Line-Driven Accretion Disk Winds

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Outline

Disk Winds

- Why do they matter?

The Physics of Line-Driving

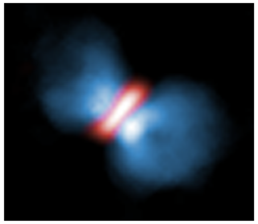
- Free vs Bound Electrons
- Force Multipliers

Line-Driven *Disk* Winds

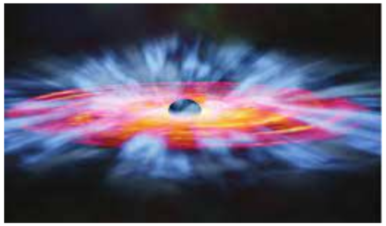
- Previous efforts
- New results

Accretion Disk Winds: Why Should We Care?

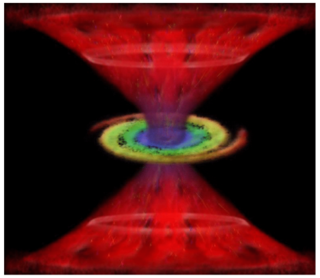
- **Universal**



YSO



Compact Binary



AGN

- **Significant sinks for**
  - **Mass**:

    $$0.1 \lesssim \frac{\dot{M}_w}{\dot{M}_{input}} \lesssim 10$$

  - **Energy**:

    $$0.1 \lesssim \frac{L_{k,w}}{L_{acc}} \lesssim 10$$

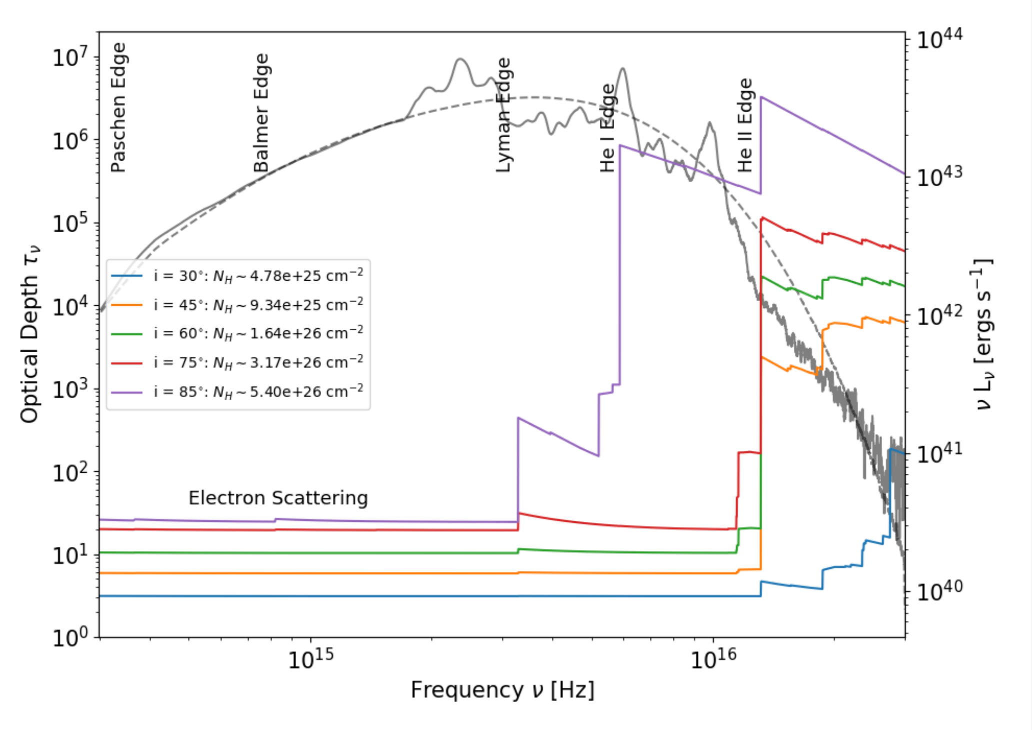
  - **Angular Momentum**:

    $$0.1 \lesssim \frac{\dot{J}_w}{\dot{J}_{disk}} \lesssim 1$$

    - Disk winds might be *required* to drive accretion!

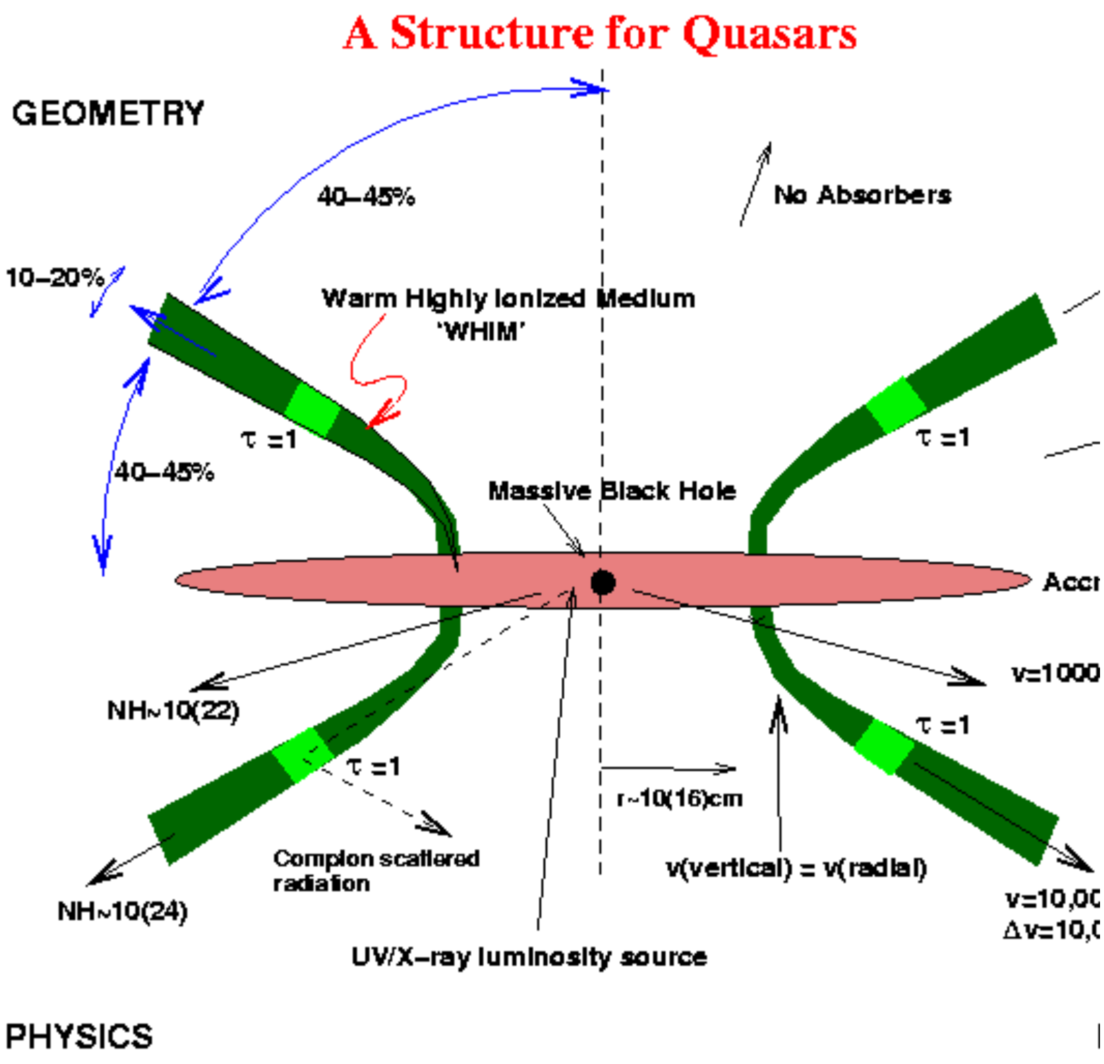
- **Veiling**

A Disk Wind Model for TDEs (Parkinson, Knigge et al 2020)

