CALCULATION OF ECHO IMAGES FROM FIRST PRINCIPLES:

SELF-CONSISTENTLY COMBINING PHOTOIONIZATION MODELING & ASTROPHYSICAL FLUID DYNAMICAL SIMULATIONS

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ECHO IMAGES FROM FIRST PRINCIPLES

1. **Input the SED of your favorite AGN into a photoionization code and run a dense grid of models**
2. **Develop a model of the BLR, i.e. run hydrodynamical simulations with source terms taken from the photoionization calculations**

   Dyda et al. (2016, submitted)

3. **Post-process the simulations**
   1. Velocity field ➔ Isofrequency surface
   2. Isofrequency + isodelay surface ➔ 'sketch' of the echo image
   3. Temp. + density fields ➔ photoionization structure + responsivity
   4. Ion fraction + responsivity ➔ IRF (the echo image)
   5. IRF * ΔL_X ➔ ΔL_{line}

Waters et al. (2016)

Weerasooriya et al. (2016)

STEP 3: POST-PROCESSING

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In [1]: run hydroSimRM.py

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    ._|

        ***  Inputs  ***
Benchmark: numerical CM96 solution
Observer line of sight: 75.0 degrees
Selected theta indices: 1-1 (90.0-90.0 deg)
Echo image size: (Npix_tau x Npix_vel) = (128 x 64)
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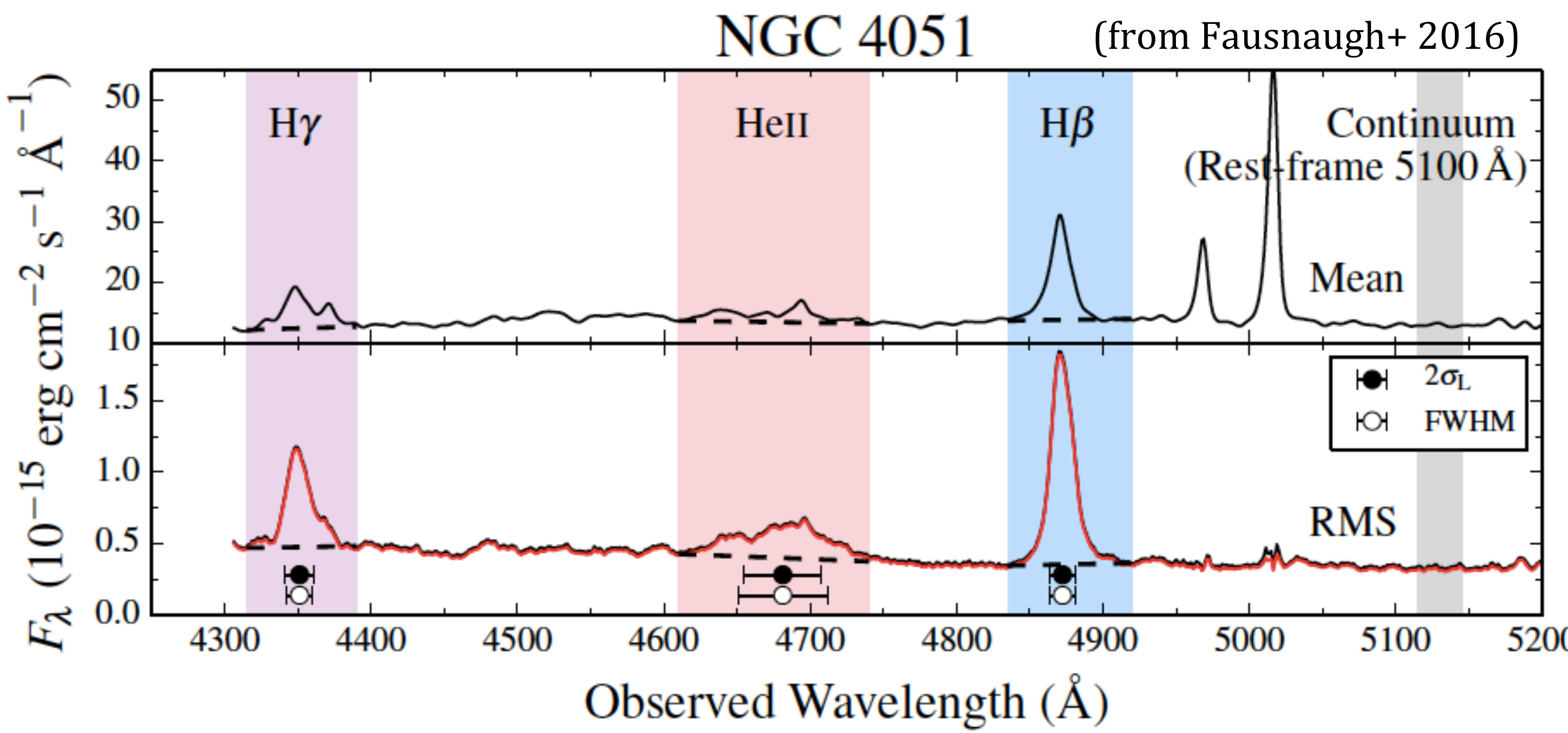
$$\Delta\mathscr{L}_\nu(t) = \int_0^\infty \Psi(\nu,\tau)\Delta L_X(t-\tau)d\tau$$

