming, use $R_{BLR}$-L relation (Kaspi+00, Bentz+09)

$$R_{BLR} \propto L^{\alpha}$$

Single Epoch (SE) virial masses

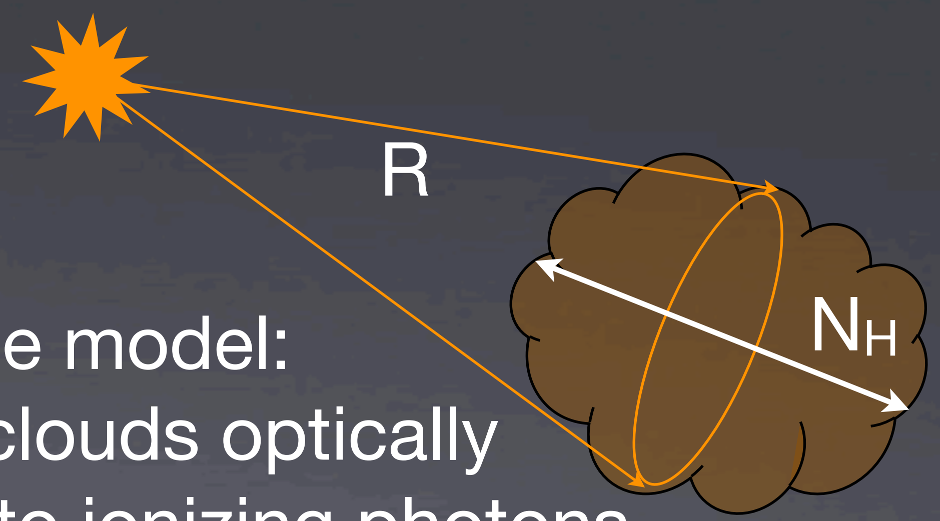
$$M_{BH} = \tilde{f} \, V^2 L^{\alpha}$$

$$\frac{M_{BH}(SE)}{M_{BH}(RM)} \sim 0.4 \, dex \, \mathrm{rms}$$

Vestergaard & Peterson 06

# The effect of radiation pressure

BLR clouds are photoionized;
radiation pressure on BLR clouds
is an unavoidable physical effect.




Simple model:
BLR clouds optically
thick to ionizing photons

Corrected mass estimator:

$$M_{BH} = f \frac{V^2 R}{G} + g \lambda L_\lambda$$

$$g = \frac{(L_{ion}/\lambda L_\lambda)}{4\pi G c m_p N_H}$$

Empirical calibration for g (Hβ):
g value corresponds to $N_H \sim 10^{23}$ cm$^{-2}$; consistent with photoionization models, direct measurements from X-ray observations (Risaliti et al. 2007, 2008, 2009)

When radiation pressure is taken into account:

Improved accuracy of SE masses w.r.t RM ones
($M_{BH}$(SE)/$M_{BH}$(RM) rms 0.4 → 0.2 dex)

NLS1 galaxies lie ON the $M_{BH}$-σ/L relation

(Marconi+08,09)