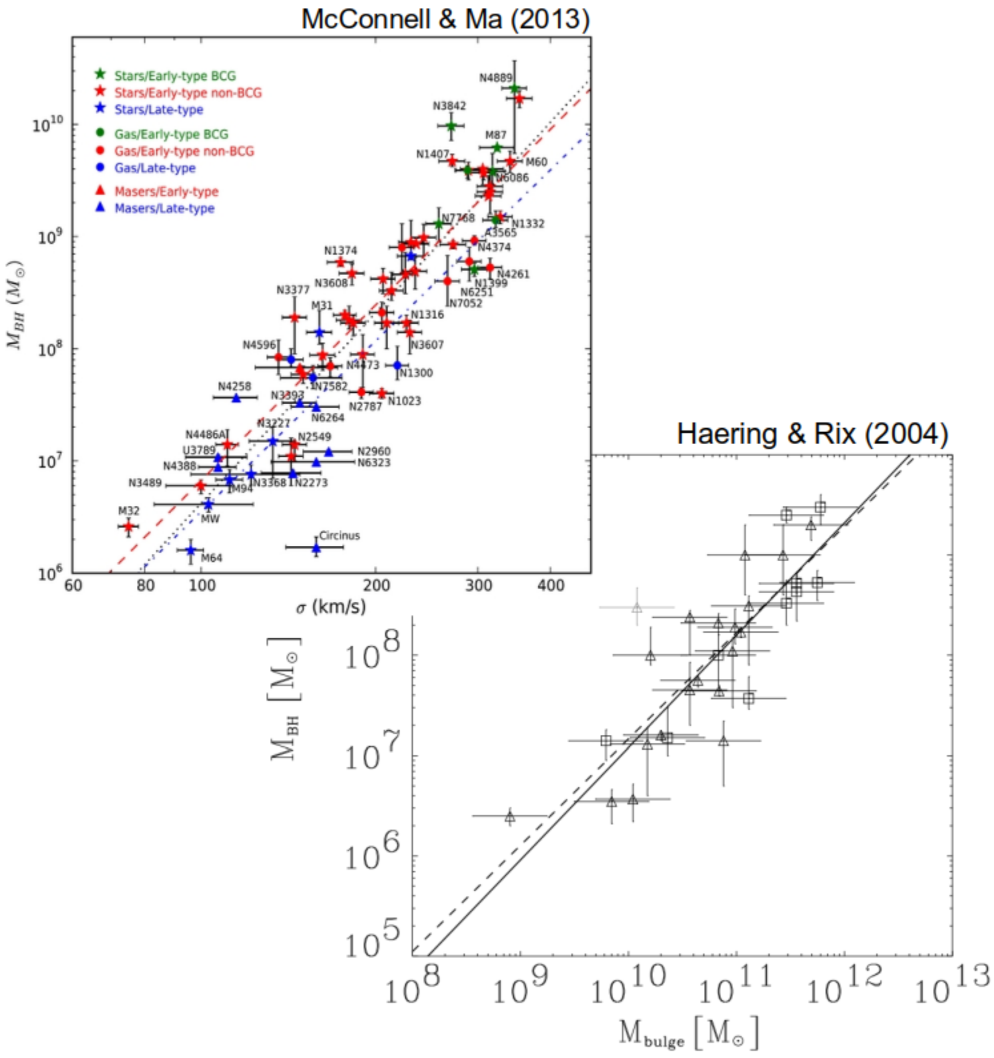


- **AGN Unification**

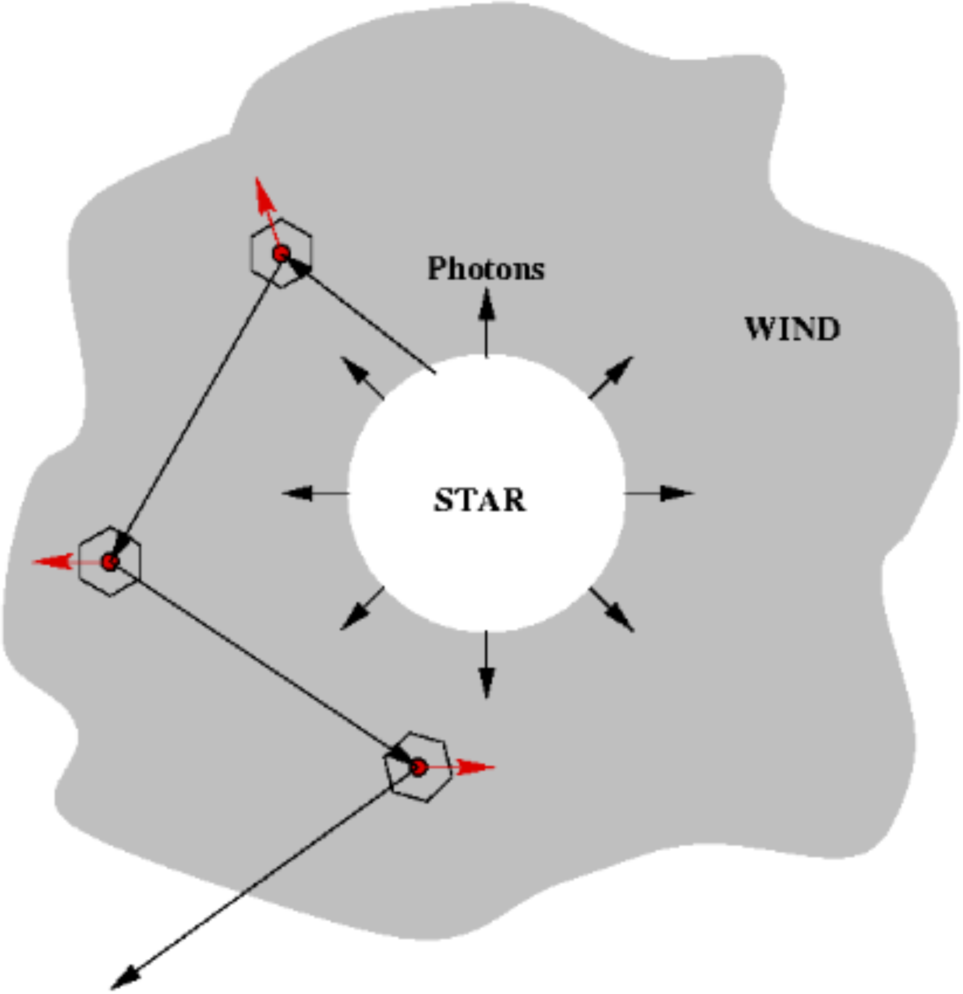
Elvis 2000



- **Feedback**


McConnell & Ma (2013)
Stars/Early-type BCG
Stars/Early-type non-BCG
Stars/Late-type
Gas/Early-type BCG
Gas/Early-type non-BCG
Gas/Late-type
Masers/Early-type
Masers/Late-type
M_{BH} ($M_\odot$)
10^6
10^7
10^8
10^9
10^{10}
60
80
100
200
300
400
σ (km/s)
N4889
N3842
M87
N1407
M60
N6086
N7768
N1332
A3565
N4374
N4261
N1399
N6251
N7052
N1374
N3608
N3377
M31
N1316
N3607
N4596
N4473
N1300
N7582
N4258
N3393
N2787
N1023
N6264
N3227
N2549
N4486A
U3789
N2960
N6323
N4388
N3368
N2273
N3489
M94
M32
MW
Circinus
M64
Haering & Rix (2004)
M_{BH} [$M_\odot$]
10^5
10^6
10^7
10^8
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
M_{bulge} [$M_\odot$]