$$\mathscr{L}_\nu(t) = \langle\mathscr{L}_\nu\rangle + \underline{\Delta\mathscr{L}_\nu(t)}$$

$$\mathscr{L}_\nu(t) = \int dV\, j_\nu(\mathbf{r},t)\beta_\nu(\mathbf{r},t)$$

(from Fausnaugh+ 2016)



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THE CM96 SOLUTION

Sobolev optical depth

$$\tau_\nu = \int \alpha_\nu dr = \alpha_\nu \frac{c}{|dv_l/dl|}$$

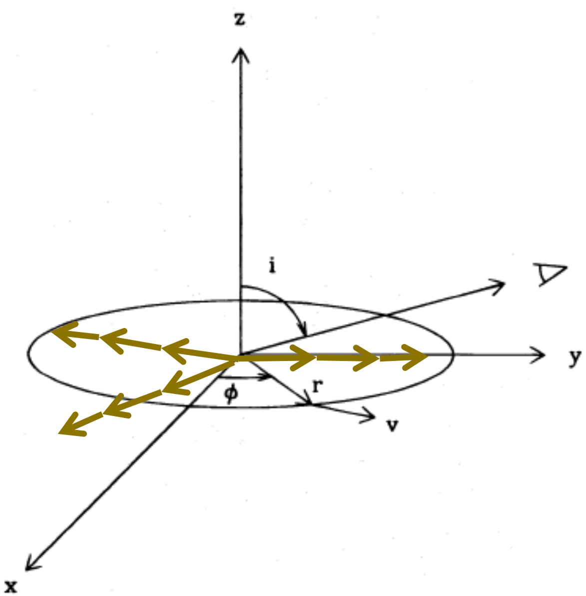
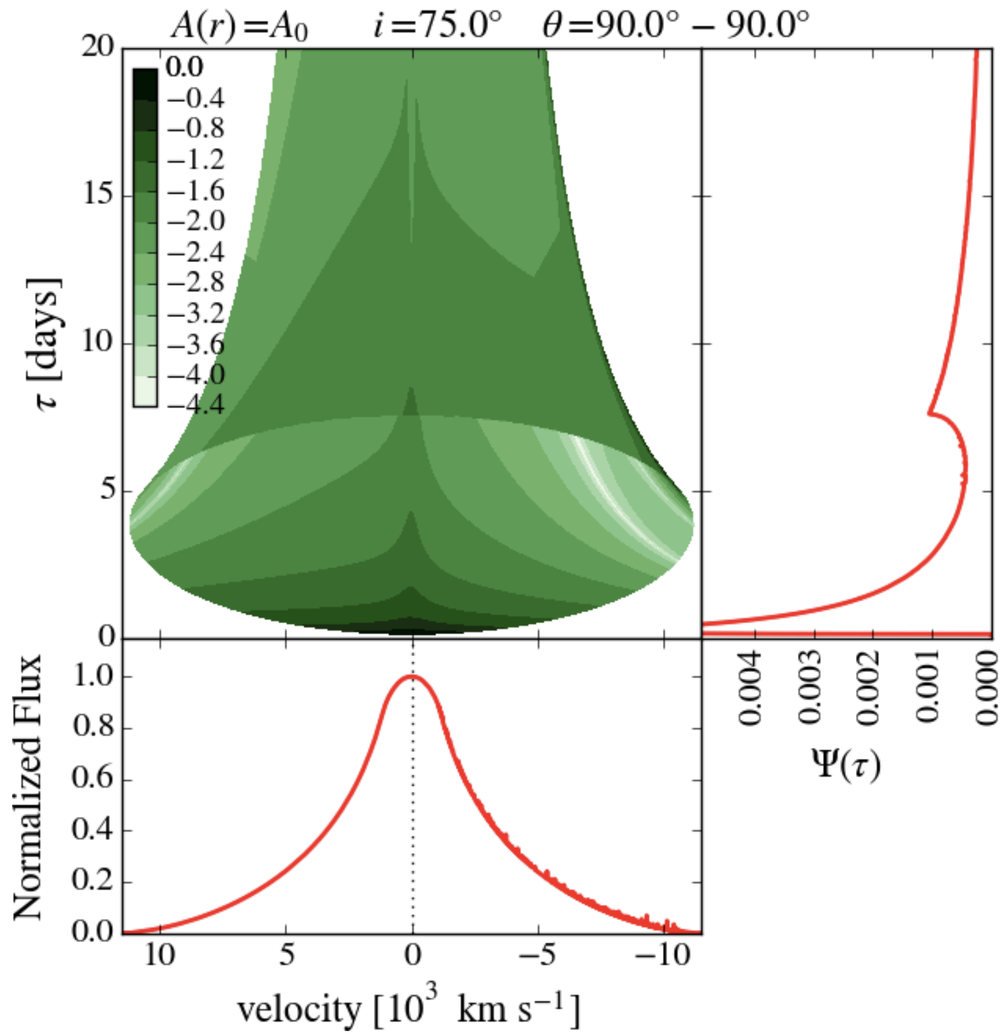


