A semi-empirical two-component reverberation model of the BLR

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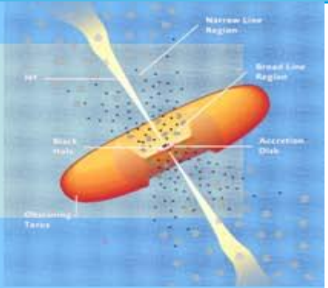
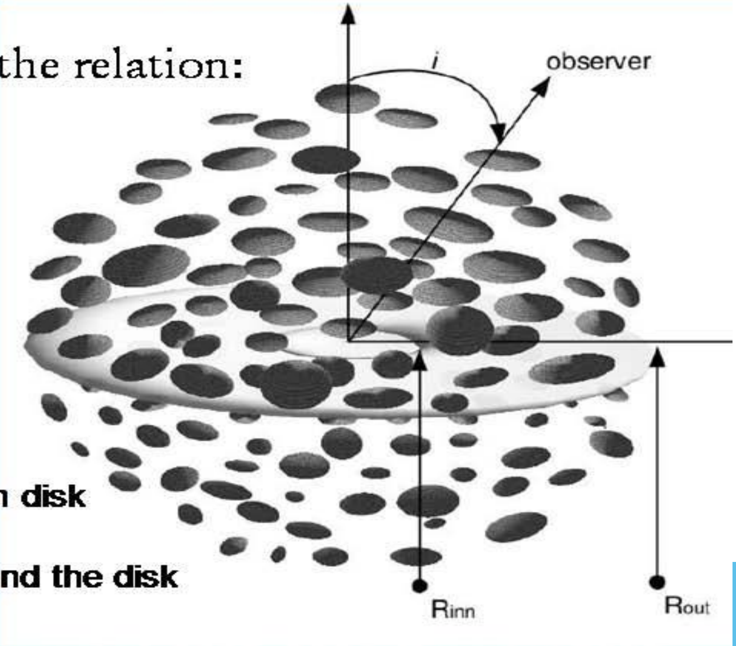
Motivation

Two-component model



- The disk is contributing to the wings of the lines,
- a spherical medium arround the disk to the core of the lines.

The whole line profile can be described by the relation:



$$I(\lambda)=I_{AD}(\lambda)+I_{G}(\lambda)$$

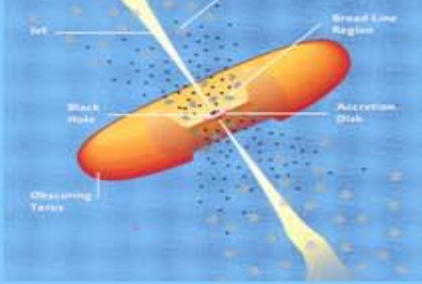
Where:

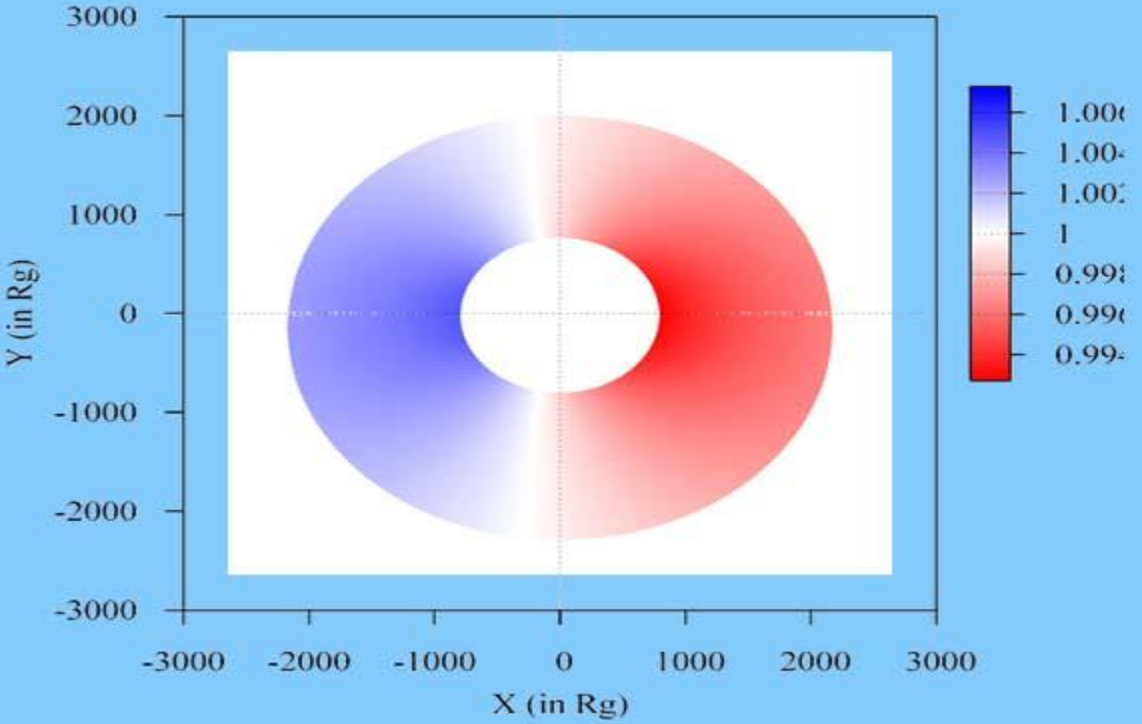
$I_{AD}(\lambda)$ the emissions of the relativistic accretion disk

$I_{G}(\lambda)$ the emissions of the spherical region around the disk

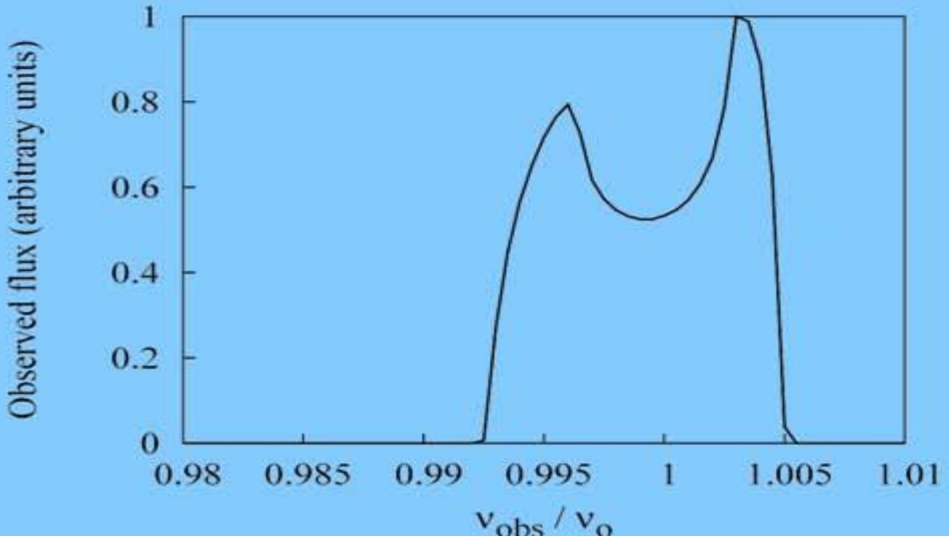
Popović et al, 2003, 2004, Bon et al 2006

Disk model





Chen & Halpern (1989).



Chen-Halpern disk model

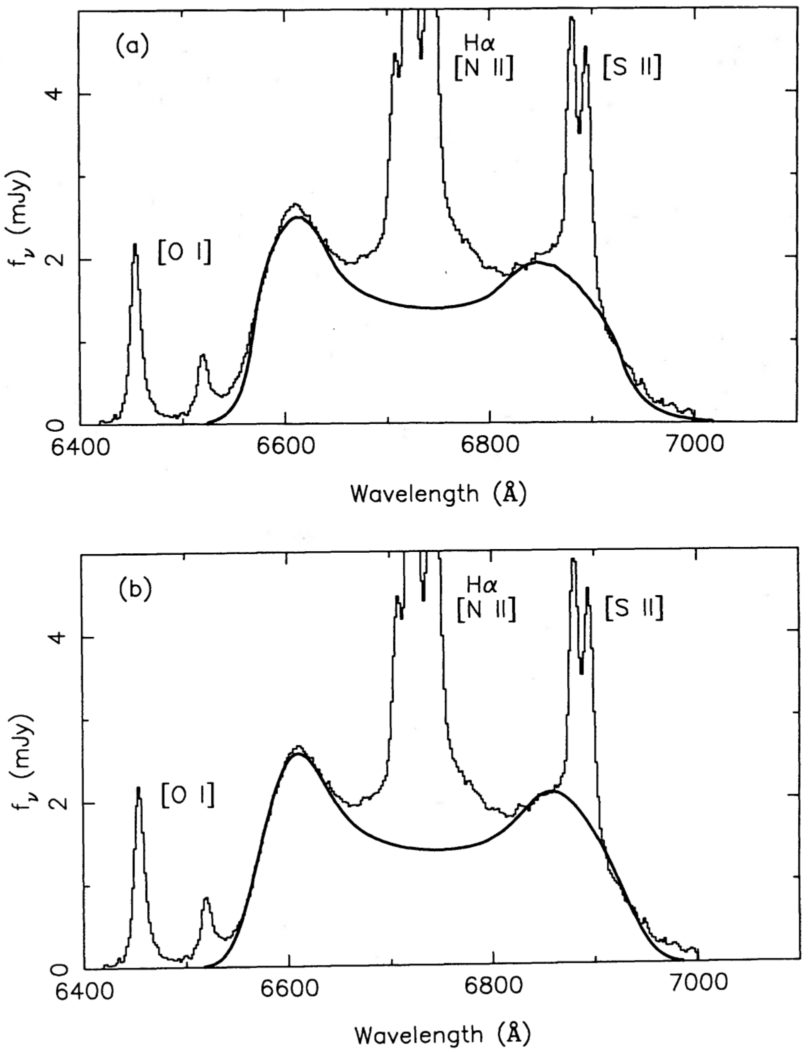
- Arp 102 B case:

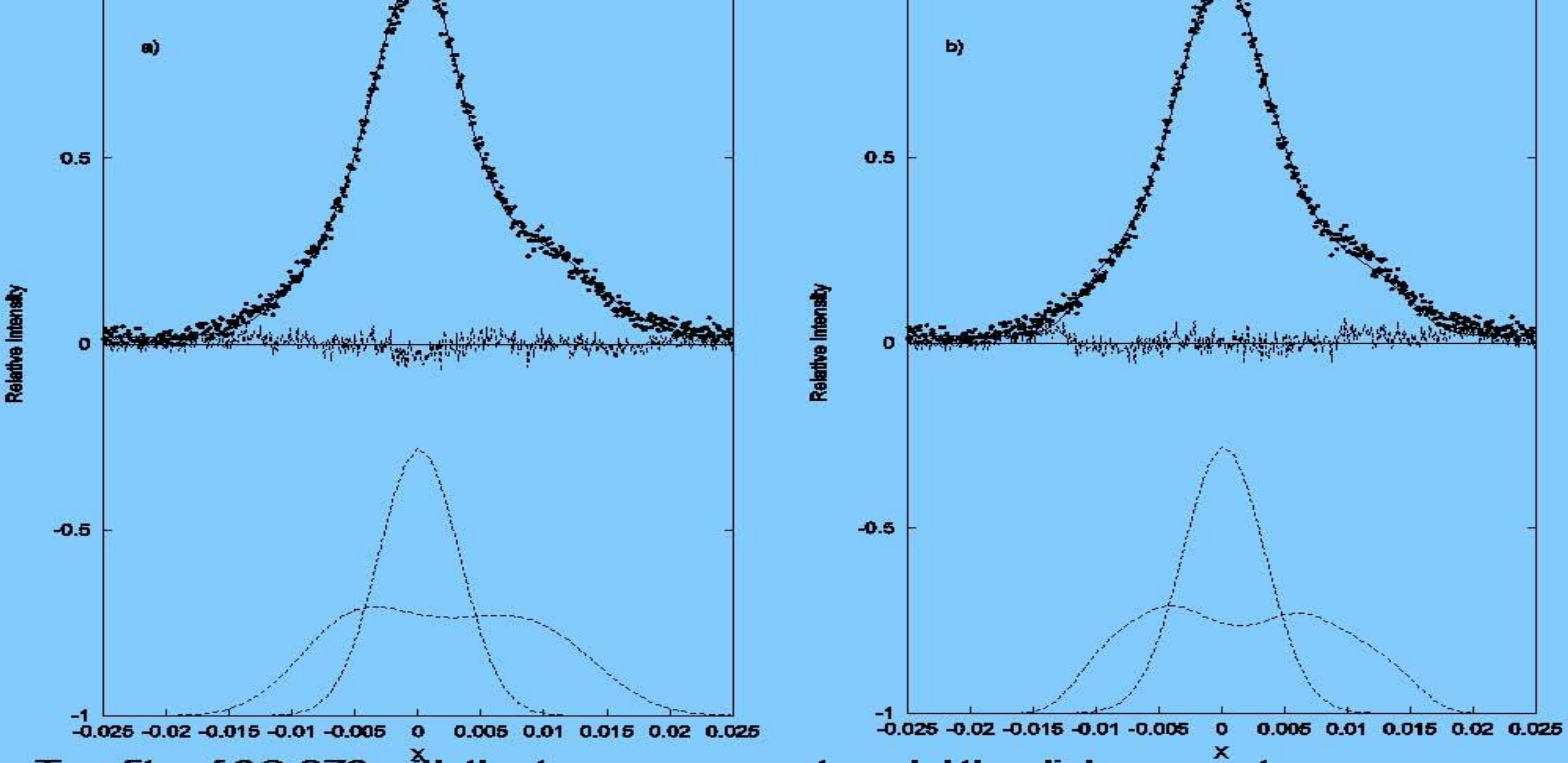
$$F_X = \frac{2\epsilon_0 M^2 \cos i}{4\pi d^2} \frac{\nu_0}{(2\pi)^{1/2}\sigma} \int_{\xi_1}^{\xi_2} \int_{-\pi/2}^{\pi/2} d\xi\, d\varphi' \exp\left[-\frac{(1+X-D)^2\nu_0^2}{2\sigma^2 D^2}\right] D^3 \xi^{1-q} g(D) ,$$

$$g(D) = 1 + \xi^{-1}\left\{\frac{2D^2}{D^2\cos^2 i + \xi[D-(1-3/\xi)^{1/2}]^2} - 1\right\} .$$

Chen, K., & Halpern, J. P. 1989, ApJ, 344, 115

LINE-EMITTING ACCRETION DISKS IN AGNs





Two fits of 3C 273 with the two-component model the disk parameters are:

a) $i=14^\circ$, Rinn=400 Rg, Rout=1420 Rg, Wd=1620 km/s, p=3.0 (WG=1350 km/s);

b) $i=29^\circ$, Rinn=1250 Rg, Rout=15000 Rg, Wd=700 km/s, p=2.8 (WG=1380 km/s)

Popović, L. Č., Mediavlilla, E.G., Bon, E., Ilić, D., 2004, ***ApJ***

Model summarized

$F_{tot}(\nu,T) = F_{disk} + \Delta F_{disk} + F_{core} + \Delta F_{core}$

light curves | profile sequence | velocity–delay map

$$U = \frac{Q_{\rm H}}{4\pi d^2 c\, n_{\rm H}},\qquad U_{\rm base}(r) = U_{\rm ref}\left(\frac{r}{r_0}\right)^{-2}\frac{n_{\rm H,0}}{n_{\rm H}(r)},$$

$$U_{\rm fl}(\boldsymbol{r},t) = U_{\rm ref}\,A_U\,\frac{[L_{\rm del}(\boldsymbol{r},t) - L_{\rm base}]_+}{L_{\rm base}}\left(\frac{r_0}{d_{\rm X}}\right)^2\frac{n_{\rm H,0}}{n_{\rm H}(r)},$$

Gaussian component (line core):

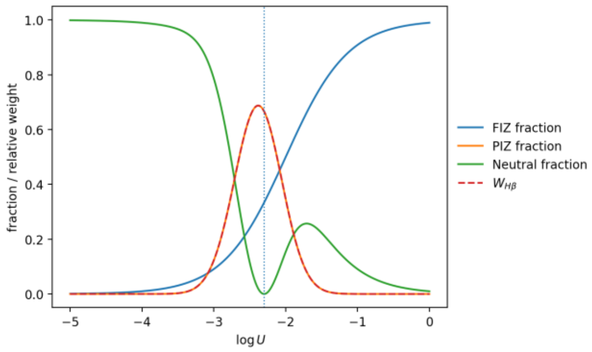
$$G(v;\sigma_{\rm core}) = \frac{1}{\sqrt{2\pi}\,\sigma_{\rm core}}\exp\left[-\frac{(v-v_0)^2}{2\sigma_{\rm core}^2}\right]$$

The perturbed core response is modelled by a set of N_{cl} macro-clouds. A macro-cloud is not a single physical cloud, but a packet representing many unresolved emitters with a local Gaussian velocity kernel.