Radiation-Driven Mass Loss and the Physics of Line Driving



Scattering by *free* electrons: the Eddington limit

- **At , gas will be blown away by radiation pressure on free electrons**

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- **At , gas will be blown away by radiation pressure on free electrons**

Scattering by *bound* electrons: line-driving

- **A bound electron presents a cross section to a photon near line center that is many orders of magnitude larger than the cross section of a free electron**

The CAK Ansatz

- The acceleration solely due to *electron scattering* is

$$g_e \;=\; \left(\frac{\mathcal{F}_{tot}}{c}\right)\;\left(\frac{n_e\,\sigma_e}{\rho}\right)$$

- Write $\mathbf{g_{rad,tot}}$ as a multiple of g_e

$$g_{rad,tot} \;=\; g_e\;\mathcal{M}$$

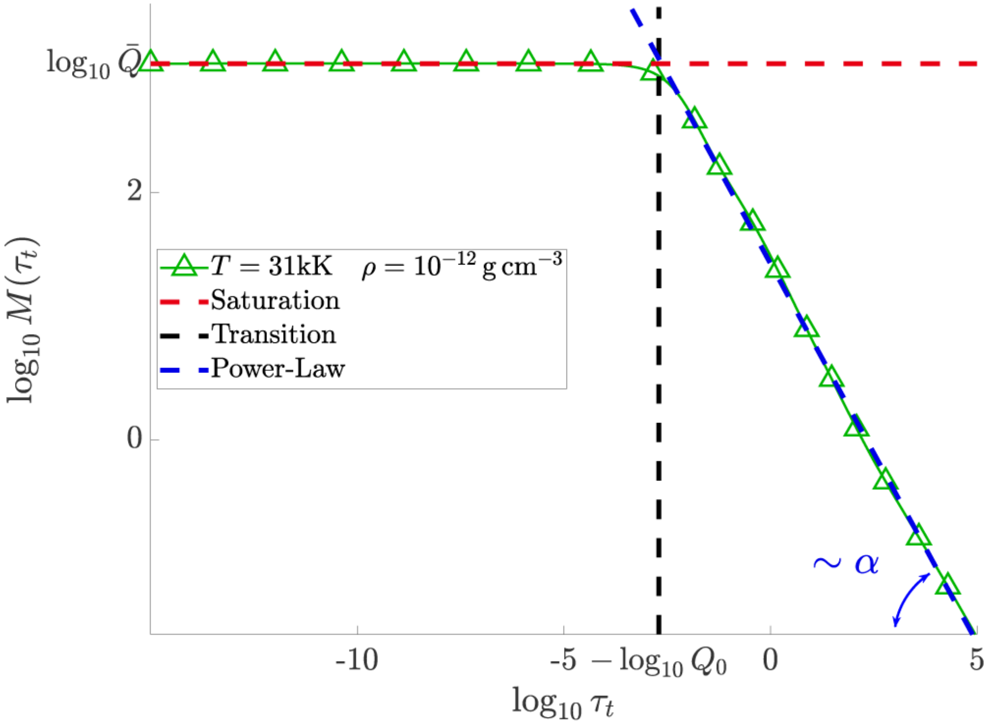
- $\mathcal{M}$ is the so-called **"force multiplier"**

- Then try to parameterize the force multiplier as

$$\mathcal{M} \;=\; k\;t^{-\alpha}$$

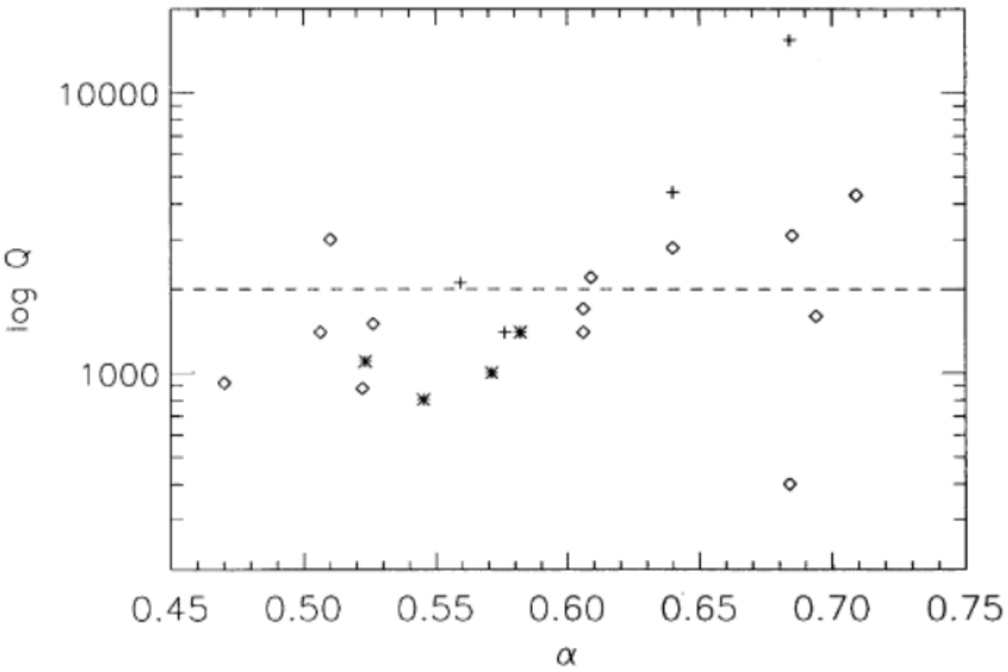
- where t is a measure of the line optical depth
  - **IMPORTANT: t depends on the velocity gradient**

Line-by-line calculations show that this is a pretty good approximation, but the relationship asymptotes



from Poniatowski et al (2022)

Crucially, $\mathcal{M}_{\mathbf{max}} \simeq \mathbf{constant} \simeq \mathbf{2000}$ (Gayley 1995)$



from Gayley (1995)

Line-Driving *REQUIRES*

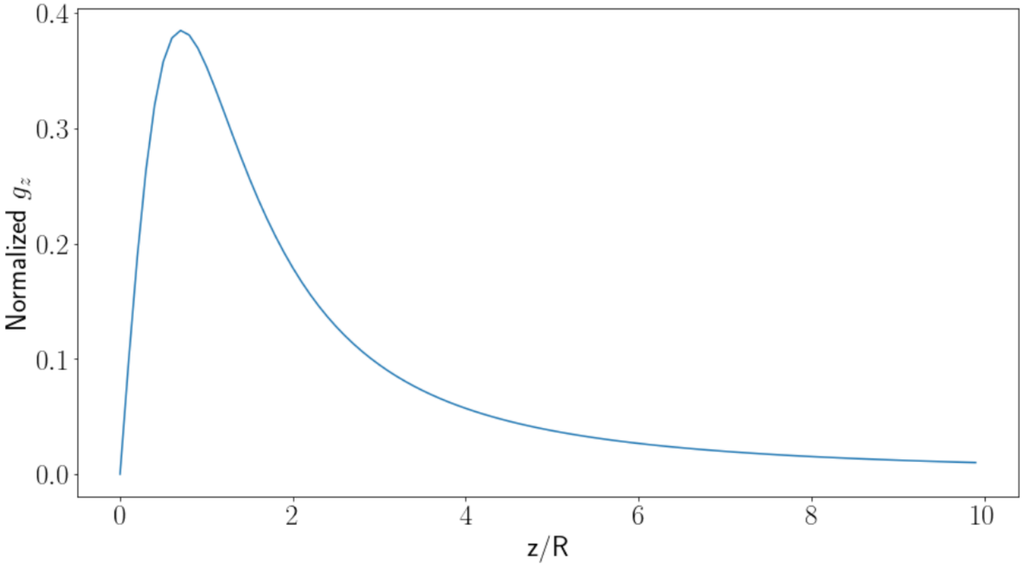
$$\Gamma_{Edd} = L/L_{Edd} \;>\; \frac{1}{\mathcal{M}_{max}} \;\simeq\; 5 \times 10^{-4}$$