# Is it really important?

The correction for radiation pressure on virial $M_{BH}$ is

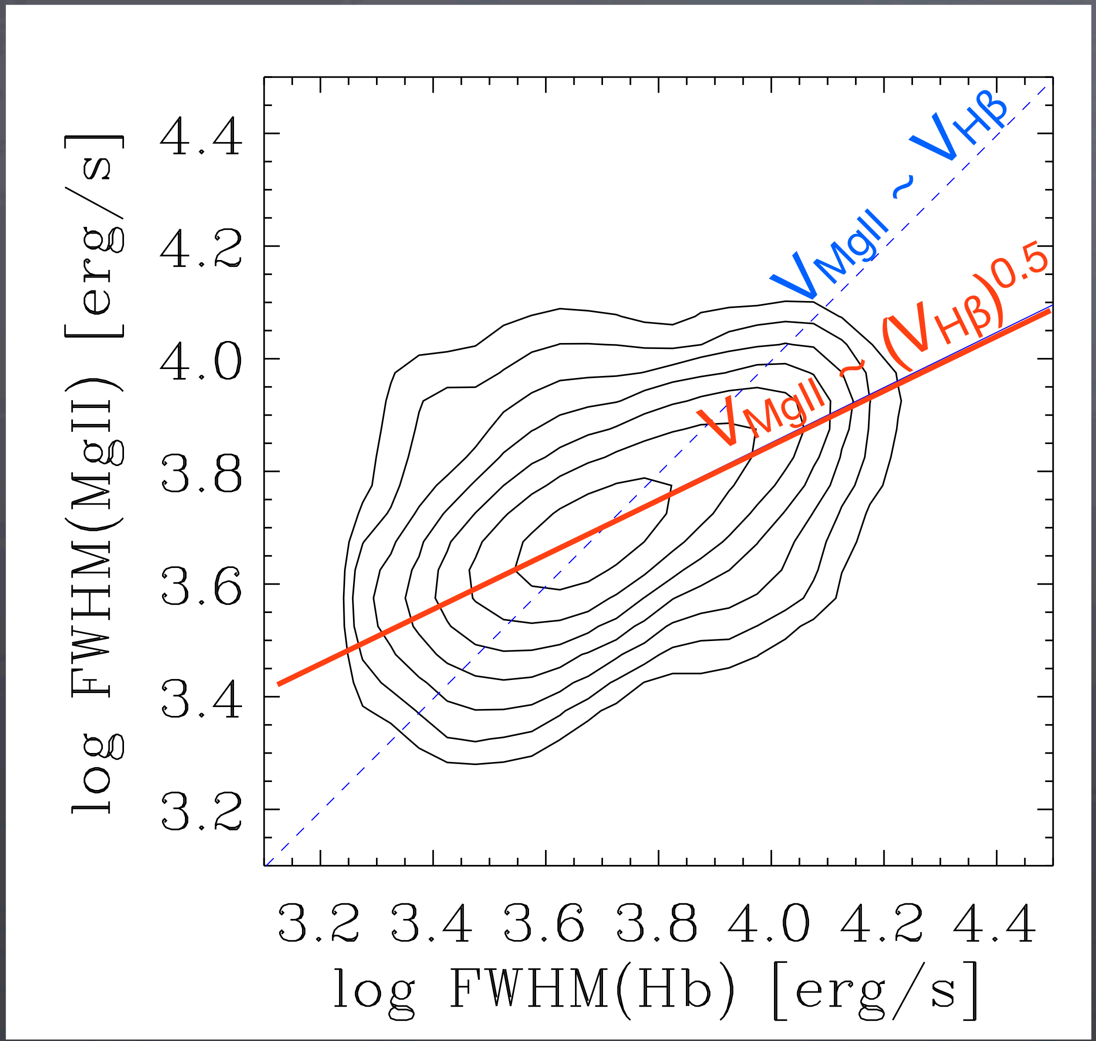
a) important if $N_H < 10^{24}$ cm$^{-2}$

b) negligible if $N_H > 10^{24}$ cm$^{-2}$

Is there any evidence for a or b ?

Consider the database of ~60000 quasars from SDSS (Shen et al. 2008) and select quasars with both Hβ and MgII in their spectra.

Puzzling result: non linearity of FWHM(MgII) vs FWHM(Hβ): $V_{MgII} \sim (V_{H\beta})^{0.5}$




$$M_{BH} = f_1 V_1^2 L_1^a = f_2 V_2^2 L_2^b$$

$$V_2 \propto V_1 L_1^a / L_2^b \propto V_1 L_1^{a-b} \text{ with } L_2 \propto L_1$$