FIG. 1.—Geometry of the disk broad-line region. The angle, *i*, is the disk inclination relative to the observer. The quantities (r, ϕ) label locations on the disk.



Figures 1 & 4 of Chiang & Murray (1996)

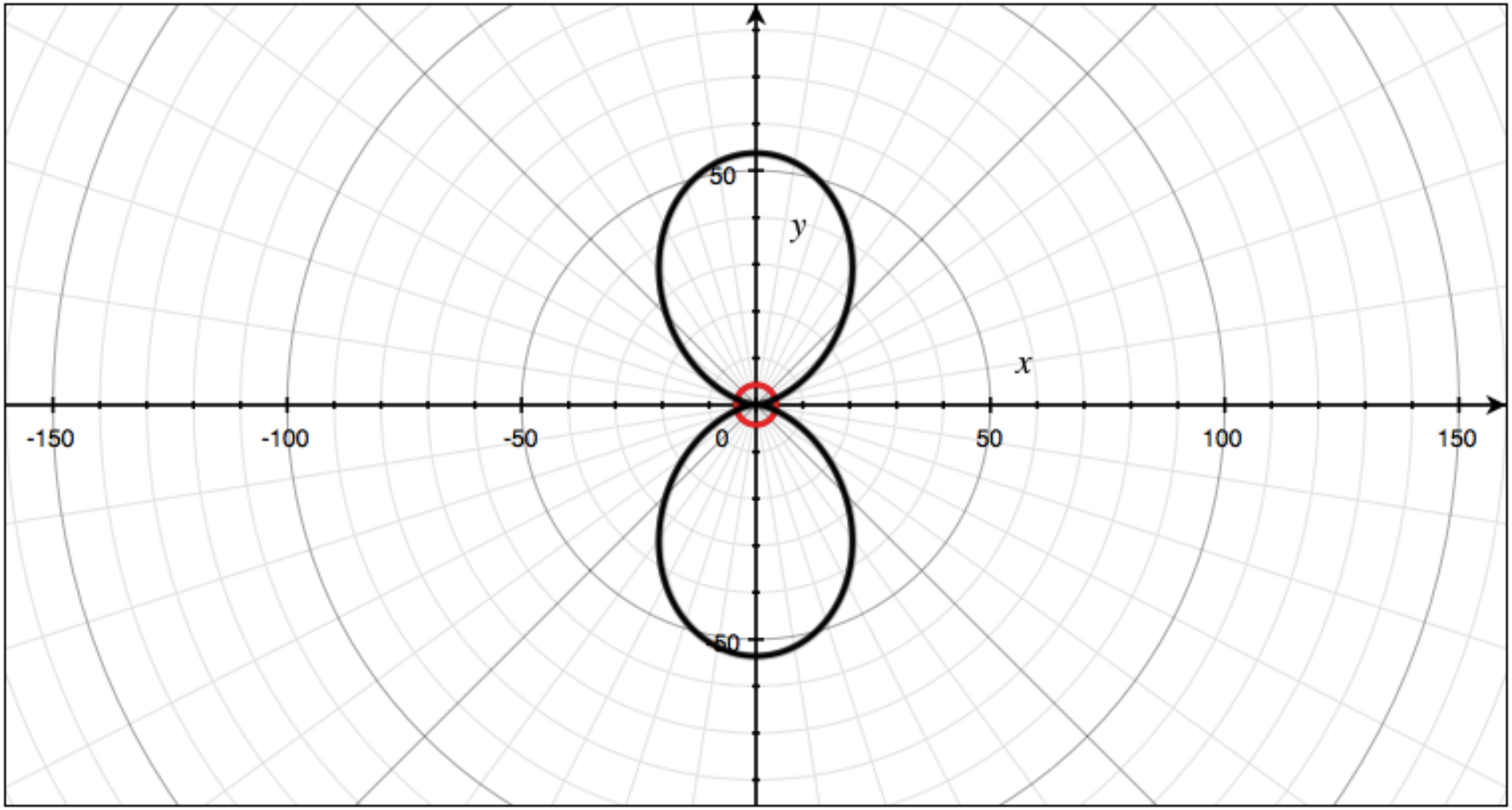
Isodelay surface

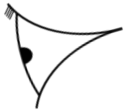
$$r\ [\mathrm{ld}] = \frac{\mathrm{t\ [days]}}{1 - \cos\phi \sin \mathrm{i}}$$