$\mathcal{M}_{max}$ **is the most we can hope to get out of line-driving, over and above what we can get from electron scattering**

Line-Driven ***Disk*** Winds

Challenges: Geometry & Dynamics

- No spherical symmetry
- Rotation *must* be important
- The vertical component of gravity initially **increases**: $g_z \propto \frac{z}{\left(R_{cyl}^2+z^2\right)^{3/2}}$



Challenges: Ionization / Radiative Transfer

- Complex geometry & kinematics make ionization & RT computationally difficult
    - e.g. dv/dr becomes a *tensor*
- Typically have *multiple* radiation sources with different geometries and SEDs
    - Accretion disk
    - Central source
        - Accreting object
        - Boundary layer
        - Corona
        - ....

Challenges: (Radiation)Hydrodynamics

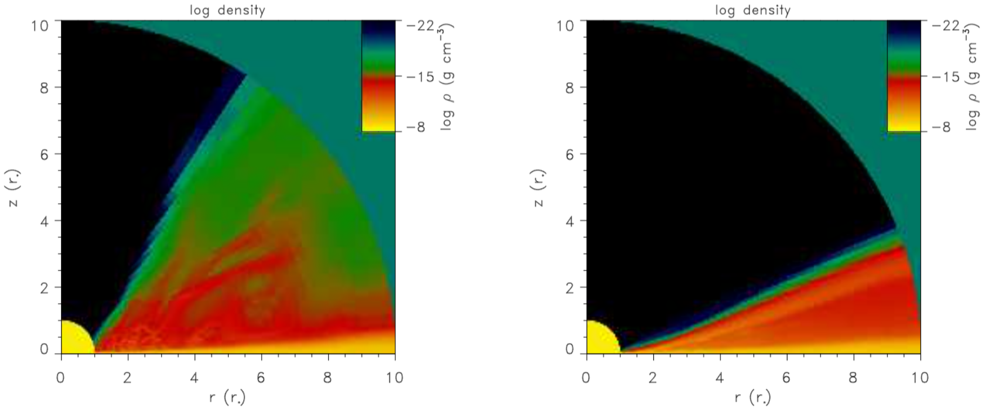
- **Hydrodynamics and ionization/RT are strongly and non-linearly coupled**
    - Hydrodynamics depends strongly on radiation force
    - Radiation force depends strongly
        - temperature
        - velocity field
        - density structure
        - ionization

Previous Efforts: Detailed Hydrodynamics, Approximate Ionization & RT

- Detailed hydrodynamics
    - At least 2-D + rotation:
        - Proga+98,99,00,04, Pereyra+03, Nomura+16,18,20,21
    - Some 3-D:
        - Dyda+18ab
- Detailed radiation geometry, but various levels of "dv/dr accuracy"
- "Quasi-1D", "quasi-optically-thin" RT & ionization with self-shielding
- At best two frequency bands
    - "UV" $\longrightarrow$ line force
    - "X-ray" $\longrightarrow$ ionization

Previous Results: Basic Characteristics of LIne-Driven DIsk Winds

- An accreting white dwarf without (left) and with (right) a strong central source | | | :---: | |