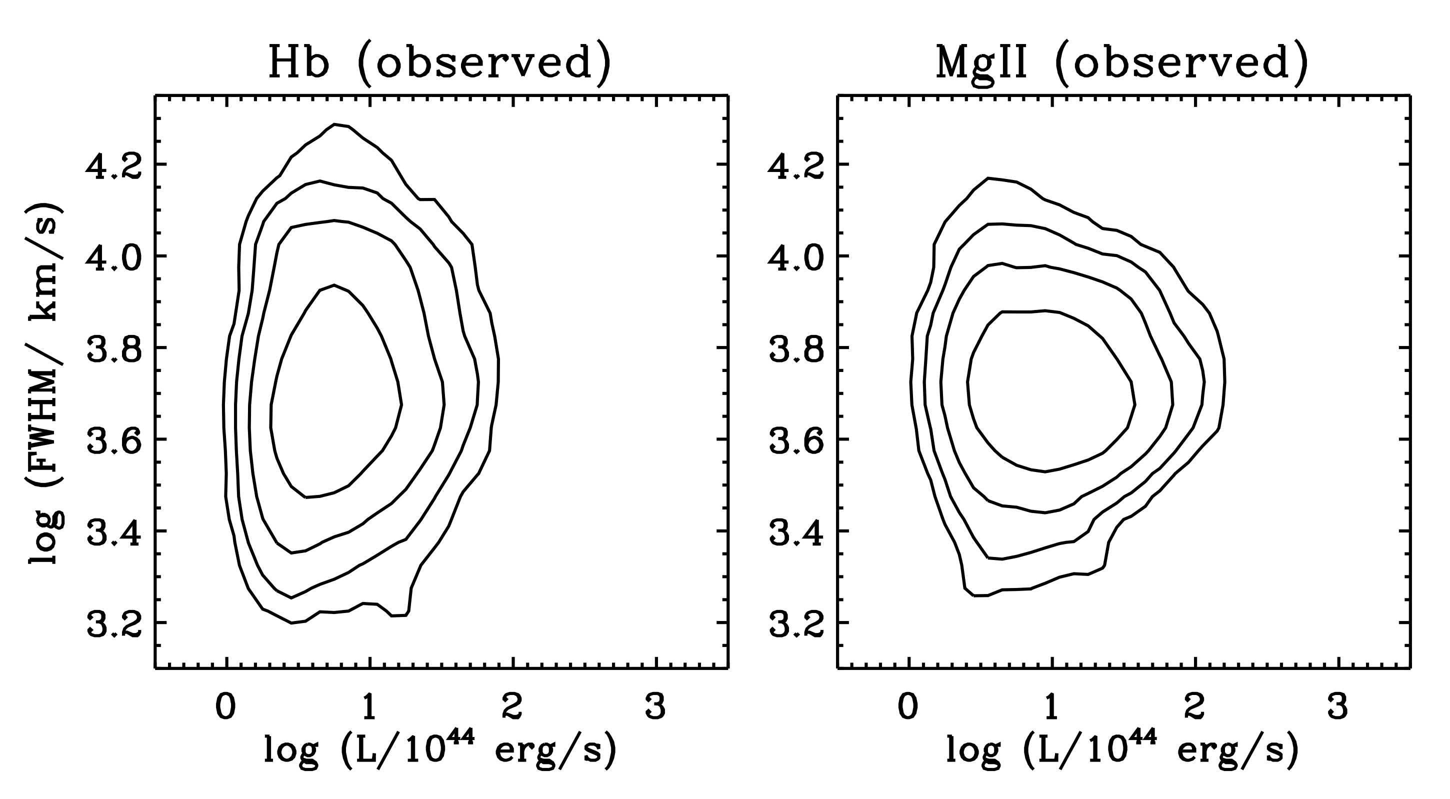
But ...

NO dependence of $V_2/V_1$ with L observed!

# Comparing Hβ and MgII ...

Instead of considering $M_{BH}$, $L/L_{Edd}$ (combination of V, L), consider only observed quantities:

$L_1$, $V_1$ (Hβ)
$L_2$, $V_2$ (MgII)