Each macro-cloud has a local Gaussian kernel of width h σ_{loc}:

$$K_i(v) = \frac{1}{\sqrt{2\pi}\,\sigma_{\rm loc}}\exp\left(-\frac{(v-v_i)^2}{2\sigma_{\rm loc}^2}\right)$$

$$\sigma_{\rm core}^2 = \sigma_{\rm cl}^2 + \sigma_{\rm loc}^2 .$$



$$U_{\rm tot} = U_{\rm base} + U_{\rm fl},$$

$$f_{\rm FIZ} = \frac{(U_{\rm tot}/U_{\rm FIZ})^{\beta}}{1 + (U_{\rm tot}/U_{\rm FIZ})^{\beta}},$$

$$g_{\rm PIZ} = \exp\left[-\frac{(\log_{10}U_{\rm tot} - \log_{10}U_{\rm PIZ})^2}{2\sigma_{\log U}^2}\right],$$

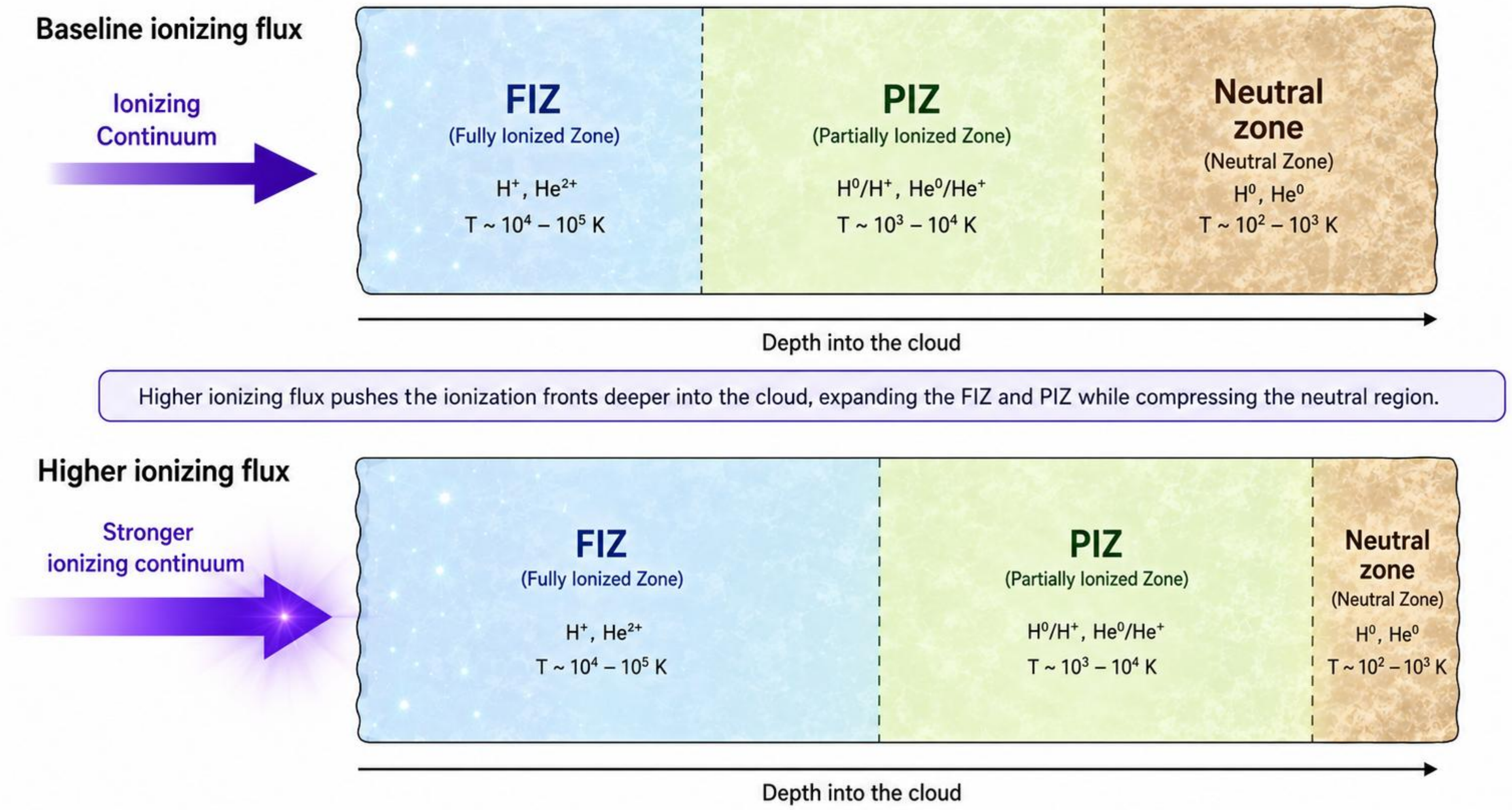
$$f_{\rm PIZ} = (1 - f_{\rm FIZ})\,g_{\rm PIZ},$$

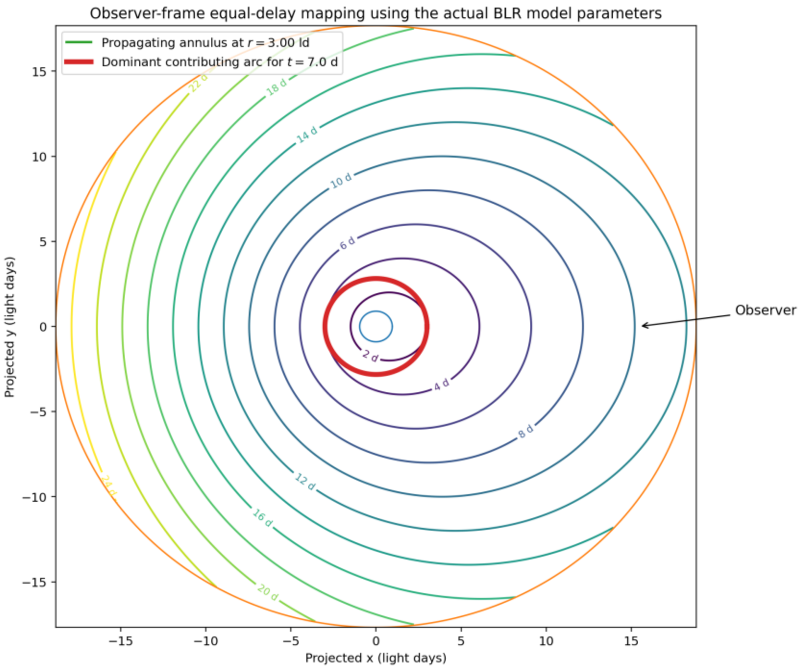
$$f_{\rm neutral} = 1 - f_{\rm FIZ} - f_{\rm PIZ},$$

$$N_i = f_i N_{\rm H},$$

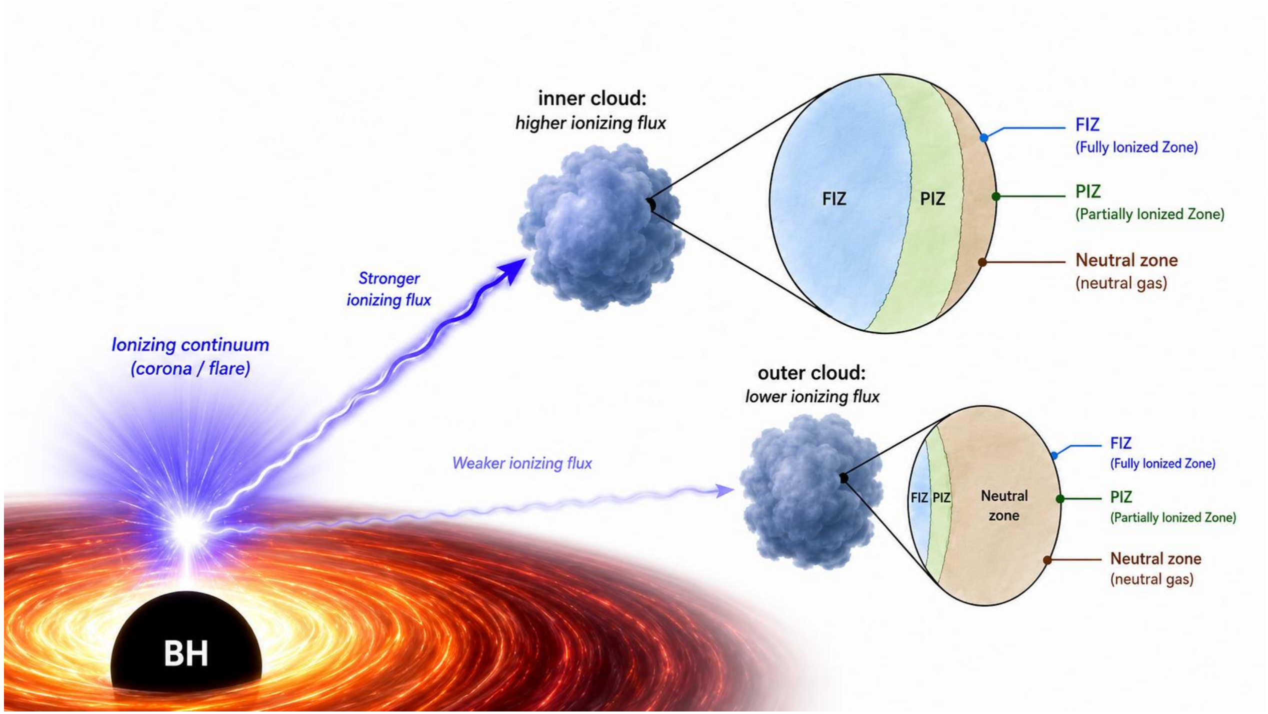
$$W_{\rm H\beta} = f_{\rm PIZ}^{\gamma}.$$

Effect of Increasing Ionizing Flux on BLR Cloud Structure



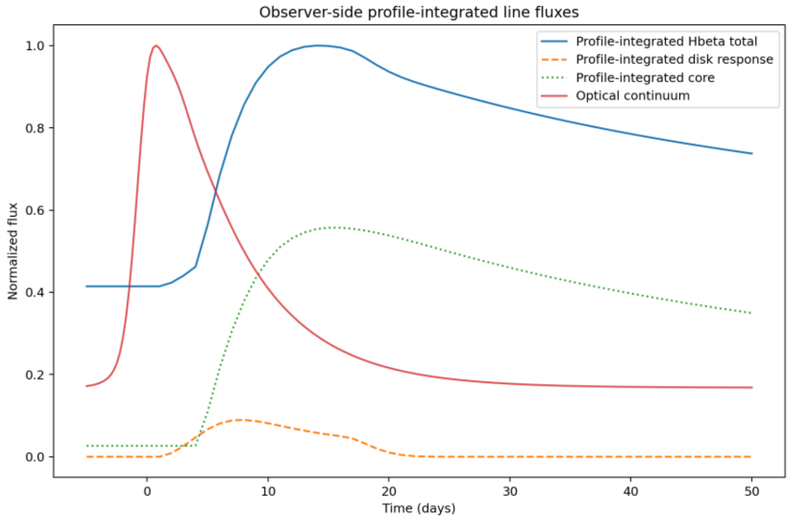


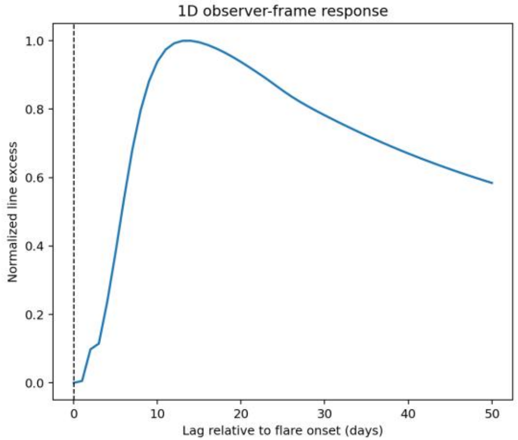
Observer-frame equal-delay mapping using the actual BLR model parameters
Propagating annulus at $r = 3.00$ ld
Dominant contributing arc for $t = 7.0$ d
Observer
Projected x (light days)
Projected y (light days)
2 d
4 d
6 d
8 d
10 d
12 d
14 d
16 d
18 d
20 d