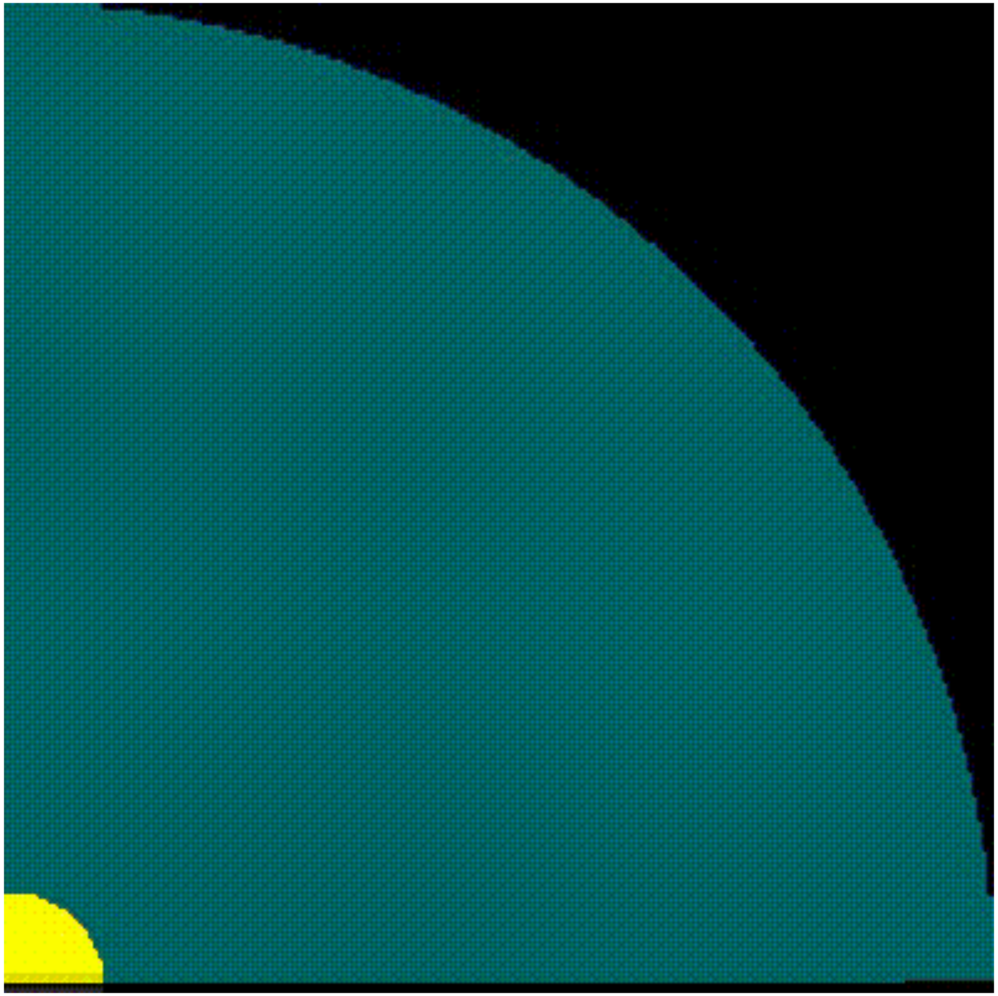


|

from Proga 1999

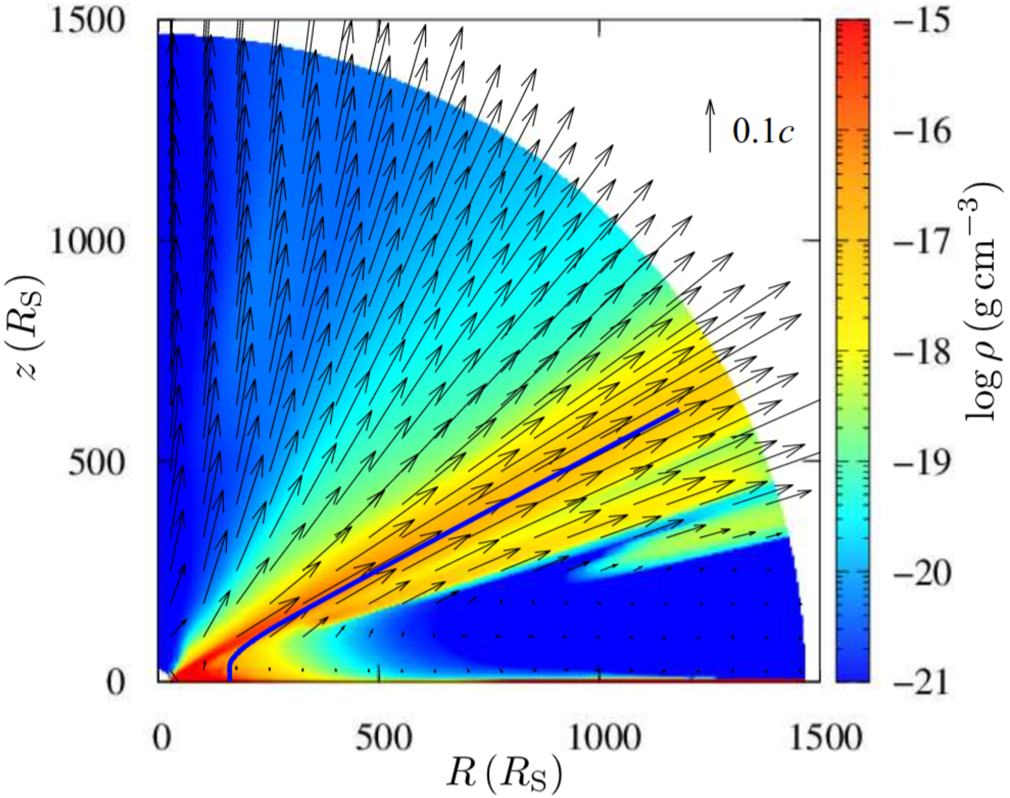
- Most of the mass tends to be carried away in a fast "stream"
- Pure disk winds tend to be highly non-steady

- an X-ray irradiated AGN | Wide view | (both from Proga+00) | Zoom
  | | :---: |:---: | :---:| |



| |

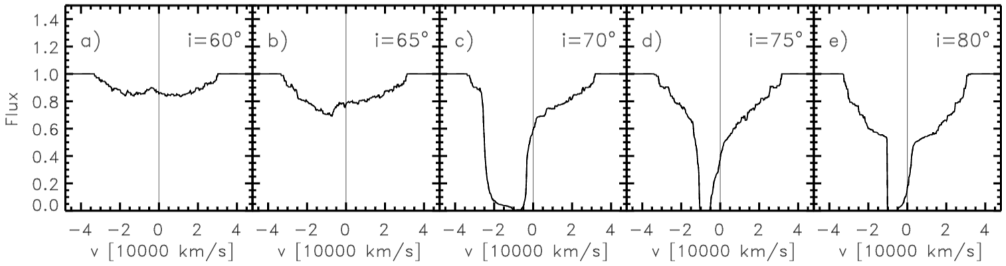
- a near-Eddington AGN



from Nomura+20

Previous Results: Observables

- Hydro models seem to do a pretty reasonable job at matching (some) observables
- UV line profiles ("BALQSOs")



from Proga & Kallman 2004

HOWEVER: All of these results are based on quasi-1D radiative transfer and/or ionization calculations

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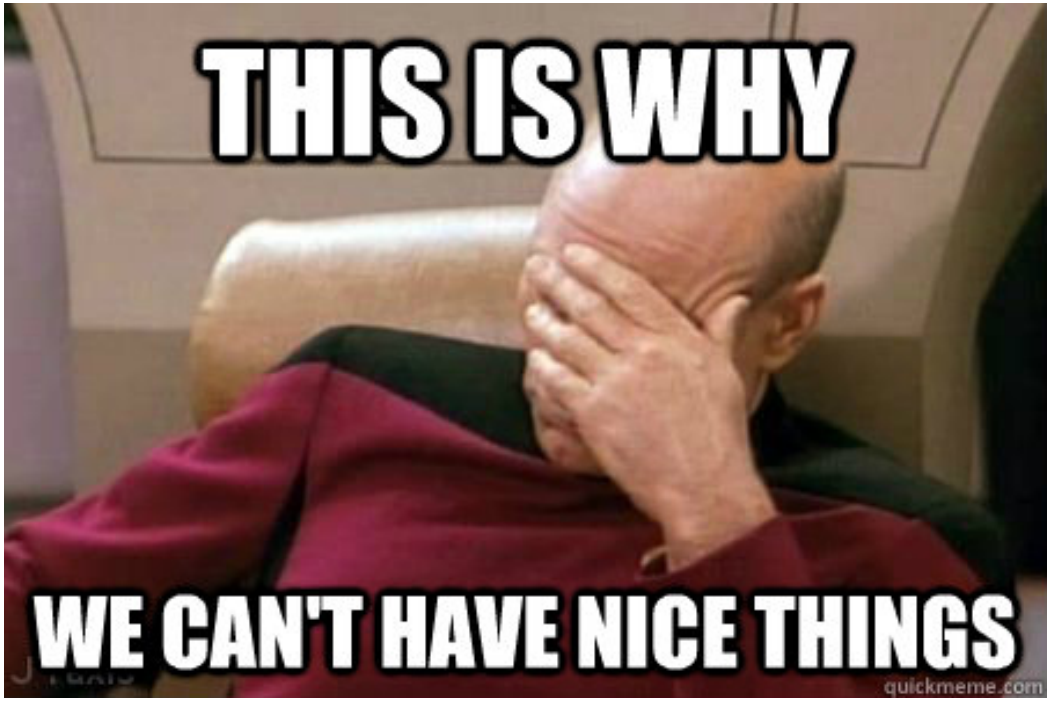
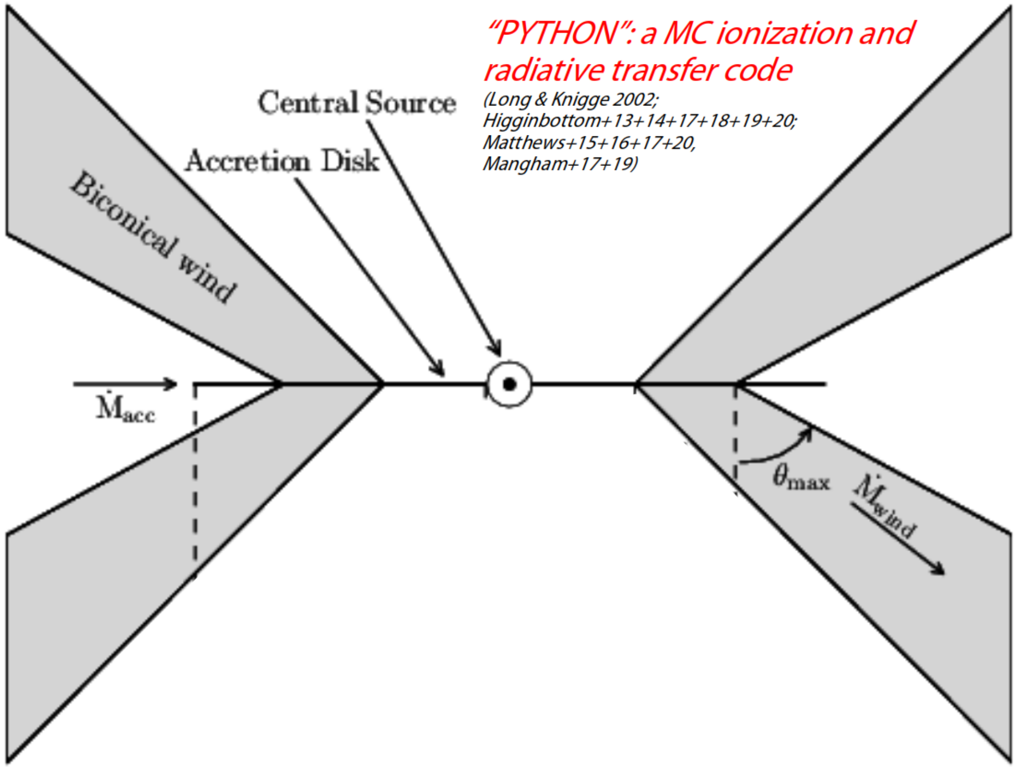