Observed L,V distributions: Hβ: $P_1(L_1, V_1)$ MgII: $P_2(L_2, V_2)$

$$P_2(L_2, V_2) = \int\int K(L_2, V_2 | L_1, V_1) P_1(L_1, V_1) dL_1 dV_1$$

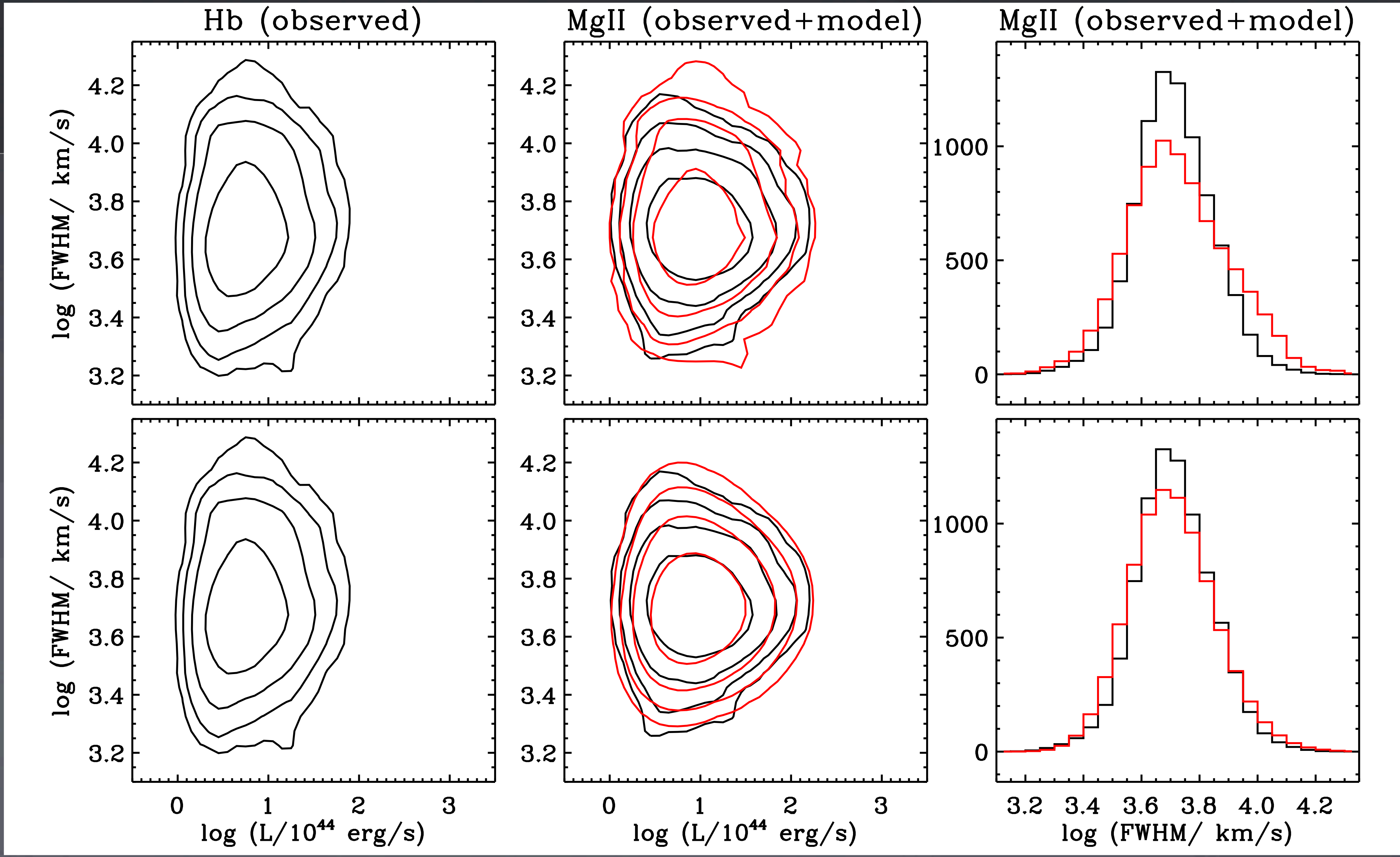
K is found by imposing that $M_{BH} = f_1 V_1^2 L_1^a + g_1 L_1 = f_2 V_2^2 L_2^b + g_2 L_2$

Convolve $P_1$ with K and find best $f_2$, $g_2$ and b to match $P_2$

# Hβ-MgII

NO radiation pressure ($\chi^2$/dof = 1.9 )

WITH radiation pressure on Hβ ($\chi^2$/dof = 1.2 )




The case without radiation pressure is excluded, expected FWHM distribution for MgII is broader than observed.

Much better agreement if we allow for radiation pressure on Hβ.