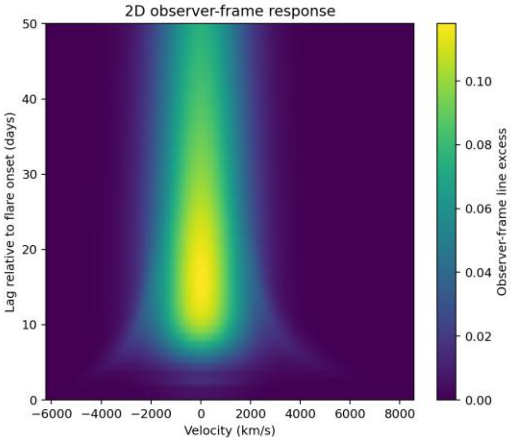


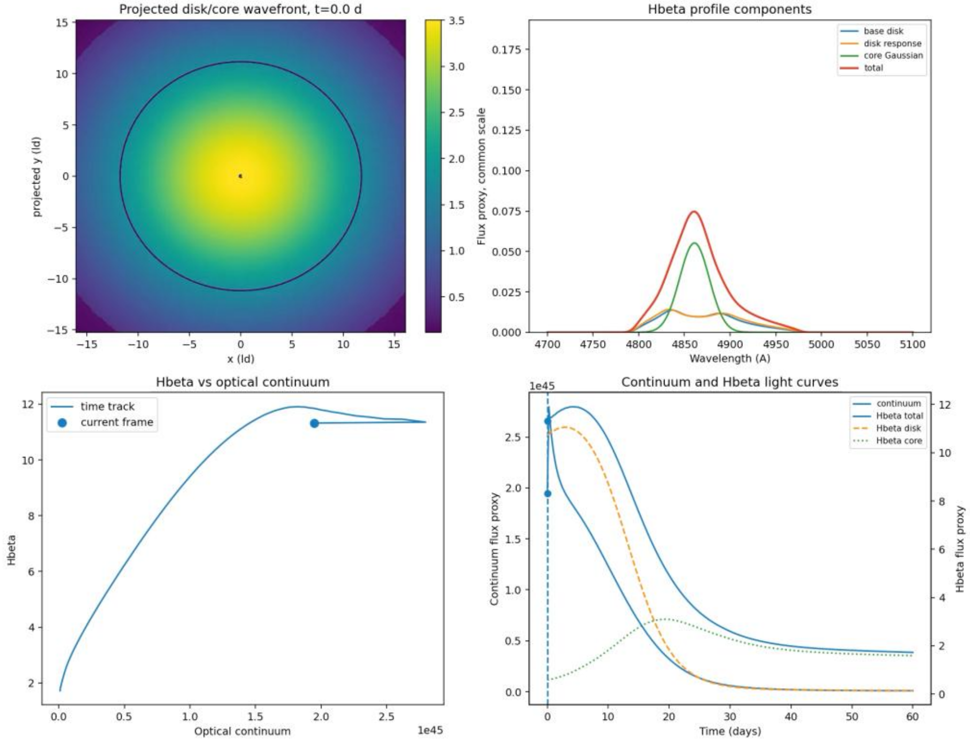
inner cloud:
higher ionizing flux
FIZ
PIZ
FIZ
(Fully Ionized Zone)
PIZ
(Partially Ionized Zone)
Neutral zone
(neutral gas)
Stronger
ionizing flux
Ionizing continuum
(corona / flare)
outer cloud:
lower ionizing flux
Weaker ionizing flux
FIZ
PIZ
Neutral
zone
FIZ
(Fully Ionized Zone)
PIZ
(Partially Ionized Zone)
Neutral zone
(neutral gas)
BH