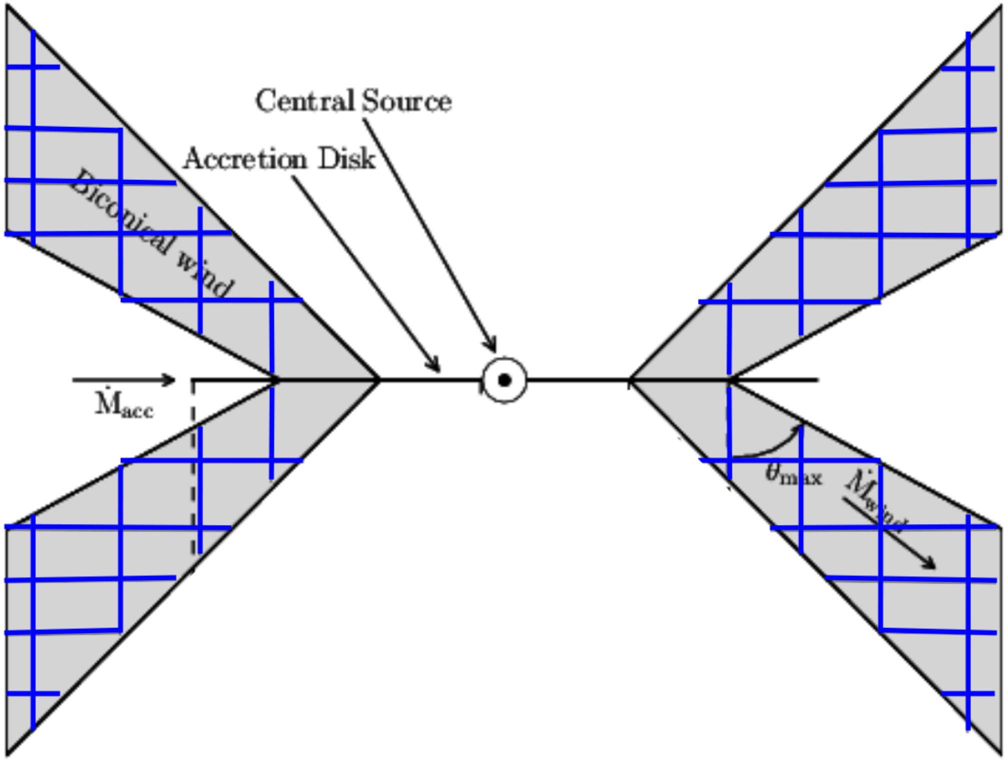
Our contribution: making everything worse

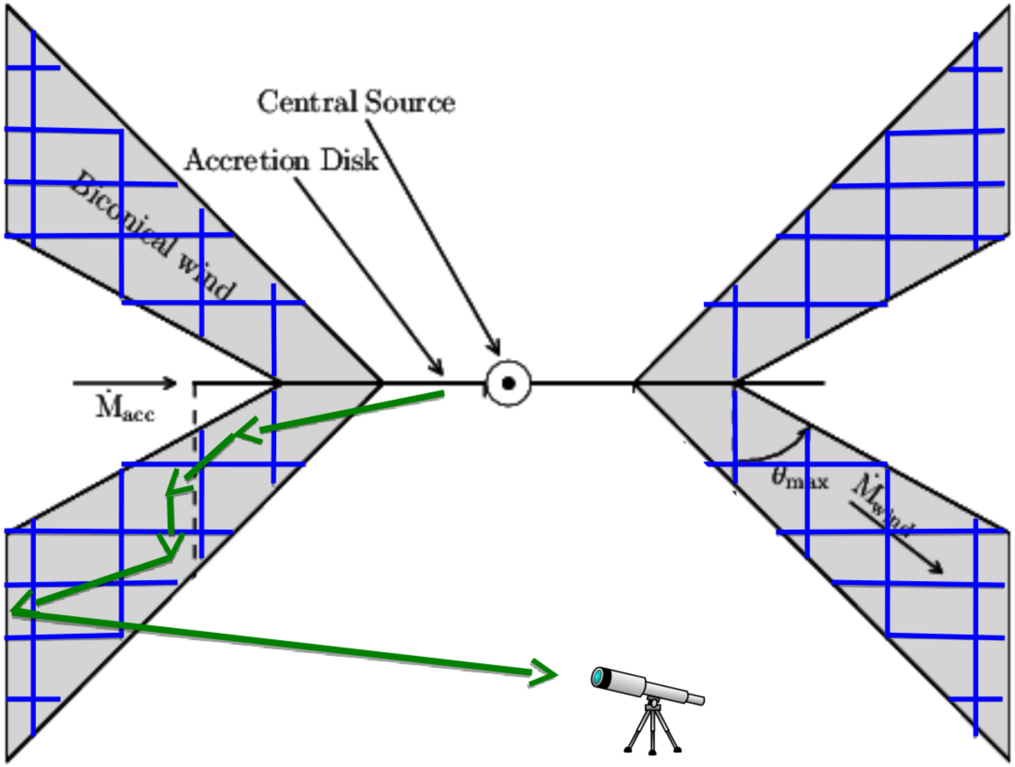
(by adding more physics)



"PYTHON": a MC ionization and radiative transfer code

(Long & Knigge 2002;
Higginbottom+13+14+17+18+19+20;
Matthews+15+16+17+20,
Mangham+17+19)


Central Source
Accretion Disk
Biconical wind
$\dot{M}_{acc}$
θ_{max}
$\dot{M}_{wind}$


Central Source
Accretion Disk
Biconical wind
$\dot{M}_{\rm acc}$
$\theta_{\rm max}$
$\dot{M}_{\rm wind}$

PYTHON (maybe soon ”Pyrite”)

- can calculate ionization state and observables (spectra, line profiles, reverberation signatures) for any given outflow model

- comes with several built-in "kinematic" (parameterized) spherical and disk wind models
    - user-specified parameters define geometry, velocity, velocity, radiation field

- can also read in models (e.g. from hydrodynamic simulations)