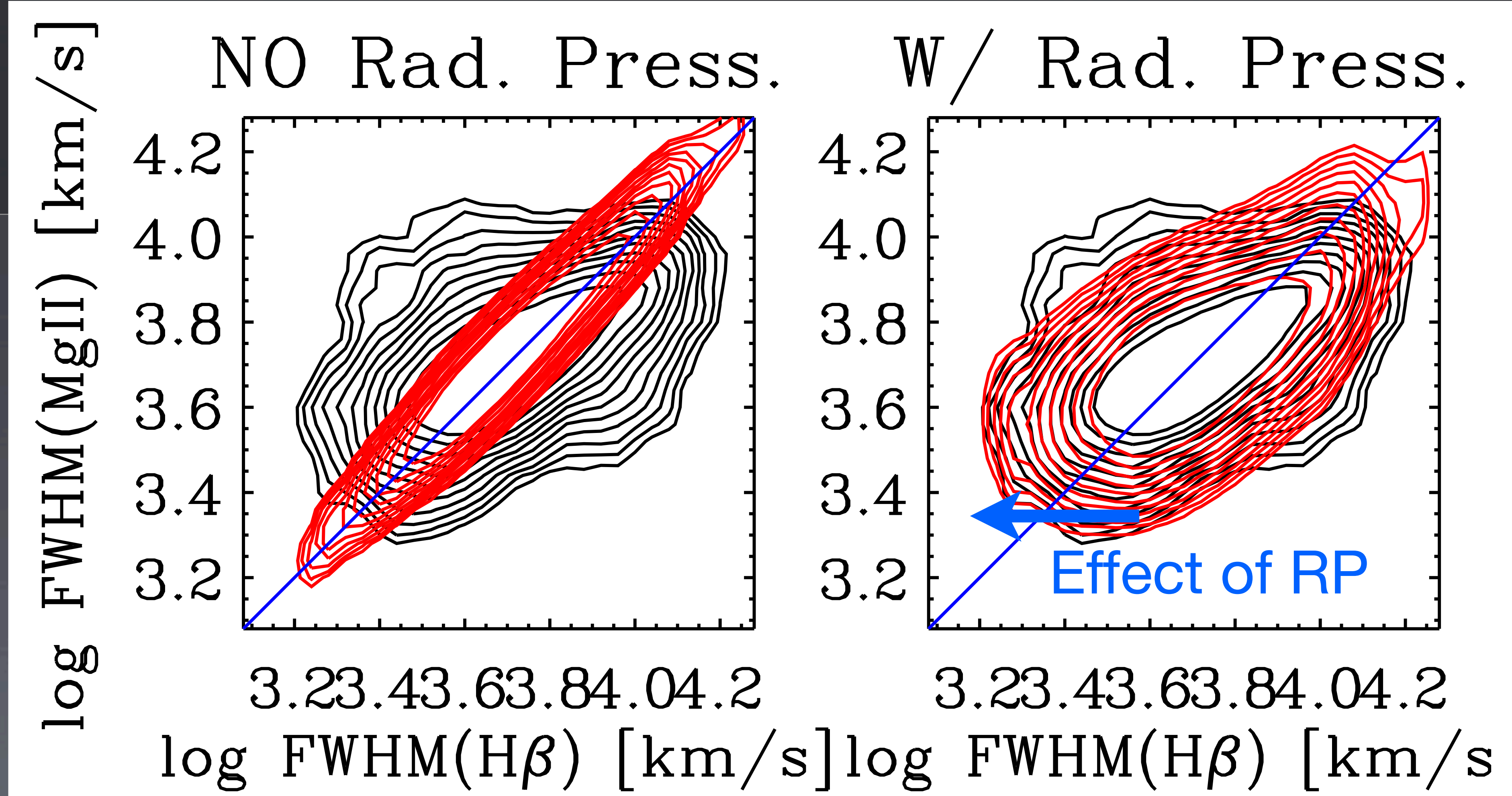
MgII calibration is

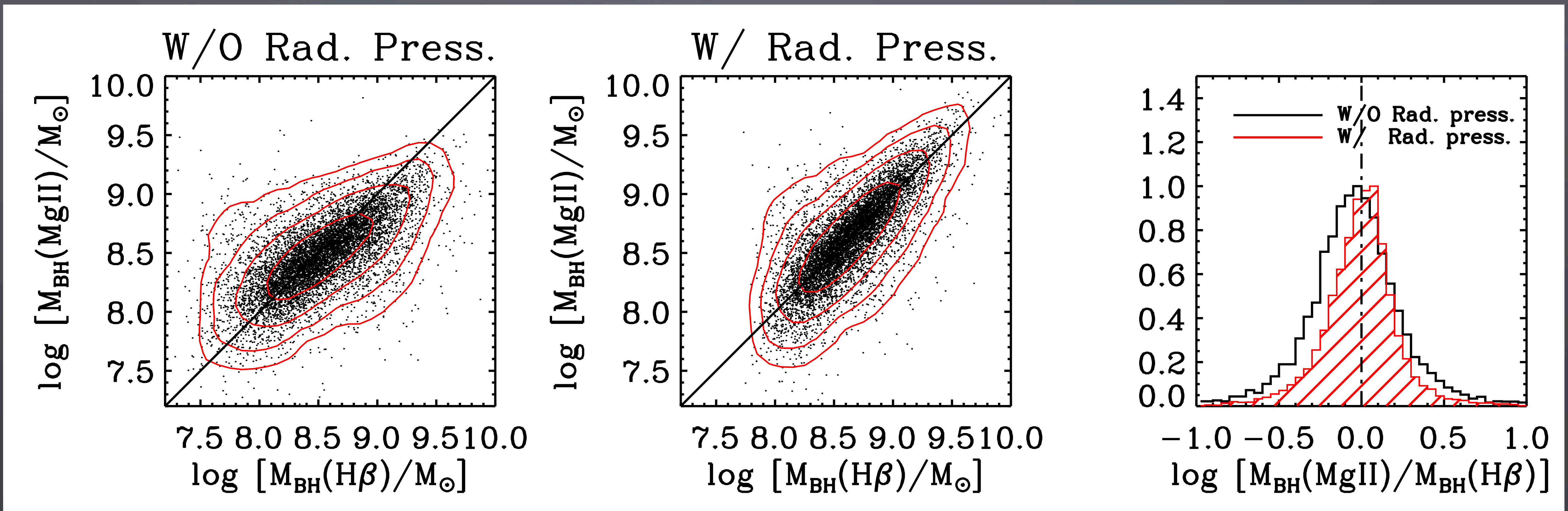
$$M_{BH}(MgII) = 10^{6.5}\, V_2^2\, L_2^{0.7} \quad g_2 < 10^{5.7} \Rightarrow N_H > 10^{23.9}\,\mathrm{cm}^{-2}$$

no radiation pressure on MgII, steep $R_{BLR}$-L relation (slope 0.7 instead of 0.5)

# Hβ vs MgII

Radiation pressure explains the tilt of the FWHM(MgII)-FWHM (Hβ) relation:
the tilt is an indication that radiation pressure affects Hβ but not MgII