Two component BLR reverberation model

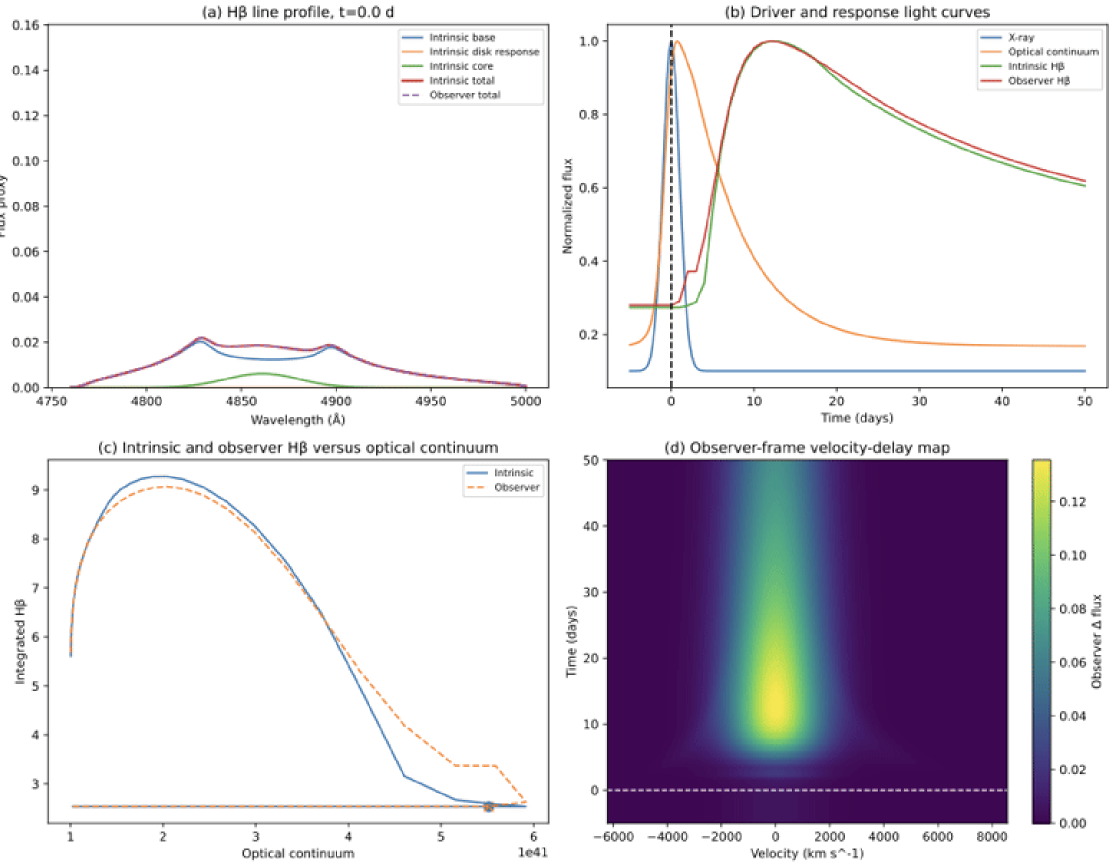


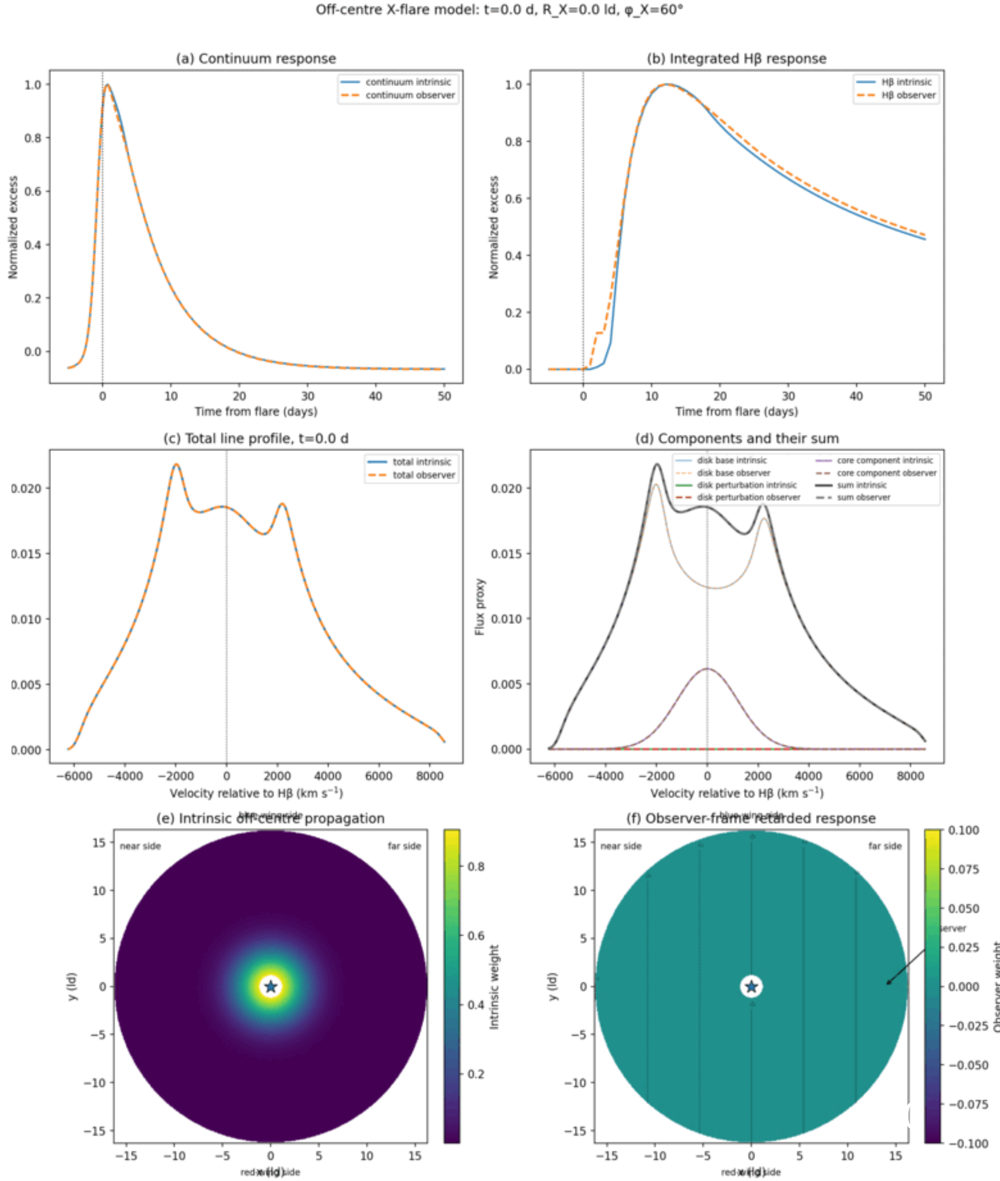




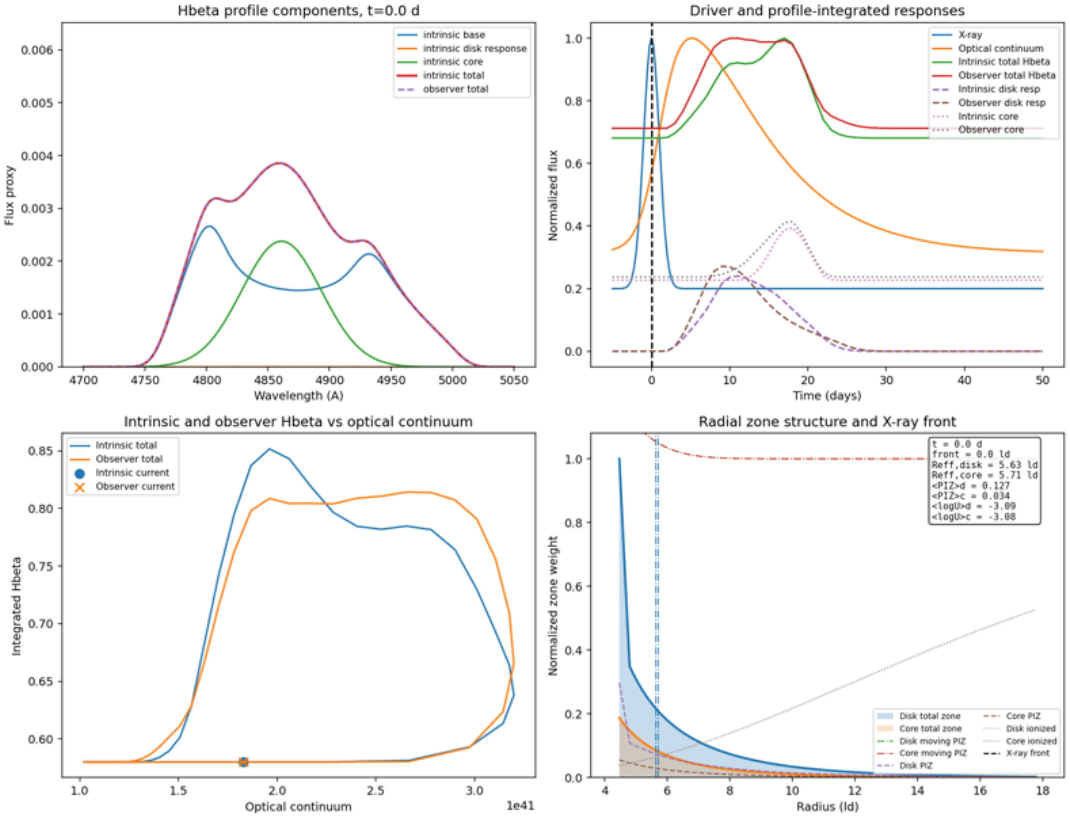


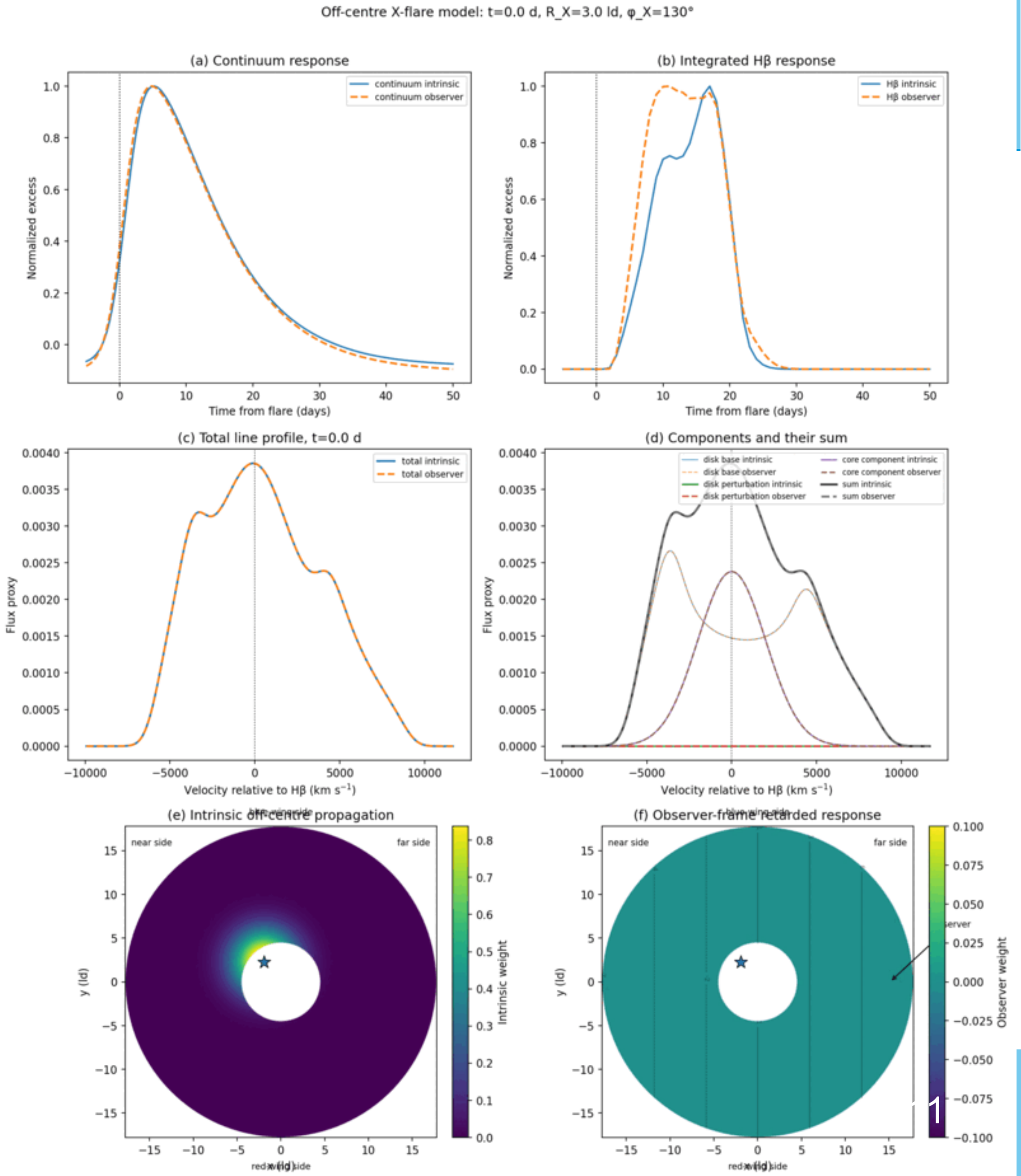
A flare example



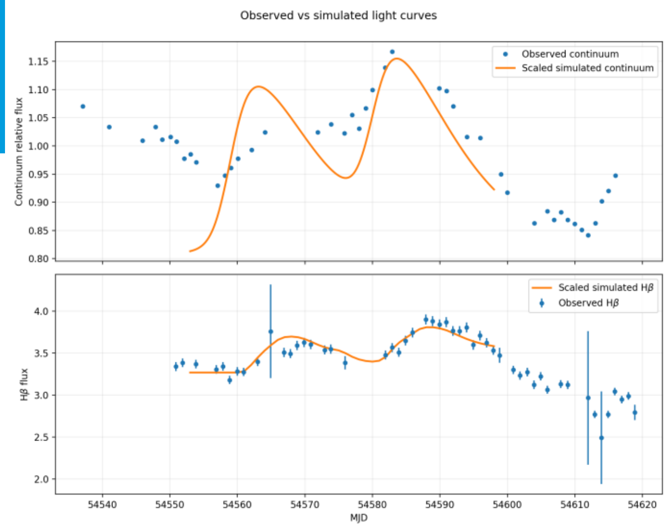


Offcentre fale rxample

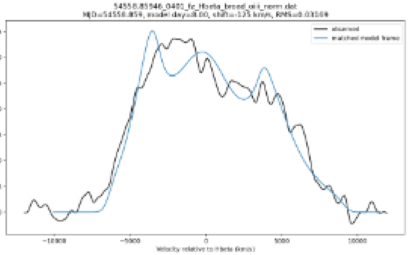


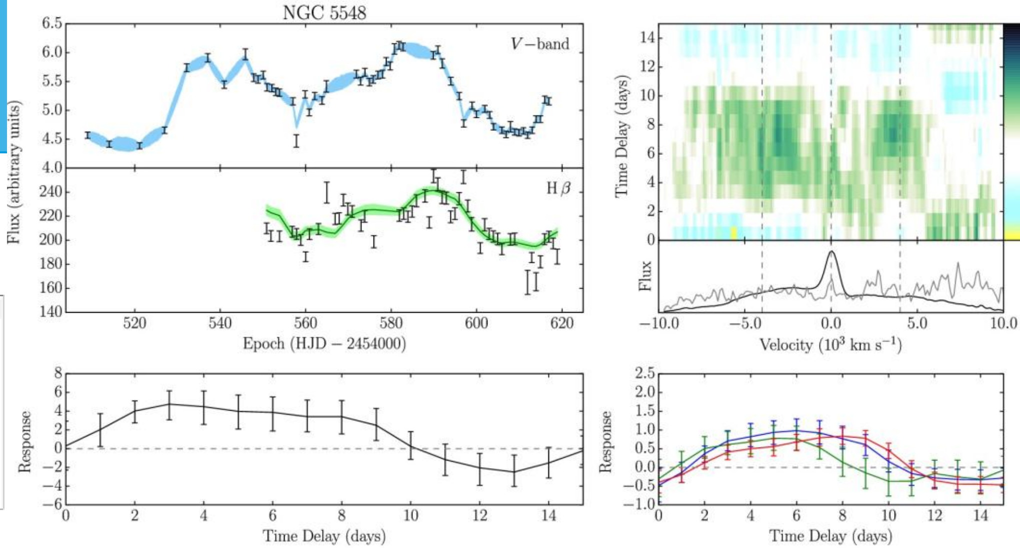


NGC5548

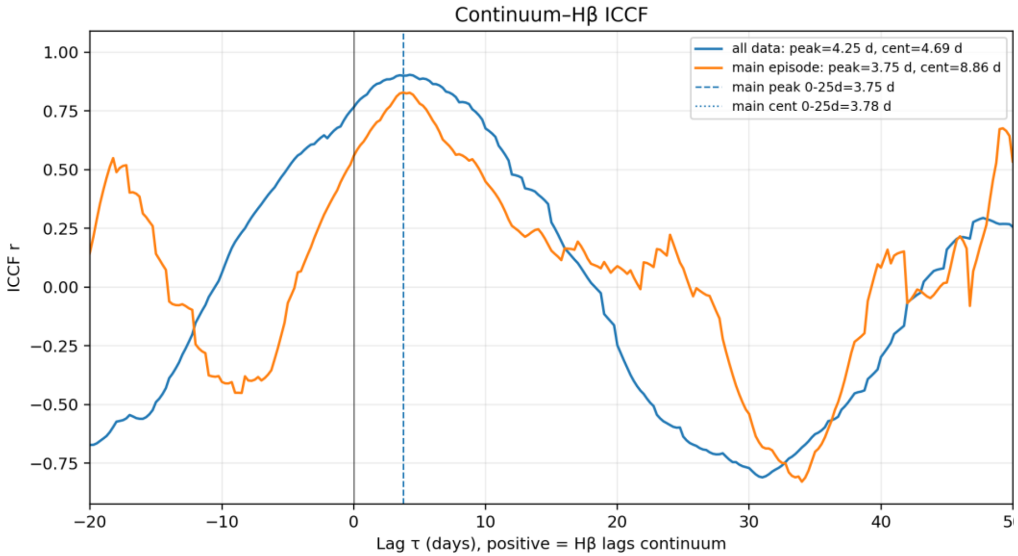


Observed vs simulated light curves
Observed continuum
Scaled simulated continuum
Continuum relative flux
Scaled simulated Hβ
Observed Hβ
Hβ flux
MJD

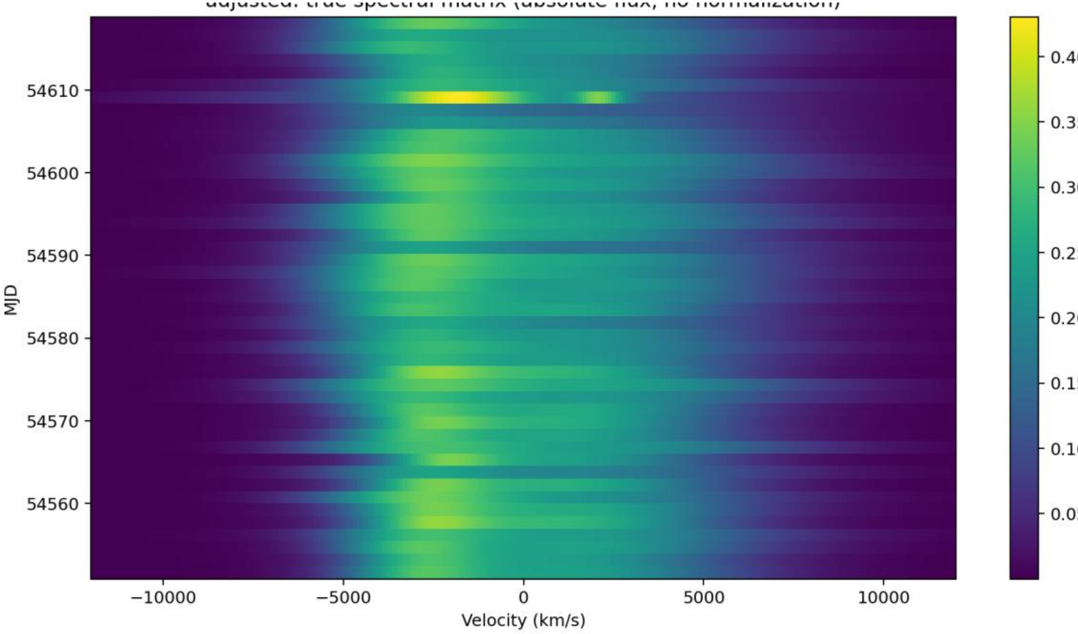




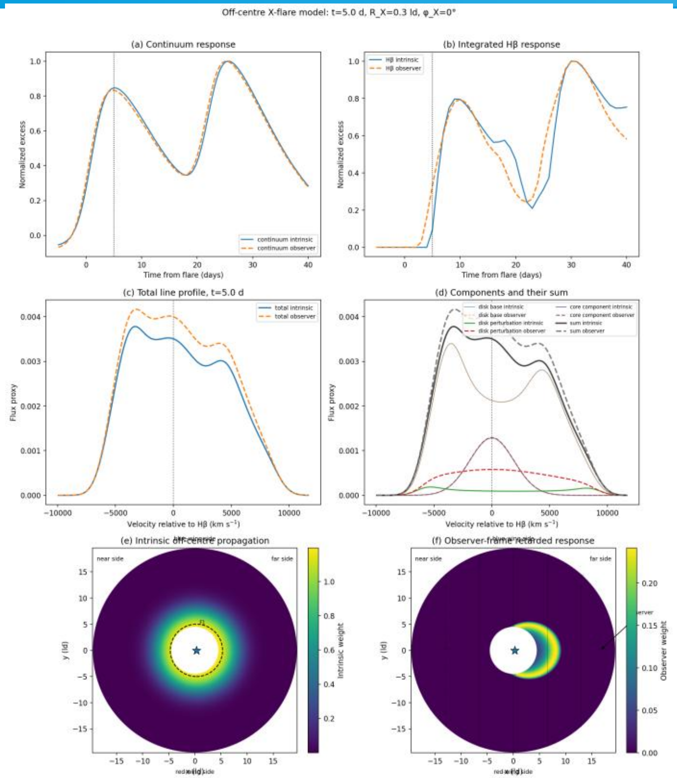
NGC 5548
V−band
Hβ
Flux (arbitrary units)
Epoch (HJD − 2454000)
Time Delay (days)
Flux
Velocity (10^3 km s^−1)
Response
Time Delay (days)
Response
Time Delay (days)

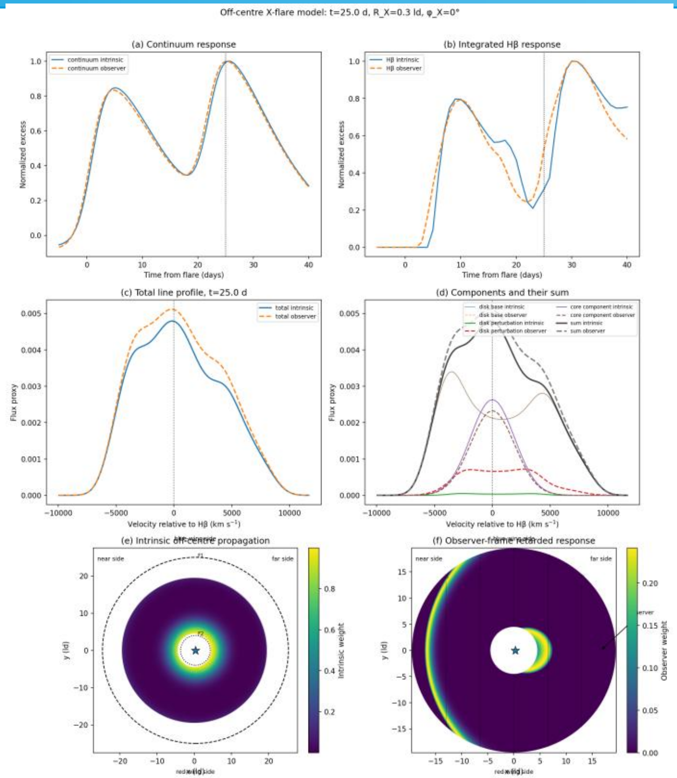


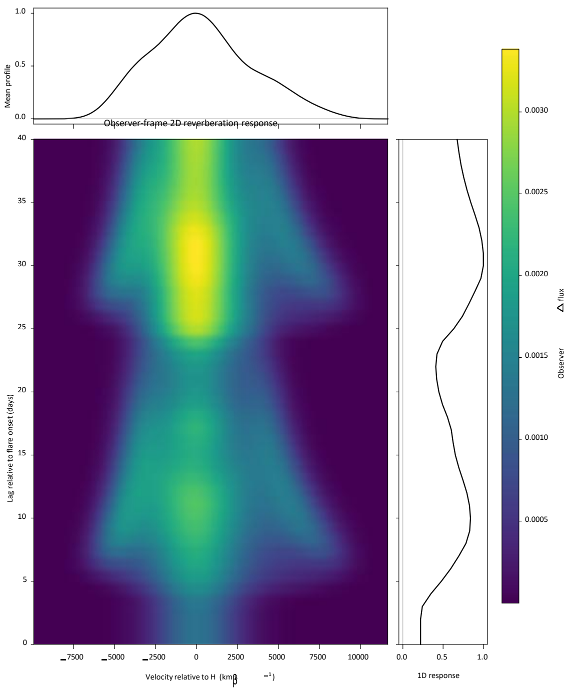
Continuum–Hβ ICCF
all data: peak=4.25 d, cent=4.69 d
main episode: peak=3.75 d, cent=8.86 d
main peak 0-25d=3.75 d
main cent 0-25d=3.78 d
ICCF r
Lag τ (days), positive = Hβ lags continuum