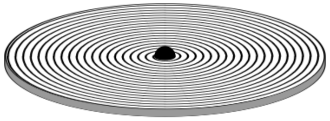
Isofrequency surface

$$r\ [\mathrm{ld}] = 517.0 \left(\frac{\mathrm{v_l}}{10^3\ \mathrm{km\ s^{-1}}}\right)^{-2} \left(\frac{\mathrm{M}}{10^8\ \mathrm{M_\odot}}\right) \sin^2\phi \sin^2 \mathrm{i}$$

CM96 ISODELAY & ISOFREQUENCY SURFACES





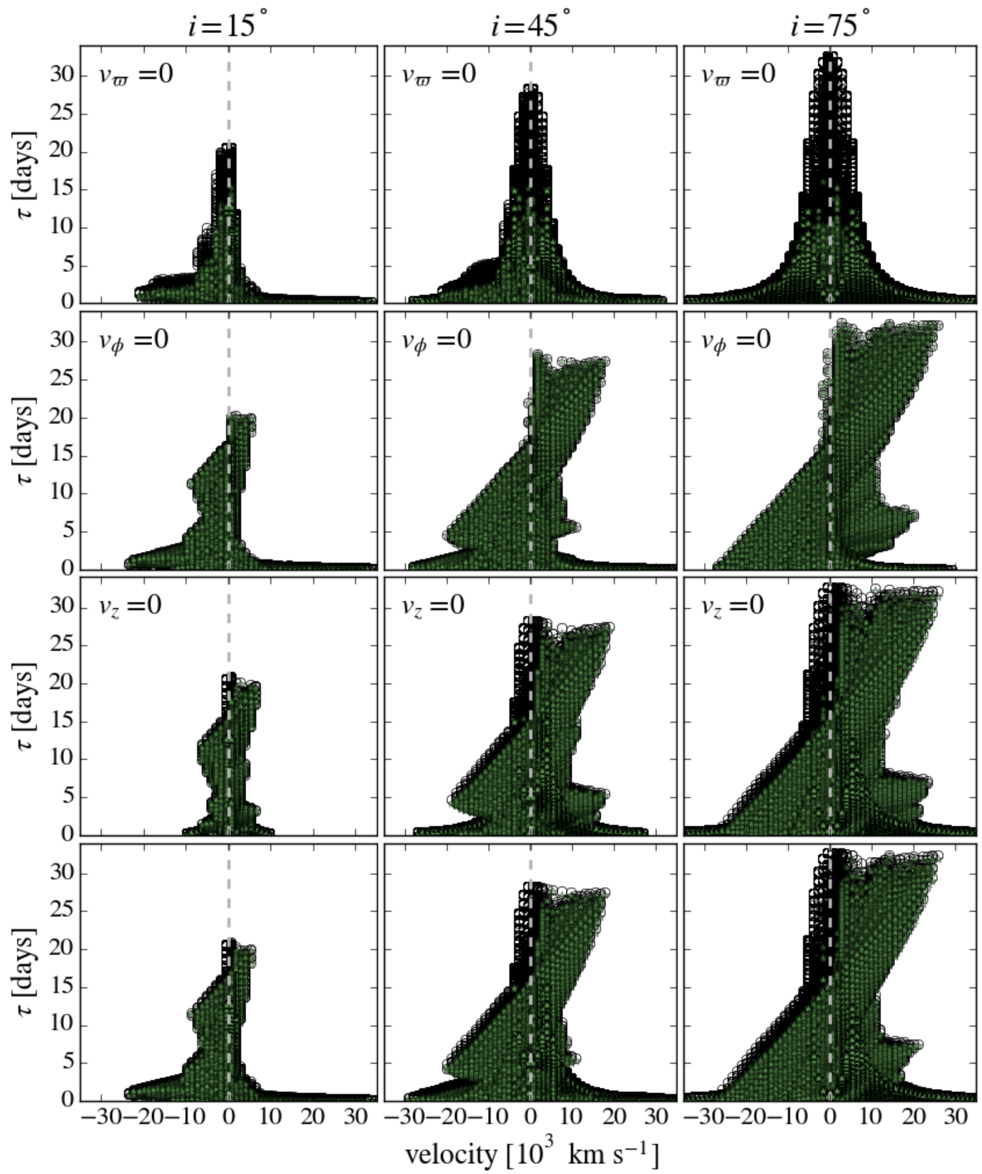


Intersection points obey:

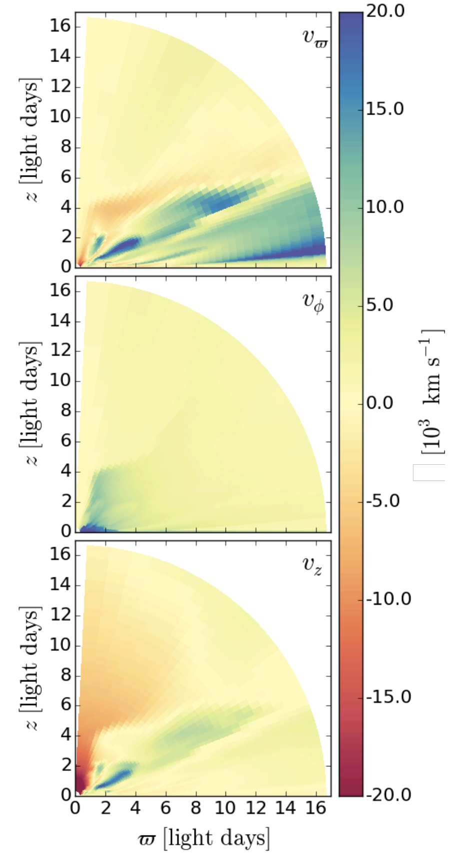
$$r^3 + \left(\frac{r_s \cos^2 i}{2y^2}\right) r^2 - \frac{r_s c\, t}{y^2} r + \frac{r_s (c\, t)^2}{2y^2} = 0$$

SKETCHING THE IMAGE

Echo image 'sketches' from Waters+ (2016)



Velocity field of Proga & Kallman (2004)



$$y \equiv \frac{\nu - \nu_0}{\nu_0}$$

$$y' \equiv y - \frac{v_z}{c} \cos i$$

$$t = \frac{r}{c}\left[1 - \cos\theta \cos i - \frac{\sin\theta}{v_\varpi'^2 + v_\phi'^2} \times \left(v_\varpi' y' \pm v_\phi' \sqrt{(v_\varpi'^2 + v_\phi'^2)\sin^2 i - y'^2} \right)\right]$$

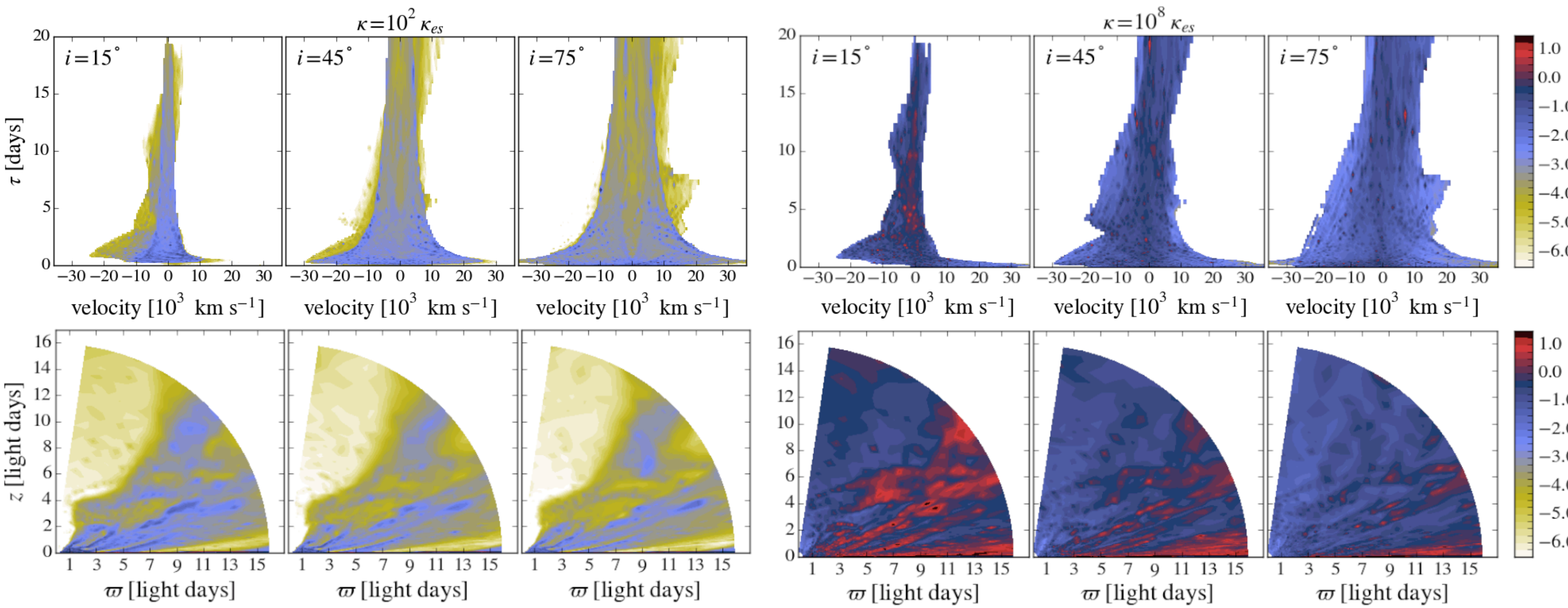
COLORING THE IMAGE

$$\Psi(y,t) = \int_{-1}^{1} d\mu \left[\frac{I}{|J|} \right]_{(\tilde{r},\mu,\tilde{\phi})}$$

$$I(\mathbf{r}) = \frac{1}{4\pi} \frac{\partial j_\nu}{\partial F_X} \frac{1 - e^{-\tau_\nu}}{\tau_\nu}$$