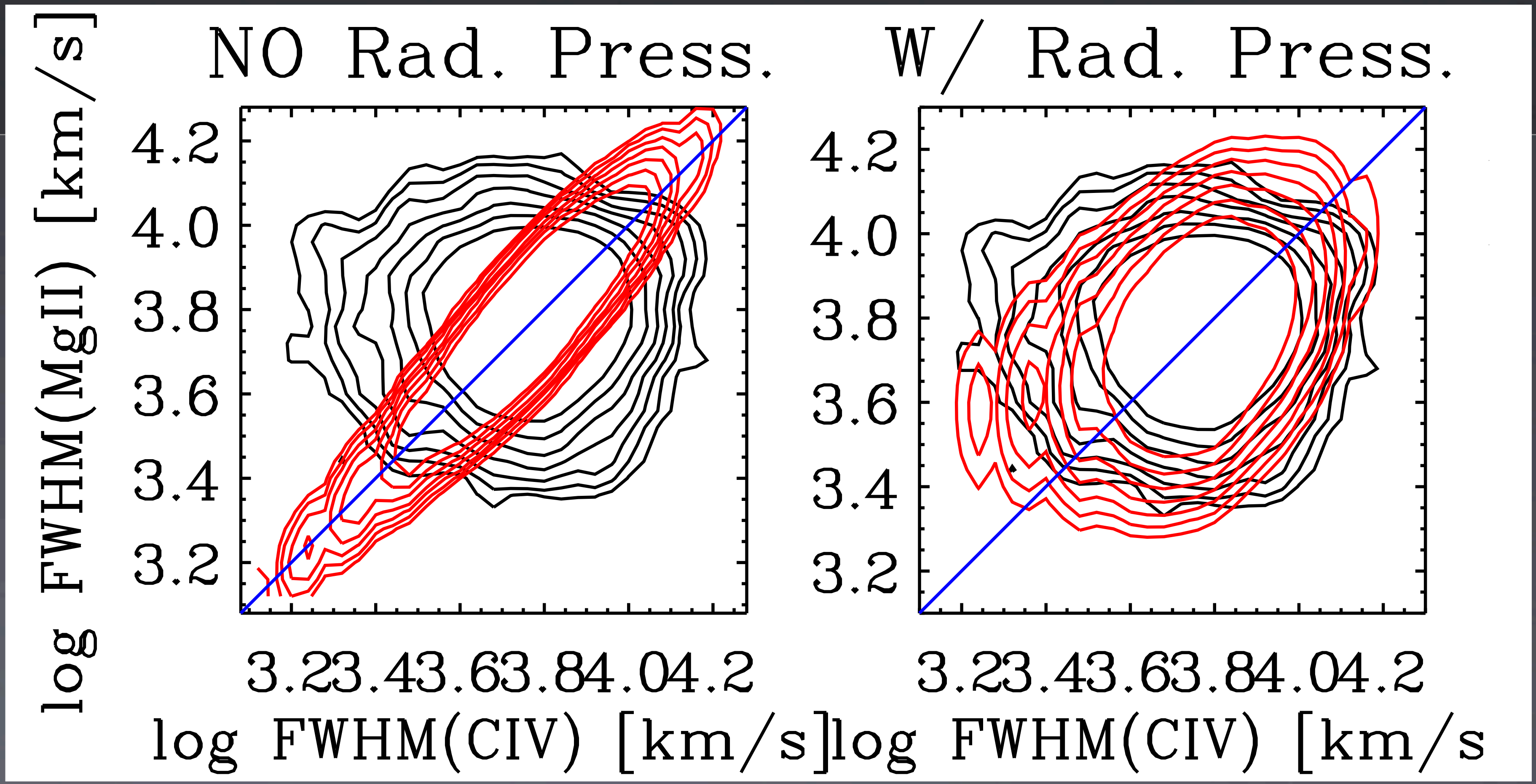


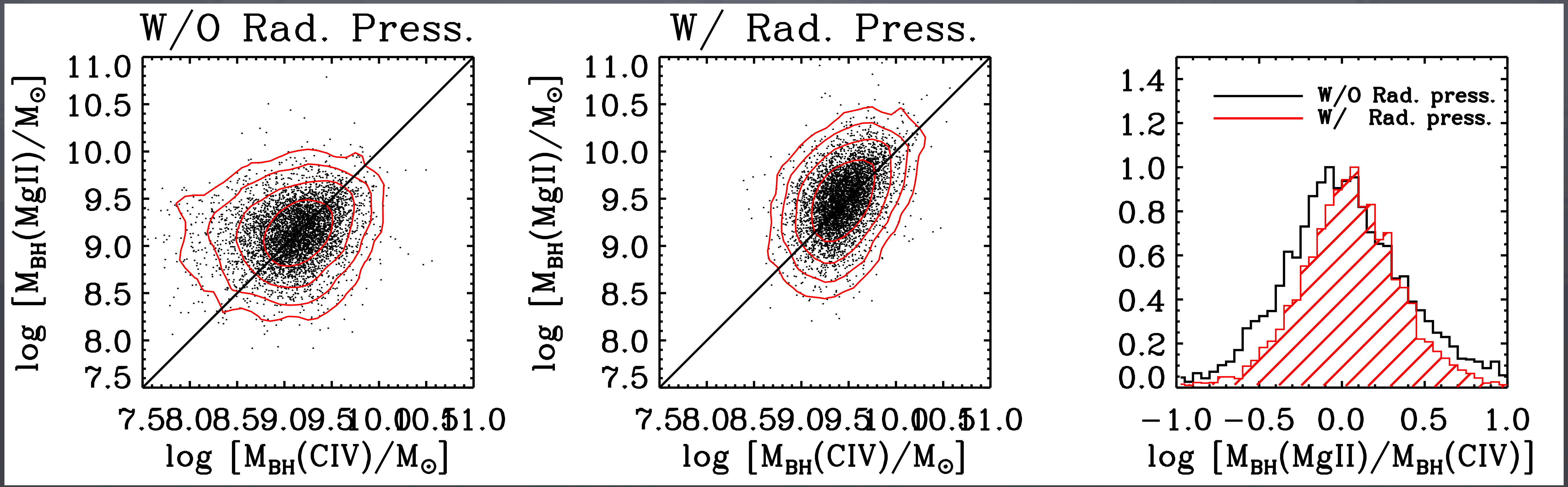




Linear $M_{BH}$(Hβ) - $M_{BH}$(MgII); smaller scatter for $M_{BH}$(MgII)/$M_{BH}$(Hβ)

# CIV vs MgII

Improved agreement $M_{BH}$(MgII)-$M_{BH}$(CIV), almost explained the absence of relation FWHM(CIV) - FWHM (MgII); some problems for CIV (outflows?)



# Virial BH masses at high z

Virial $M_{BH}$ from Hβ and CIV are affected by radiation pressure:

$$\frac{M_{BH}(H\beta)}{\mathrm{M}_\odot} = 10^{6.5} \left(\frac{FWHM(H\beta)}{1000\,\mathrm{km\,s}}\right)^2 \left(\frac{\lambda L_\lambda(5100\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5} + 10^{7.5} \left(\frac{\lambda L_\lambda(5100\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5}$$

$$\frac{M_{BH}(CIV)}{\mathrm{M}_\odot} = 10^{6.4} \left(\frac{FWHM(CIV)}{1000\,\mathrm{km\,s}}\right)^2 \left(\frac{\lambda L_\lambda(1350\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5} + 10^{7.0} \left(\frac{\lambda L_\lambda(1350\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5}$$

From the analysis of observed L, FWHM distributions MgII is little affected by radiation pressure ($N_H > 10^{24}$ cm$^{-2}$):

$$\frac{M_{BH}(MgII)}{\mathrm{M}_\odot} = 10^{6.5} \left(\frac{FWHM(MgII)}{1000\,\mathrm{km\,s}}\right)^2 \left(\frac{\lambda L_\lambda(5100\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.7}$$