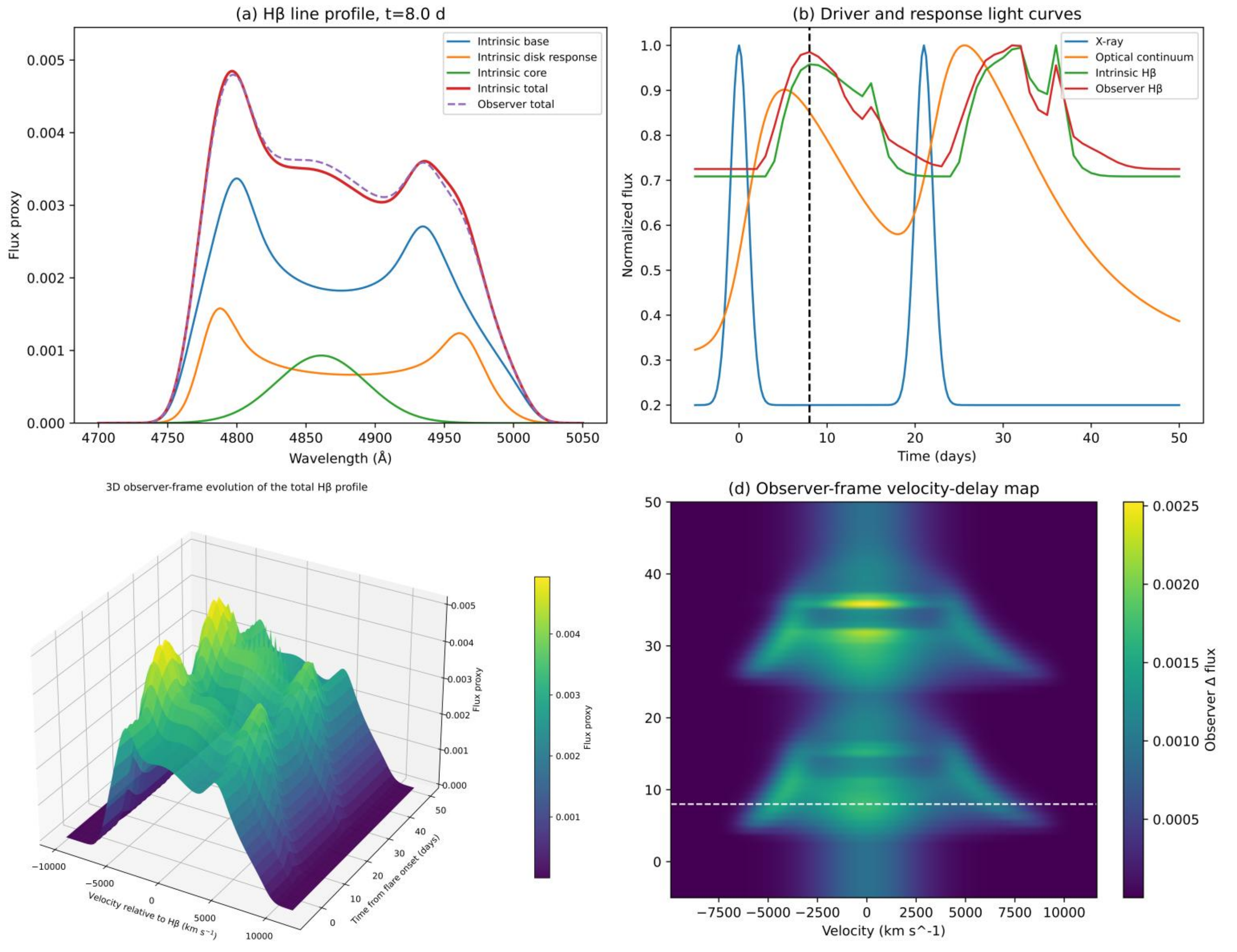
MJD
Velocity (km/s)


Off-centre X-flare model: t=5.0 d, R_X=0.3 ld, φ_X=0°
(a) Continuum response
(b) Integrated Hβ response
(c) Total line profile, t=5.0 d
(d) Components and their sum
(e) Intrinsic off-centre propagation
(f) Observer-frame retarded response
Time from flare (days)
Normalized excess
Velocity relative to Hβ (km s⁻¹)
Flux proxy
continuum intrinsic
continuum observer
Hβ intrinsic
Hβ observer
total intrinsic
total observer
disk base intrinsic
disk base observer
disk perturbation intrinsic
disk perturbation observer
core component intrinsic
core component observer
sum intrinsic
sum observer
near side
far side
Intrinsic weight
Observer weight
y (ld)


Off-centre X-flare model: t=25.0 d, R_X=0.3 ld, φ_X=0°
(a) Continuum response
(b) Integrated Hβ response
(c) Total line profile, t=25.0 d
(d) Components and their sum
(e) Intrinsic off-centre propagation
(f) Observer-frame retarded response
Time from flare (days)
Normalized excess
Velocity relative to Hβ (km s⁻¹)
Flux proxy
continuum intrinsic
continuum observer
Hβ intrinsic
Hβ observer
total intrinsic
total observer
near side
far side
Intrinsic weight
Observer weight
y (ld)


Mean profile
Observer-frame 2D reverberation response
Lag relative to flare onset (days)
Velocity relative to H β (km s⁻¹)
1D response
Observer
Δ flux

β re-


(a) Hβ line profile, t=8.0 d
Intrinsic base
Intrinsic disk response
Intrinsic core
Intrinsic total
Observer total
Flux proxy
Wavelength (Å)
(b) Driver and response light curves
X-ray
Optical continuum
Intrinsic Hβ
Observer Hβ
Normalized flux
Time (days)
3D observer-frame evolution of the total Hβ profile
Velocity relative to Hβ (km s⁻¹)
Time from flare onset (days)
Flux proxy
(d) Observer-frame velocity-delay map
Observer Δ flux
Velocity (km s^-1)

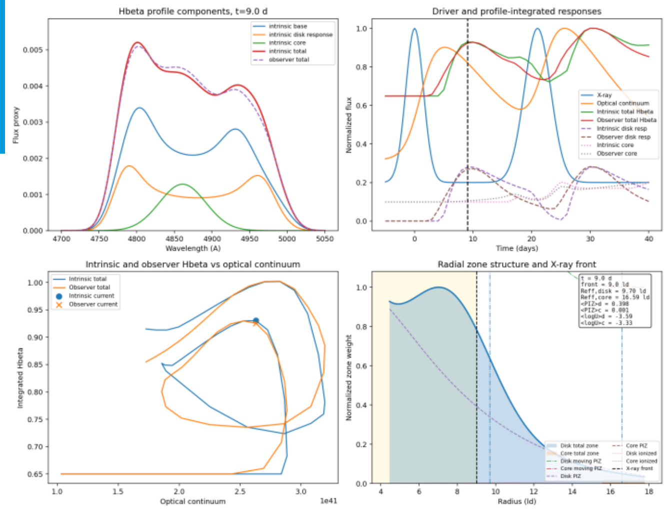
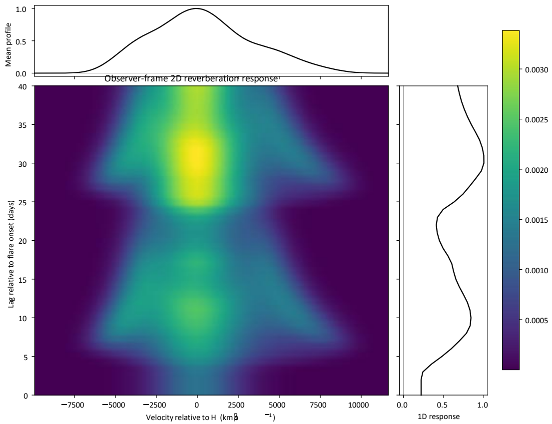
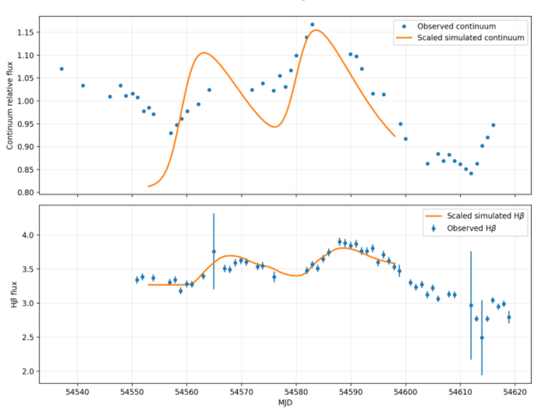
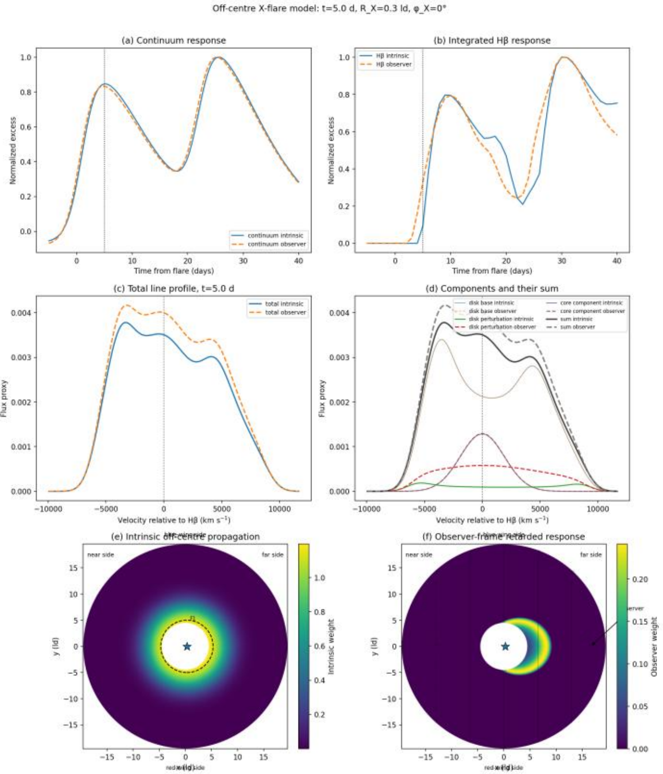
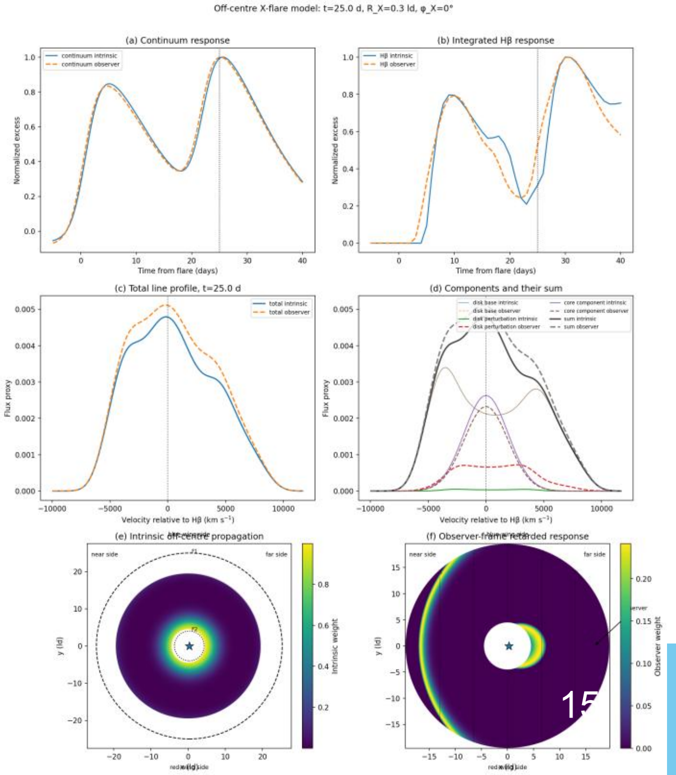


Fig. Representative diagnostic frame from the NGC 5548 sequence. The panels show the line-profile decomposition, the driver and component light curves, the integrated H β response relative to the optical continuum, and the radial ionization/PIZ diagnostics.

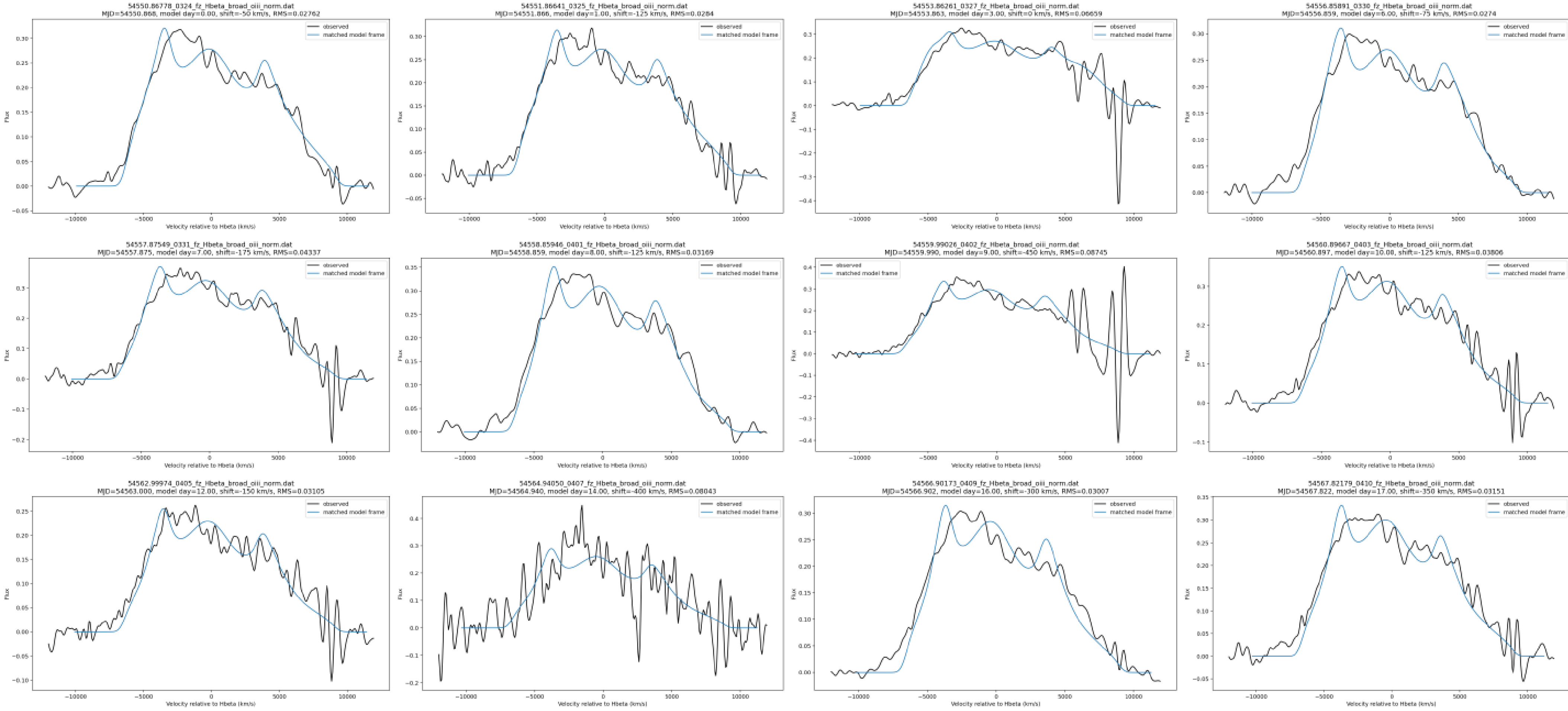


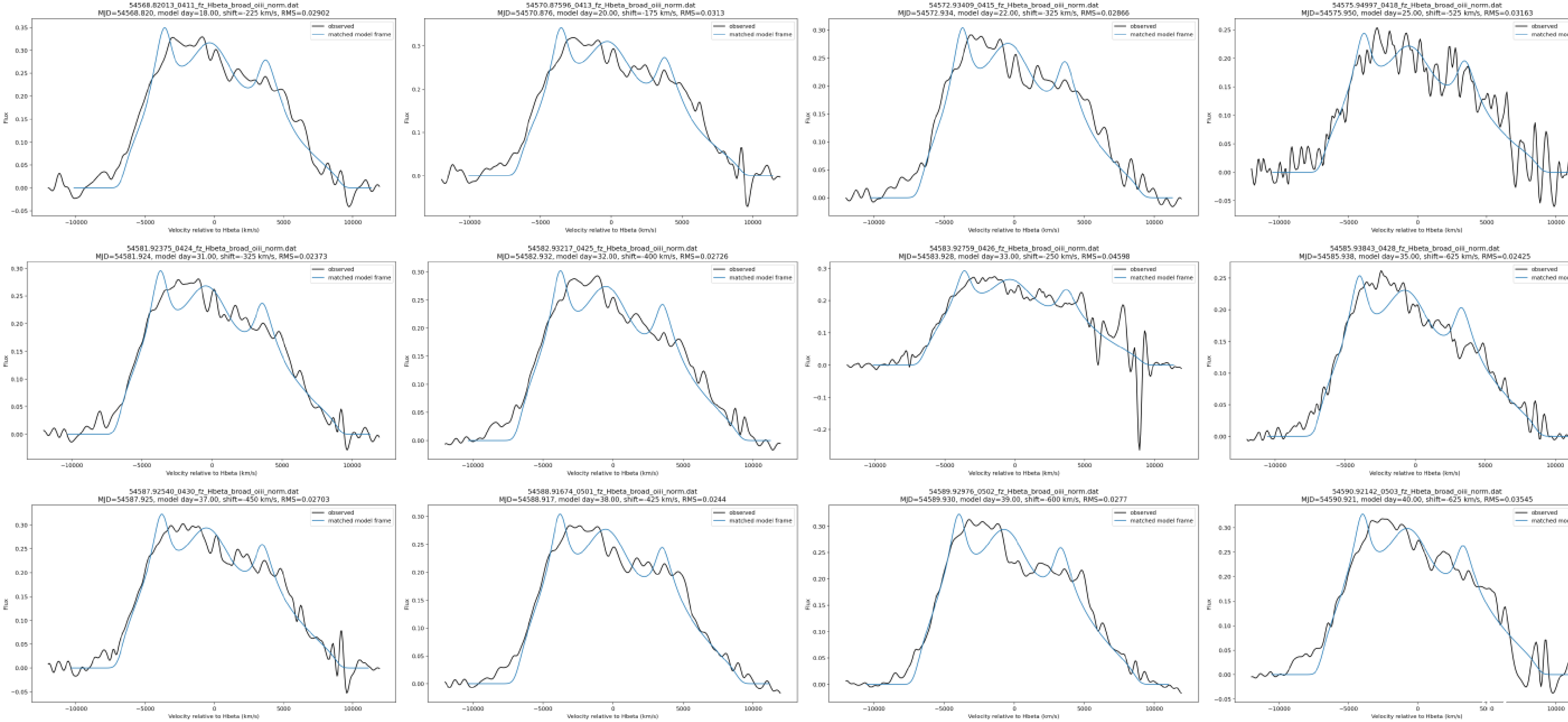






Matched simulated flare with real obs.