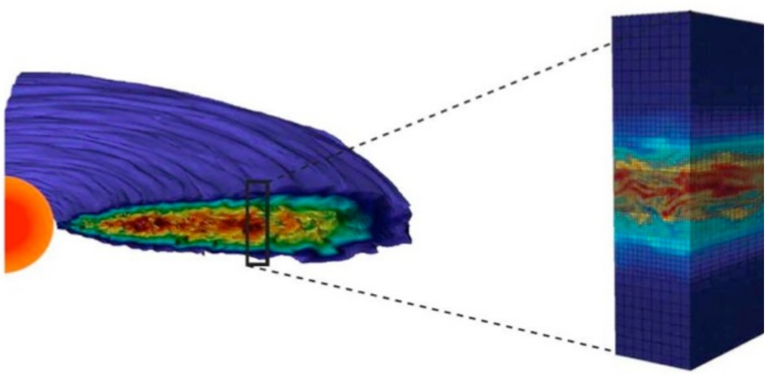
vs.

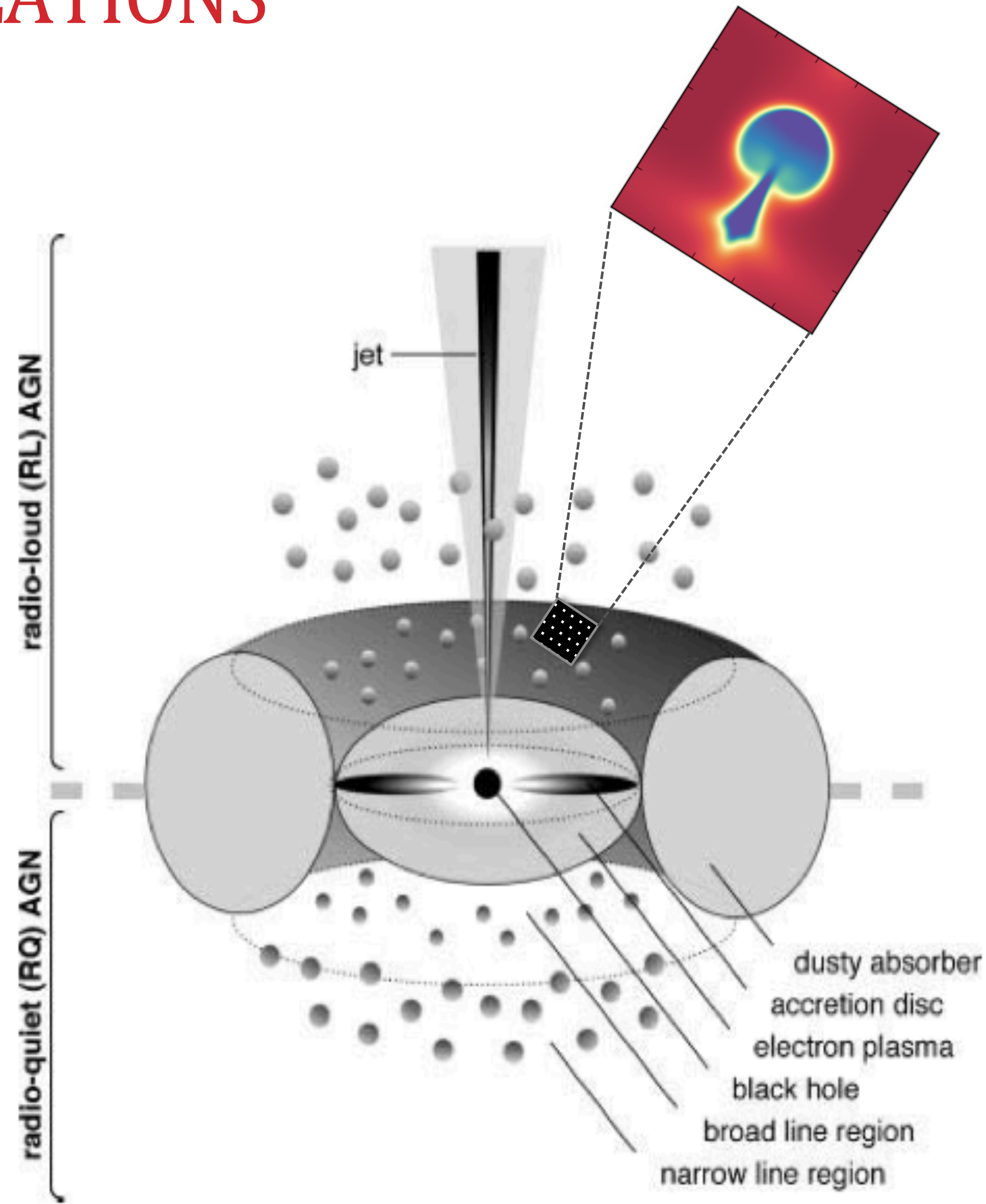
$$I(\mathbf{r}) = \frac{1}{4\pi c} A(r) \left| \frac{dv_l}{dl} \right| (1 - e^{-\tau_\nu})$$