Evidence for $N_H$ distribution in BLR clouds, where Hβ and CIV emission is dominated by low $N_H$ (~$10^{23}$ cm$^{-2}$) clouds, and MgII by large $N_H$ (~$10^{23}$ cm$^{-2}$) clouds.

MgII appears to be the best line for virial $M_{BH}$ estimates (Marconi +09, in prep.)

# Conclusions

- Cosmological evolution of BH with the Sołtan's argument (Sirigu+ in prep.)
  Taking into account a distributions of $L/L_{Edd}$ values improve matching of the local BH MF only if dependence on L or z is taken into account.
  To remove degeneracies observational constraints on $L/L_{Edd}$ are needed.
  Need reliable BH mass estimates at high z (Effect of radiation pressure?).

- BH masses at high z (Marconi+08,Marconi+09, Marconi+ in prep.)
  Virial BH masses (from single spectra of broad-line AGN) can be used to estimate $M_{BH}$ at all z.
  Estimates based on Hβ and CIV are affected by radiation pressure from ionizing photons, estimates based on MgII are not.
  This fact naturally explains the non-linear relation between FWHM(Hβ) and FWHM(MgII), and improve the agreement between $M_{BH}$ estimated from different broad emission lines.

- To obtain a clear and complete picture of the cosmological evolution of supermassive BH it is necessary to combine
  AGN Luminosity Functions AND their $L/L_{Eddington}$ distributions (ie needs$M_{BH}$)