54568.82013_0411_fz_Hbeta_broad_oiii_norm.dat
MJD=54568.820, model day=18.00, shift=-225 km/s, RMS=0.02902
54570.87596_0413_fz_Hbeta_broad_oiii_norm.dat
MJD=54570.876, model day=20.00, shift=-175 km/s, RMS=0.0313
54572.93409_0415_fz_Hbeta_broad_oiii_norm.dat
MJD=54572.934, model day=22.00, shift=-325 km/s, RMS=0.02866
54575.94997_0418_fz_Hbeta_broad_oiii_norm.dat
MJD=54575.950, model day=25.00, shift=-525 km/s, RMS=0.03163
54581.92375_0424_fz_Hbeta_broad_oiii_norm.dat
MJD=54581.924, model day=31.00, shift=-325 km/s, RMS=0.02373
54582.93217_0425_fz_Hbeta_broad_oiii_norm.dat
MJD=54582.932, model day=32.00, shift=-400 km/s, RMS=0.02726
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54585.93843_0428_fz_Hbeta_broad_oiii_norm.dat
MJD=54585.938, model day=35.00, shift=-625 km/s, RMS=0.02425
54587.92540_0430_fz_Hbeta_broad_oiii_norm.dat
MJD=54587.925, model day=37.00, shift=-450 km/s, RMS=0.02703
54588.91674_0501_fz_Hbeta_broad_oiii_norm.dat
MJD=54588.917, model day=38.00, shift=-425 km/s, RMS=0.0244
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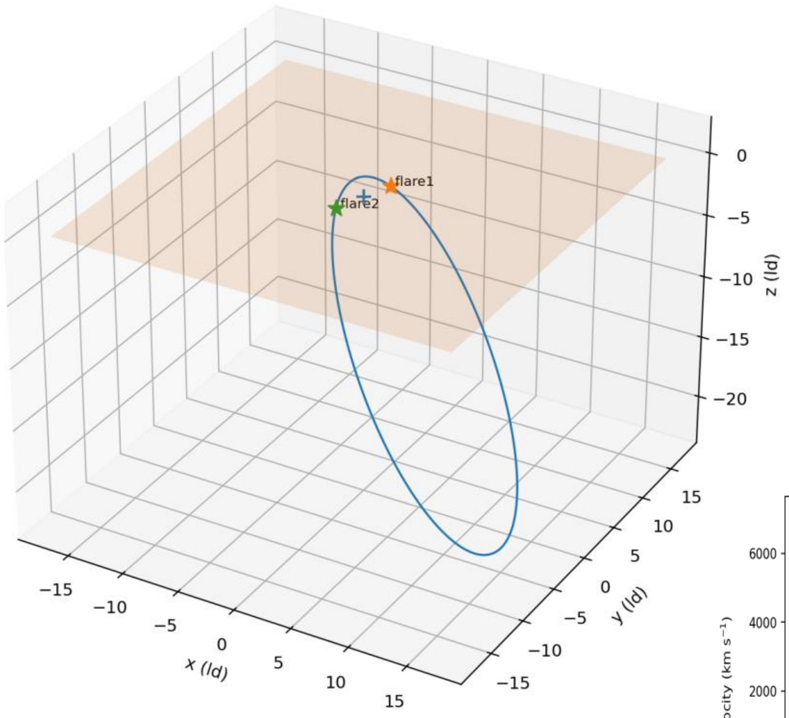
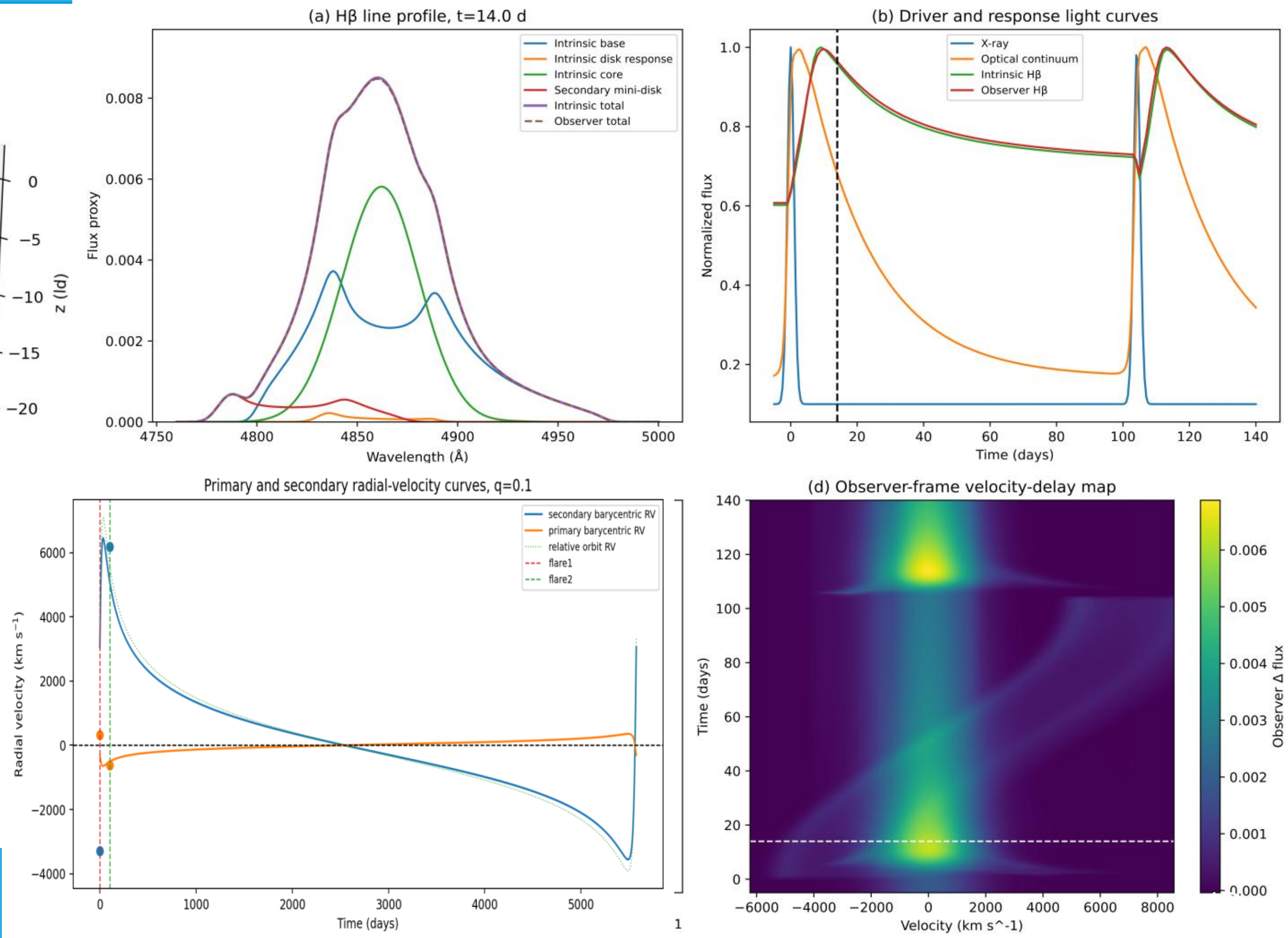
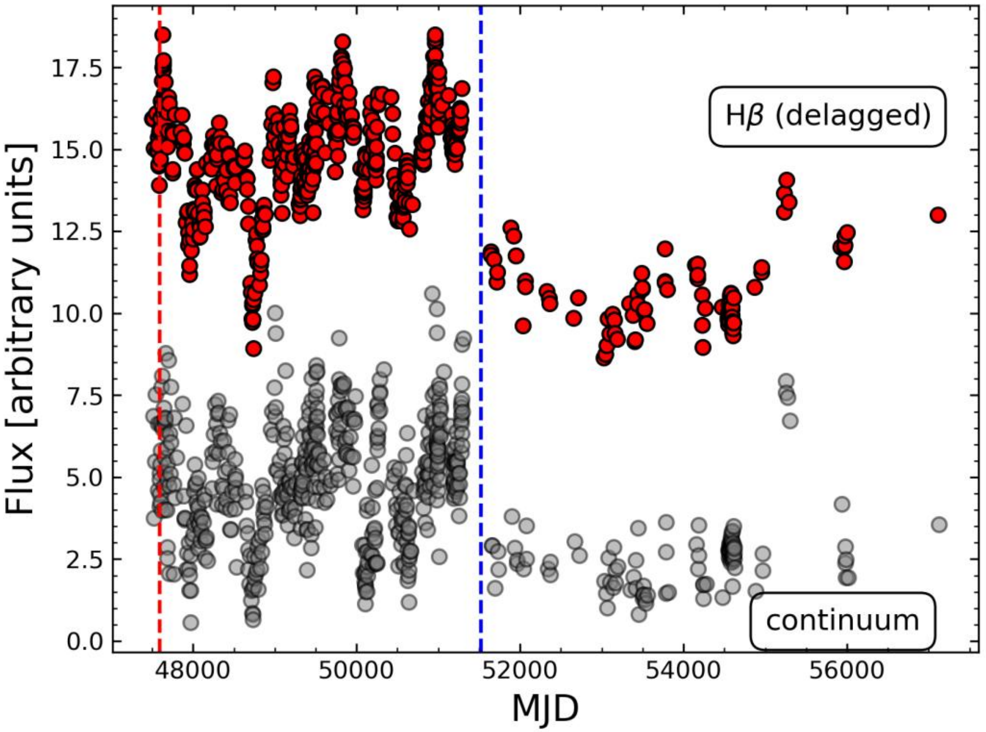
MJD=54589.930, model day=39.00, shift=-600 km/s, RMS=0.0277
54590.92142_0503_fz_Hbeta_broad_oiii_norm.dat
MJD=54590.921, model day=40.00, shift=-625 km/s, RMS=0.03545
observed
matched model frame
Flux
Velocity relative to Hbeta (km/s)