UNDERSTANDING THE RESPONSIVITY: LOCAL CLOUD SIMULATIONS

Analogous to
global vs. shearing-box
accretion disk simulations





UNDERSTANDING THE RESPONSIVITY: LOCAL CLOUD SIMULATIONS

Most past work on responsivity is by Goad & Korista.

In Korista & Goad (2004), it was shown that the responsivity of optical recombination lines is highly sensitive to the incident flux.

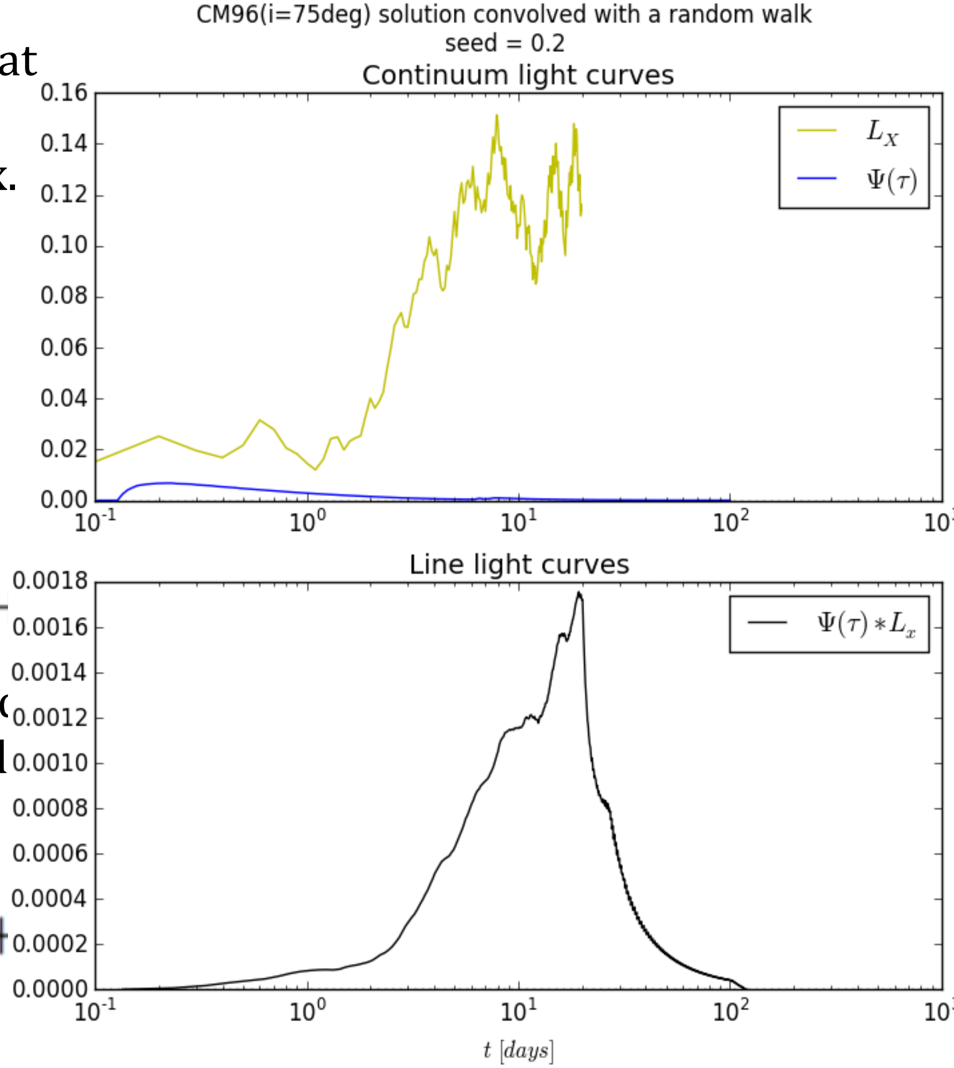
This is *bad* for RM.

$$\Delta\mathscr{L}_\nu(t) = \int_0^\infty \Psi(\nu,\tau)\Delta L_X(t-\tau)d\tau$$

$$j_\nu(\langle F_X\rangle + \Delta F_X) = \langle j_\nu\rangle + \frac{\partial j_\nu}{\partial F_X}\Delta F_X -$$