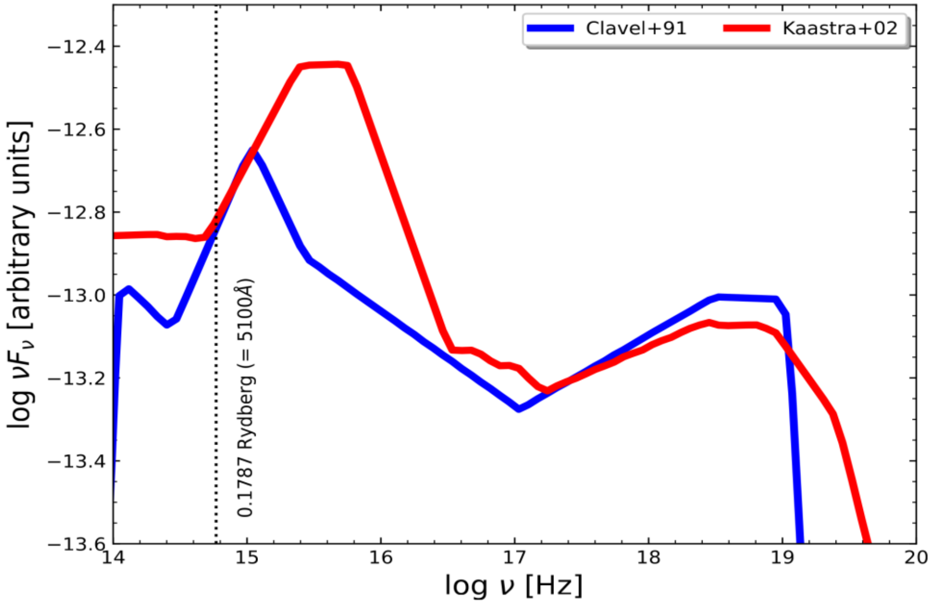
A SMBBH reverberation model

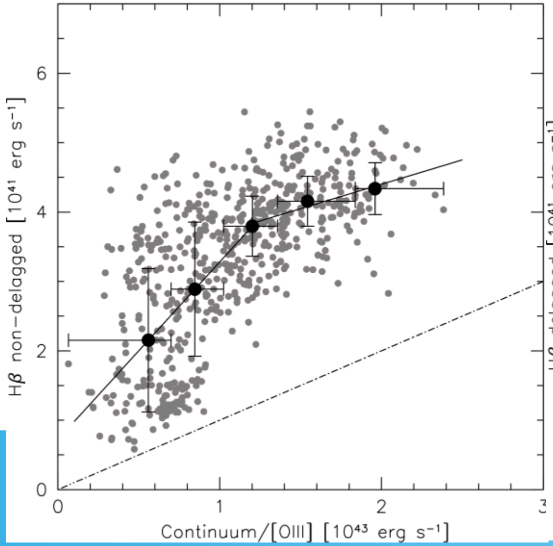


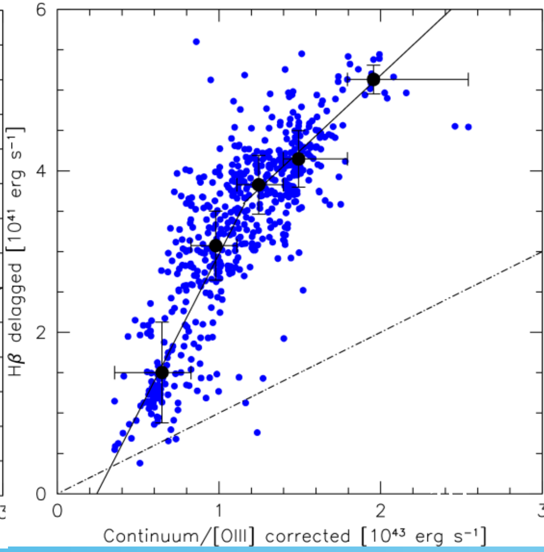


NGC 5548



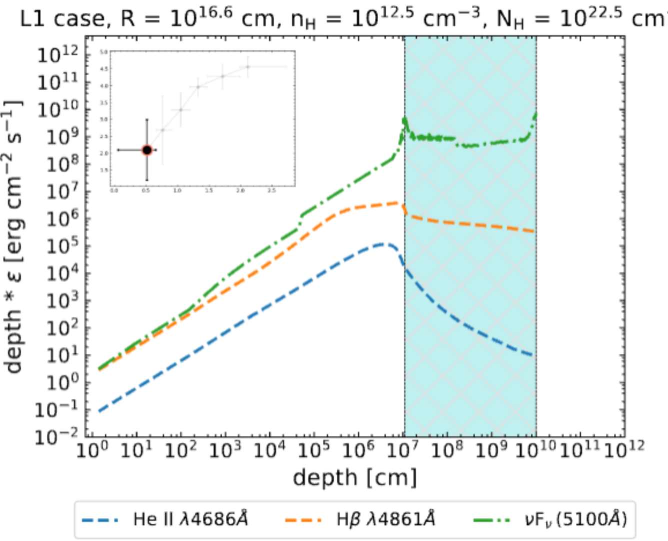


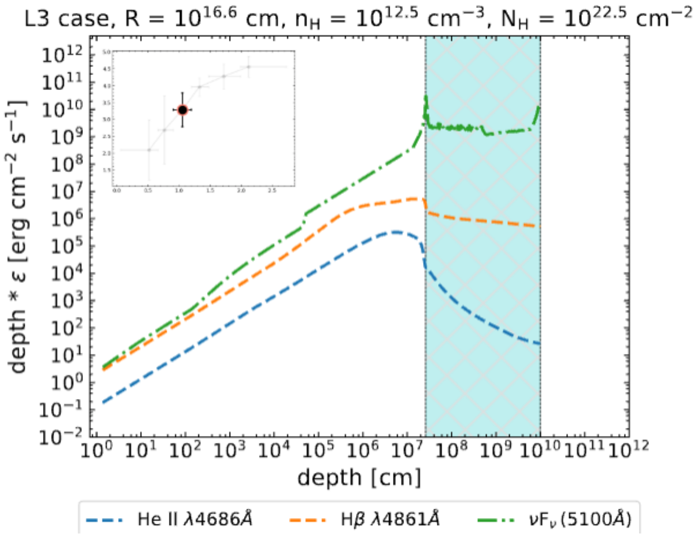


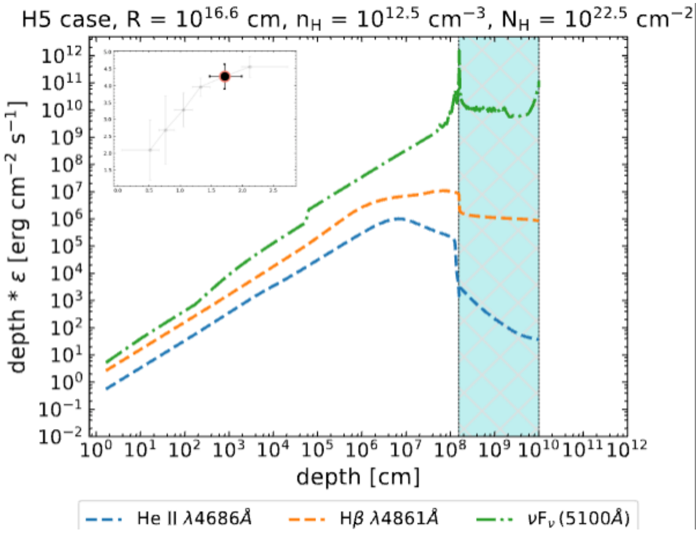


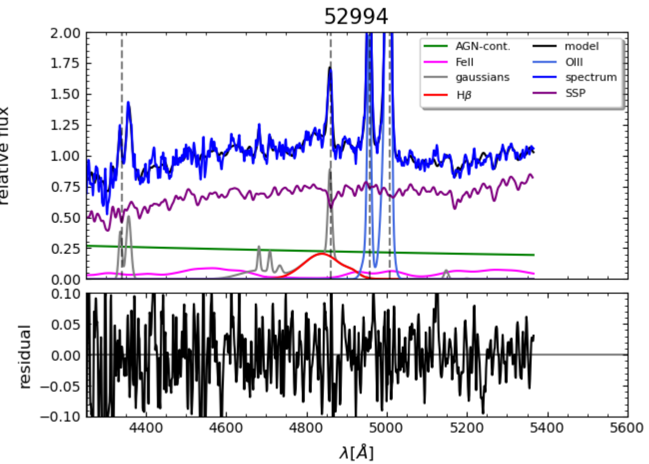
Hβ time-lag ($\tau_{H\beta}$) versus AGN luminosity (L5100) are compiled in Lu et al. (2022) from 23 reverberation mapping (RM) campaigns.

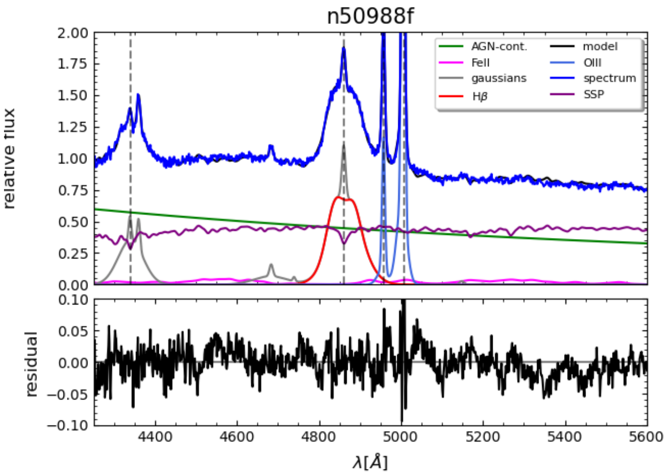
PIZ shrinking

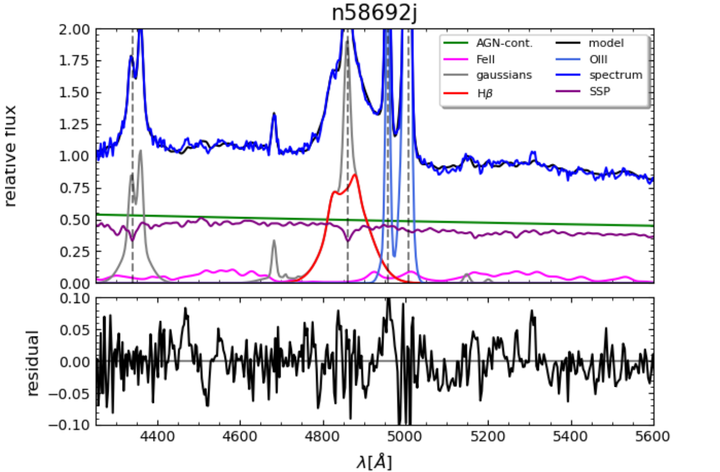




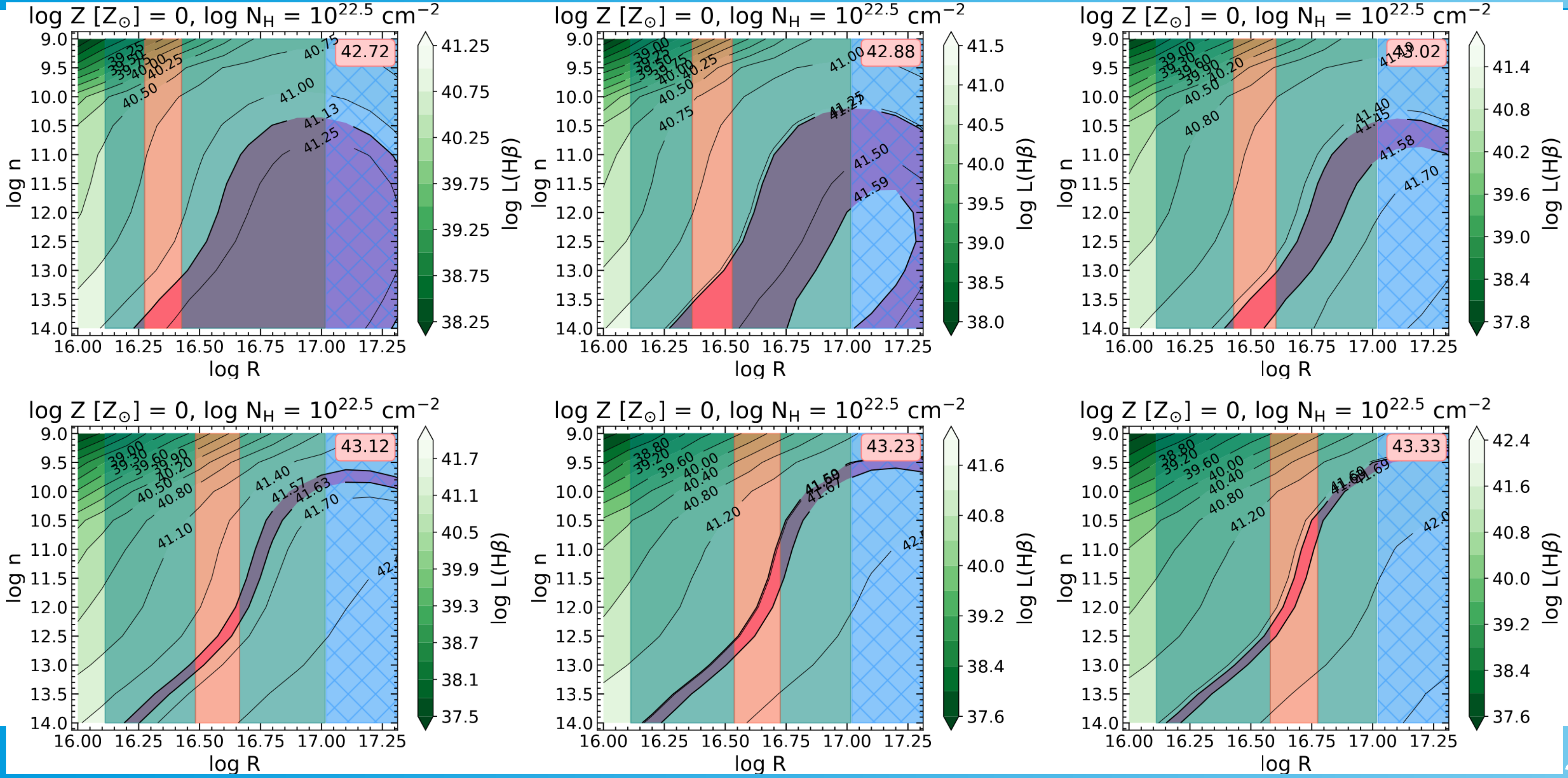


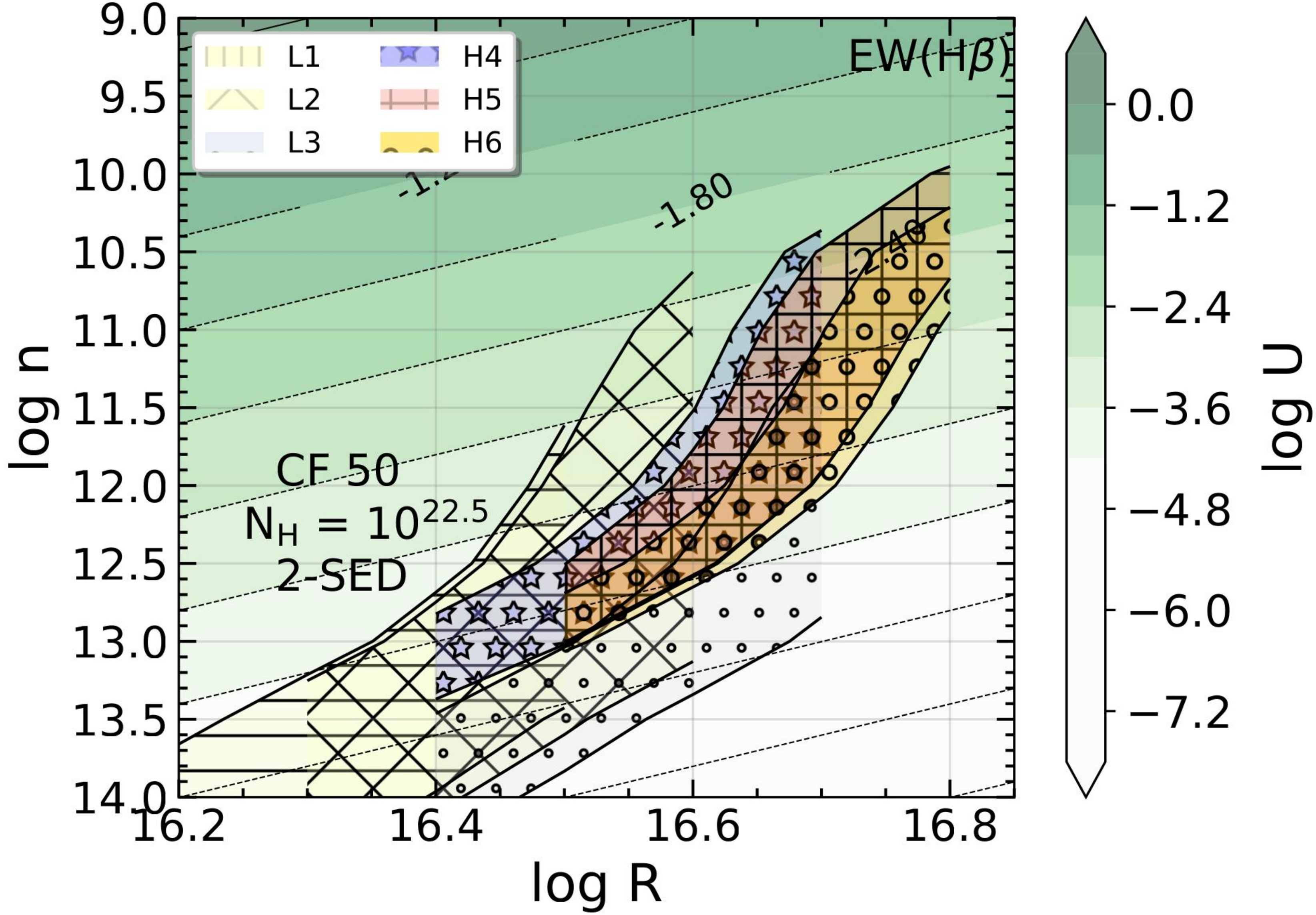






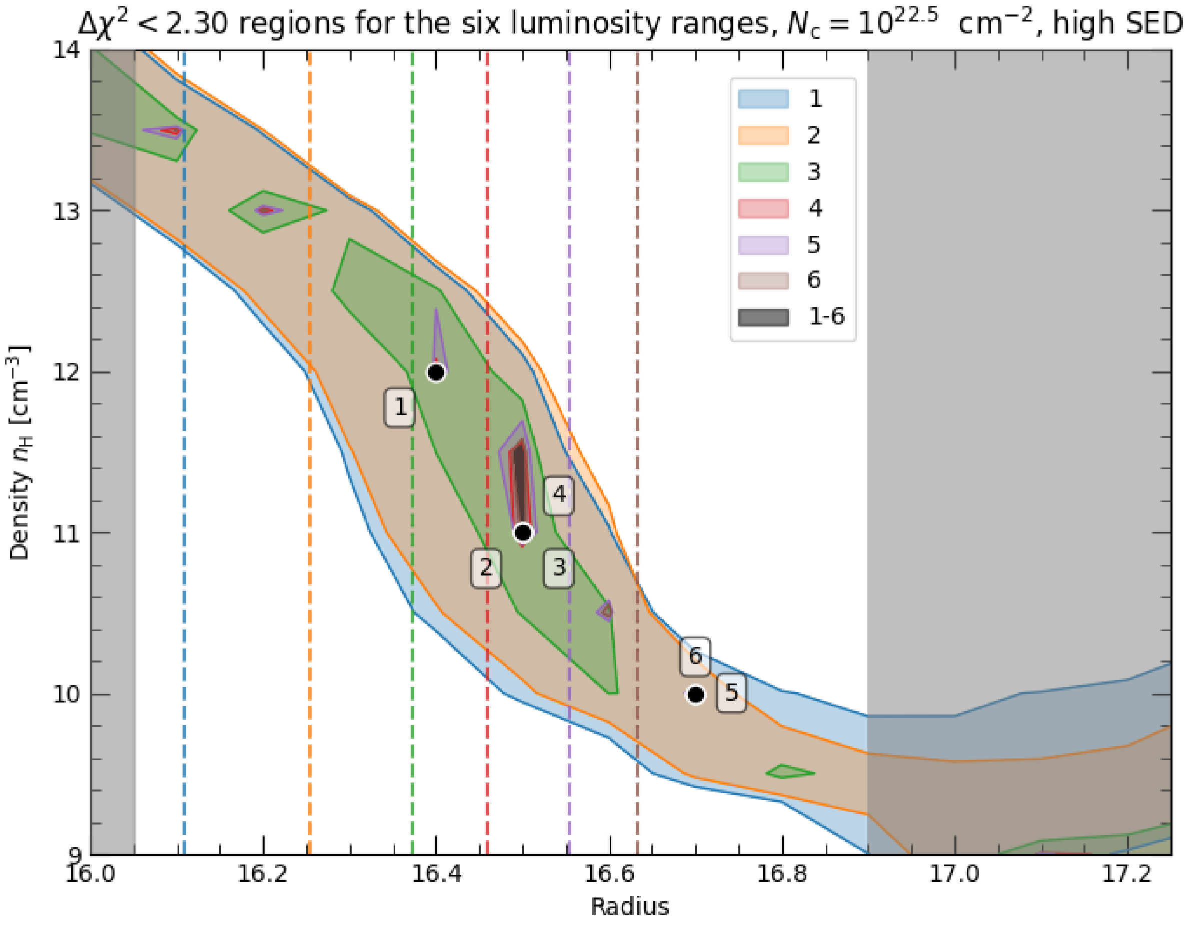
Application to Cloudy grids

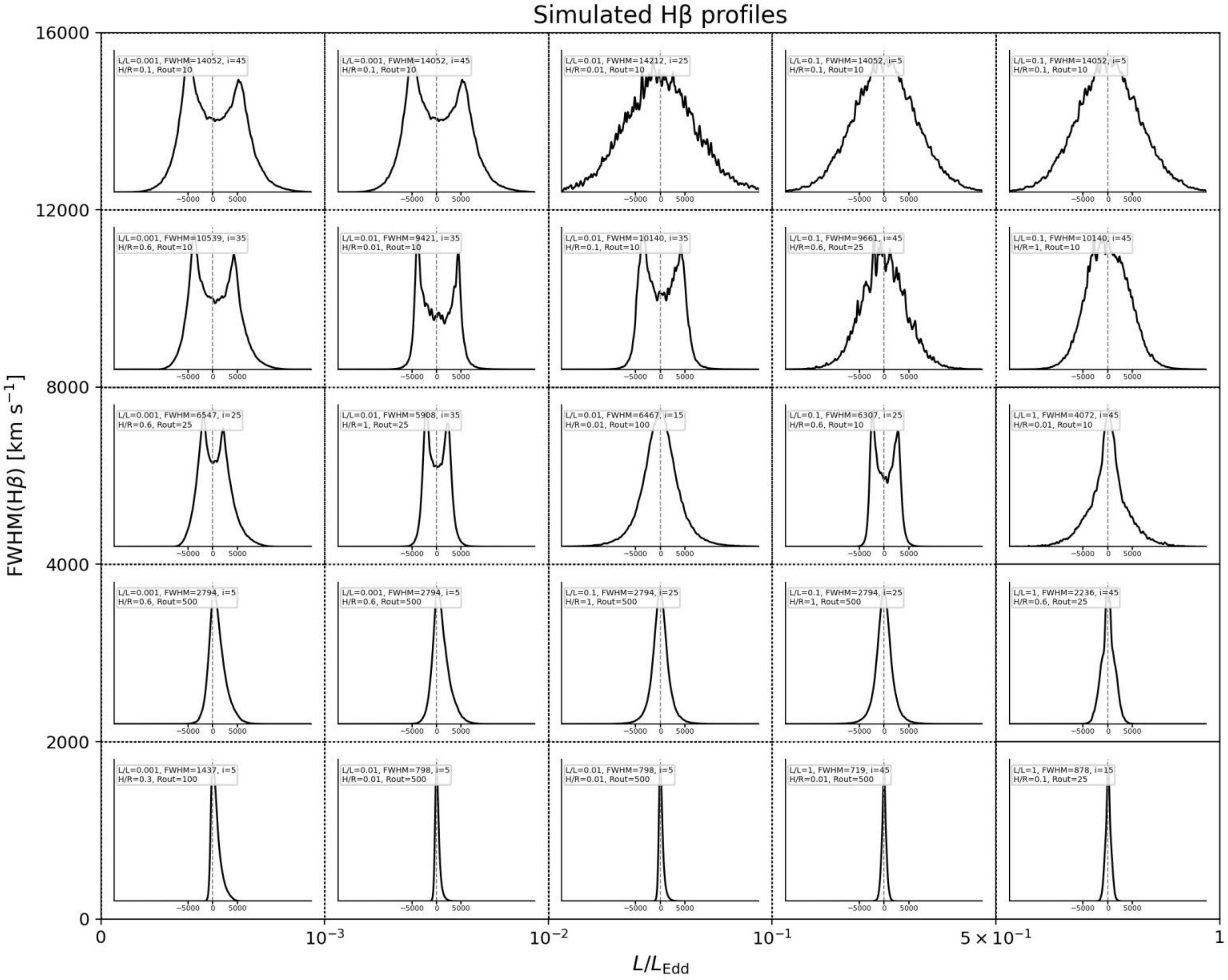


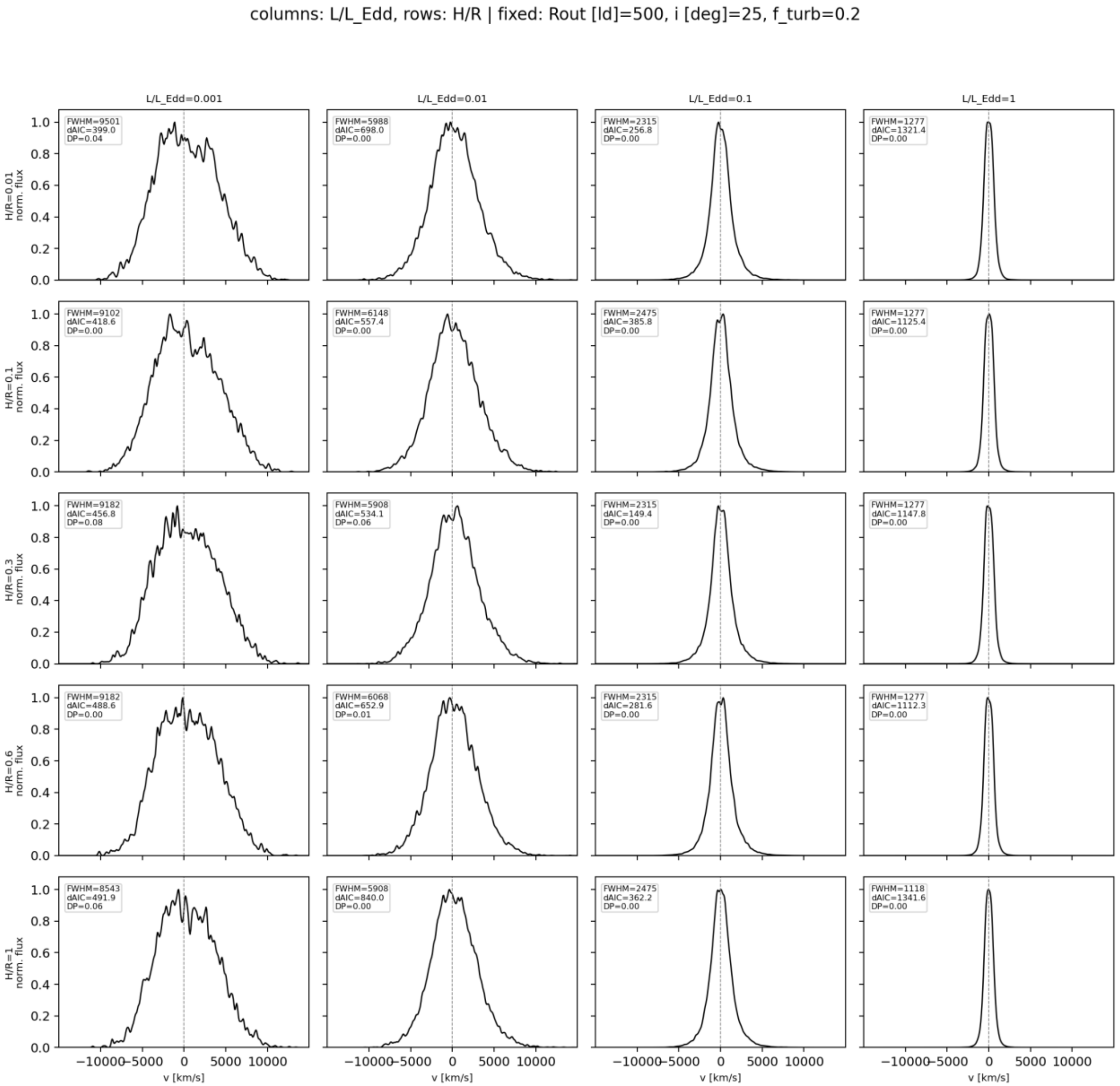


L1
L2
L3
H4
H5
H6
EW(Hβ)
-1.80
-2.40
CF 50
$N_H = 10^{22.5}$
2-SED
log n
log R
log U
9.0
9.5
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
16.2
16.4
16.6
16.8
0.0
−1.2
−2.4
−3.6
−4.8
−6.0
−7.2

Result from Chi^2 maps




Simulated Hβ profiles
FWHM(Hβ) [km s⁻¹]
L/L_Edd
16000
12000
8000
4000
2000
0
0
10⁻³
10⁻²
10⁻¹
5 × 10⁻¹
1
L/L=0.001, FWHM=14052, i=45 H/R=0.1, Rout=10
L/L=0.001, FWHM=14052, i=45 H/R=0.1, Rout=10
L/L=0.01, FWHM=14212, i=25 H/R=0.01, Rout=10
L/L=0.1, FWHM=14052, i=5 H/R=0.1, Rout=10
L/L=0.1, FWHM=14052, i=5 H/R=0.1, Rout=10
L/L=0.001, FWHM=10539, i=35 H/R=0.6, Rout=10
L/L=0.01, FWHM=9421, i=35 H/R=0.01, Rout=10
L/L=0.01, FWHM=10140, i=35 H/R=0.1, Rout=10
L/L=0.1, FWHM=9661, i=45 H/R=0.6, Rout=25
L/L=0.1, FWHM=10140, i=45 H/R=1, Rout=10
L/L=0.001, FWHM=6547, i=25 H/R=0.6, Rout=25
L/L=0.01, FWHM=5908, i=35 H/R=1, Rout=25
L/L=0.01, FWHM=6467, i=15 H/R=0.01, Rout=100
L/L=0.1, FWHM=6307, i=25 H/R=0.6, Rout=10
L/L=1, FWHM=4072, i=45 H/R=0.01, Rout=10
L/L=0.001, FWHM=2794, i=5 H/R=0.6, Rout=500
L/L=0.001, FWHM=2794, i=5 H/R=0.6, Rout=500
L/L=0.1, FWHM=2794, i=25 H/R=1, Rout=500
L/L=0.1, FWHM=2794, i=25 H/R=1, Rout=500
L/L=1, FWHM=2236, i=45 H/R=0.6, Rout=25
L/L=0.001, FWHM=1437, i=5 H/R=0.3, Rout=100
L/L=0.01, FWHM=798, i=5 H/R=0.01, Rout=500
L/L=0.01, FWHM=798, i=5 H/R=0.01, Rout=500
L/L=1, FWHM=719, i=45 H/R=0.01, Rout=500
L/L=1, FWHM=878, i=15 H/R=0.1, Rout=25
−5000 0 5000


columns: L/L_Edd, rows: H/R | fixed: Rout [ld]=500, i [deg]=25, f_turb=0.2
L/L_Edd=0.001
L/L_Edd=0.01
L/L_Edd=0.1
L/L_Edd=1
H/R=0.01 norm. flux
H/R=0.1 norm. flux
H/R=0.3 norm. flux
H/R=0.6 norm. flux
H/R=1 norm. flux
FWHM=9501 dAIC=399.0 DP=0.04
FWHM=5988 dAIC=698.0 DP=0.00
FWHM=2315 dAIC=256.8 DP=0.00
FWHM=1277 dAIC=1321.4 DP=0.00
FWHM=9102 dAIC=418.6 DP=0.00
FWHM=6148 dAIC=557.4 DP=0.00
FWHM=2475 dAIC=385.8 DP=0.00
FWHM=1277 dAIC=1125.4 DP=0.00
FWHM=9182 dAIC=456.8 DP=0.08
FWHM=5908 dAIC=534.1 DP=0.06
FWHM=2315 dAIC=149.4 DP=0.00
FWHM=1277 dAIC=1147.8 DP=0.00
FWHM=9182 dAIC=488.6 DP=0.00
FWHM=6068 dAIC=652.9 DP=0.01
FWHM=2315 dAIC=281.6 DP=0.00
FWHM=1277 dAIC=1112.3 DP=0.00
FWHM=8543 dAIC=491.9 DP=0.06
FWHM=5908 dAIC=840.0 DP=0.00
FWHM=2475 dAIC=362.2 DP=0.00
FWHM=1118 dAIC=1341.6 DP=0.00
v [km/s]


Thank you for attention