In Waters & Proga (2016), I pointed out a c
hydrodynamic effects, e.g. increasing the fl
Qualitatively, the issue is this:

$$j_\nu(\langle F_X\rangle + \Delta F_X, \langle T\rangle + \Delta T) = \langle j_\nu\rangle +$$



UNDERSTANDING THE RESPONSIVITY: LOCAL CLOUD SIMULATIONS

Simulation from Waters & Proga (2016)
(www.physics.unlv.edu/astro/wp16sims.html)

Left panel: constant flux
Right panel: variable flux

EXAMPLE OF PHOTOIONIZATION + HYDRO CALCS: SYNTHETIC ABSORPTION LINES

$$\tau_\nu = \int \alpha_\nu dr = \alpha_\nu \frac{c}{|dv_l/dl|}$$

$$\alpha_{\nu_0} = \frac{\pi e^2}{m_e c} f_{12}\, n_1\, \phi(\nu_0)$$

$$= \frac{1}{\sqrt{\pi}} \left(\frac{\pi e^2}{m_e c} \frac{A\, n_{\rm xstar}}{\nu_0 (v_{th}/c)} f_{12}\, \eta_{ion} \right) n\, n_{\rm xstar}^{-1}$$

For RM recall,

$$\Psi(y,t) = \int_{-1}^{1} d\mu \left[\frac{I}{|J|} \right]_{(\tilde{r},\mu,\tilde{\phi})}$$

$$I(\mathbf{r}) = \frac{1}{4\pi} \frac{\partial j_\nu}{\partial F_X} \frac{1 - e^{-\tau_\nu}}{\tau_\nu}$$

so for post-processing all that is needed is the optical depth and the responsivity.

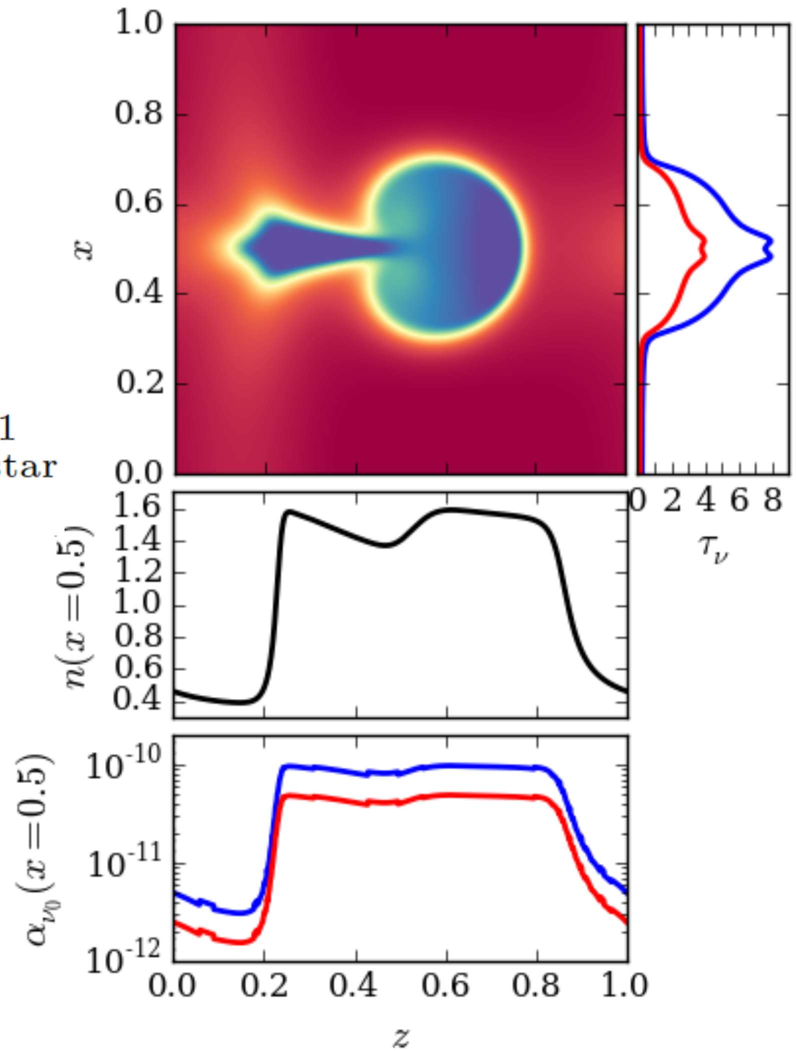


Fig. 1 of Waters et al., submitted
http://arxiv.org/abs/1611.00407

EXAMPLE OF PHOTOIONIZATION + HYDRO CALCS: SYNTHETIC ABSORPTION LINES

Fig. 2 of Waters et al., submitted
http://arxiv.org/abs/1611.00407