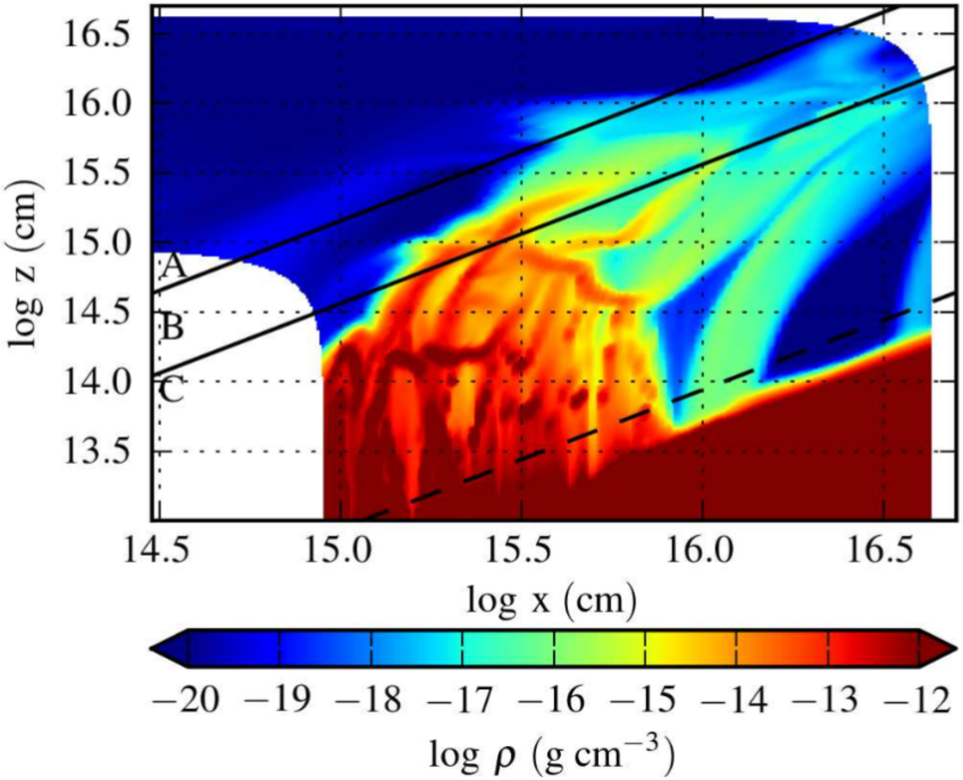
- physics included allows a wide range of applications, including:

Back to line-driving:

Are existing models with approximate ionization and radiative transfer ”good enough”?

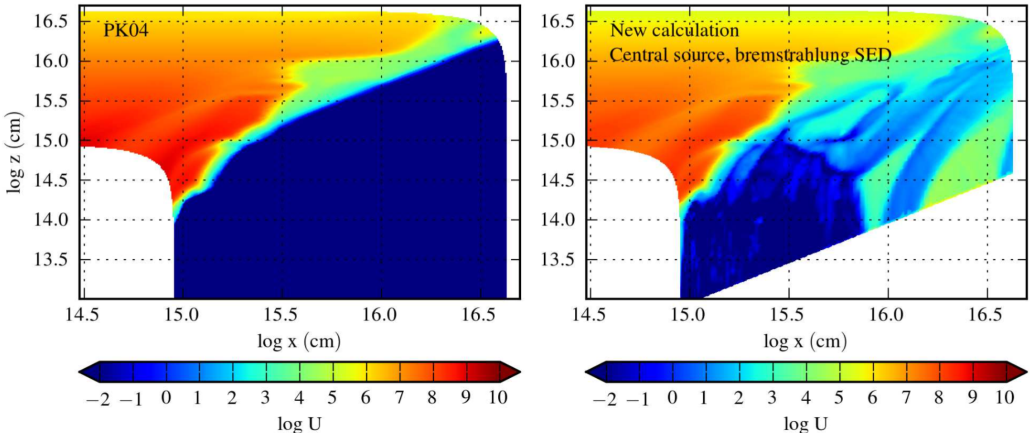
- A snapshot from Proga & Kallman 2004...

Higginbottom et al. 2014, data from Proga & Kallman 2004



- ...now reprocessed with full 2-D ionization and RT

ionization parameter from Higginbottom et al. 2014



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    - the ionizing photons just scatter around the shield

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    - they would be overionized
    - no suitable driving lines
    - **no wind**

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    - the ionizing photons just scatter around the shield
- **The winds calculated in the hydro simulations could not exist IRL**
    - they would be overionized
    - no suitable driving lines
    - **no wind**
- **This does not mean line-driving cannot work**
    - just that we do have to face up to fully coupled, 2-D, multi-wavelength radiation-hydrodnamics

Radiation-hydrodynamic simulations of line-driven disk winds:
including multi-dimensional, full-spectrum radiative transfer and ionization

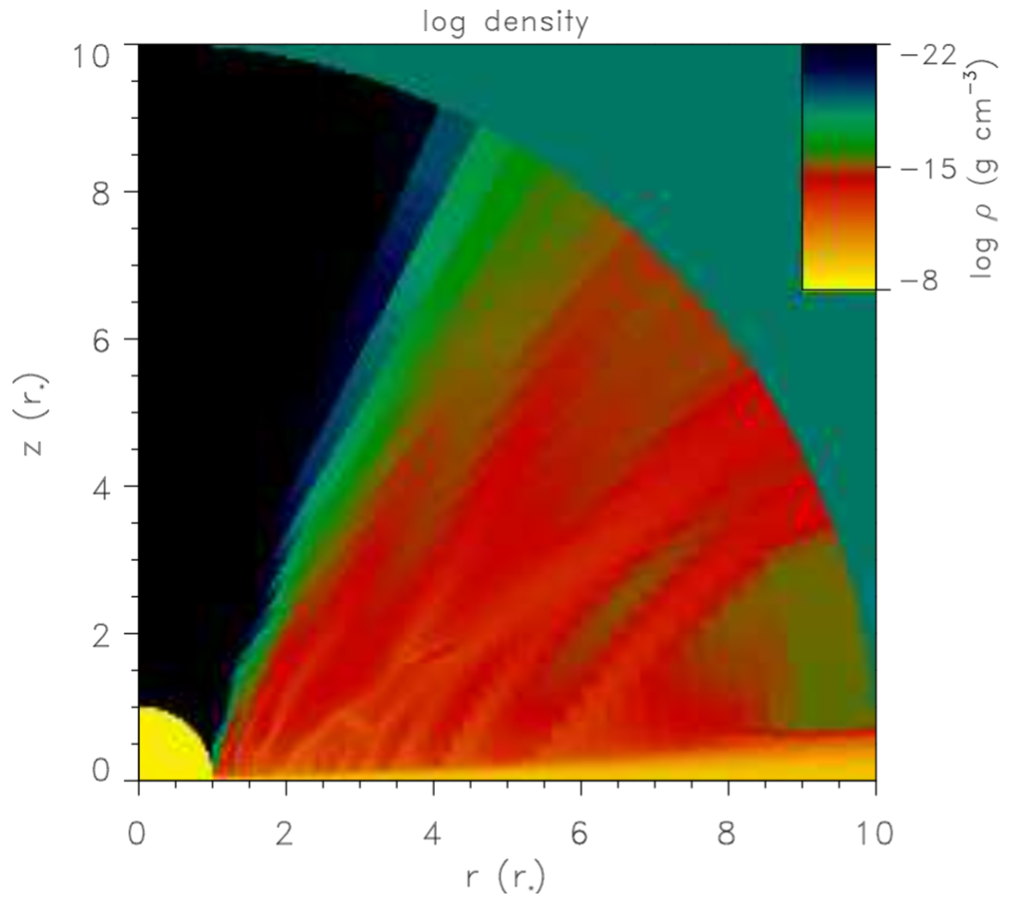
Basic idea:

- **Couple *PYTHON* with *PLUTO* via operator-splitting**
- Calculate new ionization structure after every $\simeq 1000$ hydro time-steps
- work out corresponding force multipliers by summing over huge Kurucz line list
- iterate to convergence

Start with the "simplest" problem: CVs (accreting white dwarfs)

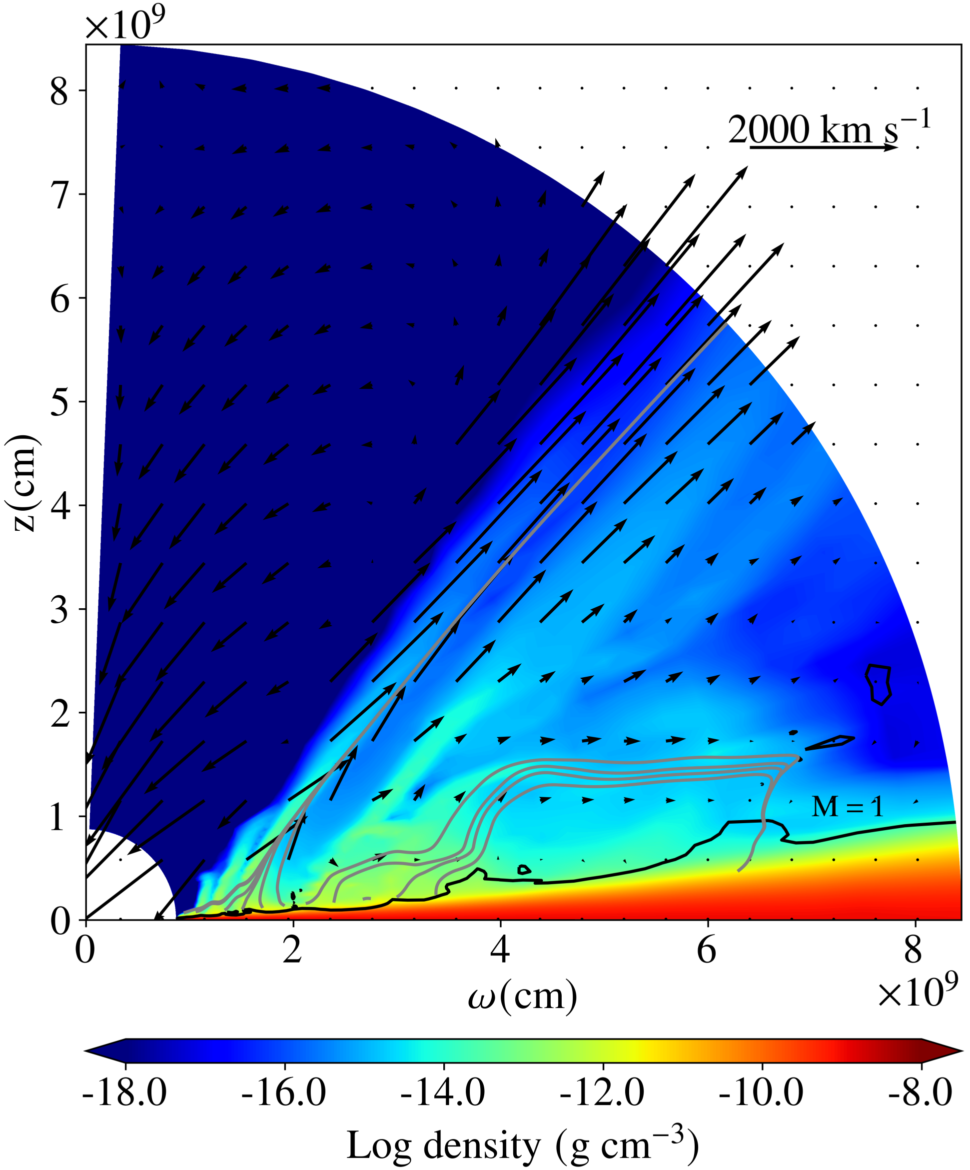
- **Pros**
    - Standard Shakura-Sunyaev disk
    - Other radiation sources
        - probably negligible (BL / WD)
        - similar SED to disk (comparable T_{eff})
    - Small dynamic range
        - $R_{disk}/R_{WD} \simeq 30$
    - No relativistic effects
    - No significant B-fields
- **Cons**
    - $L/L_{Edd} \simeq 1/1000$

Proga, Stone & Drew 1995; Dyda & Proga 2018

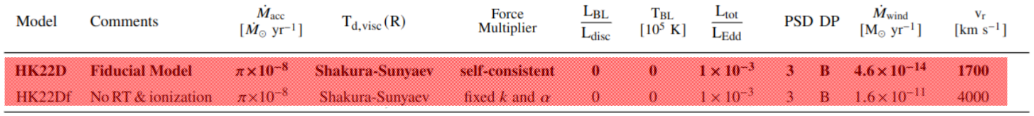


Our new, (almost) kitchen-sink simulations: much weaker outflows!

Higginbottom, Scepi, Knigge et al. 2023



Higginbottom, Scepi, Knigge et al. 2023

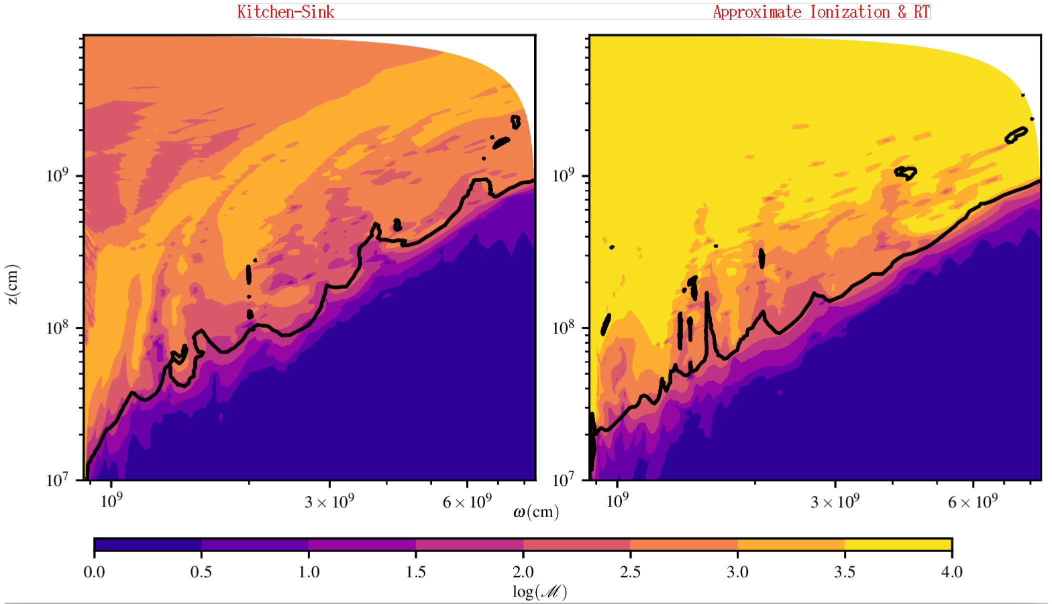


Model	Comments	$\dot{M}_{\rm acc}$ $[\dot{M}_\odot\ {\rm yr}^{-1}]$	$T_{\rm d,visc}(R)$	Force Multiplier	$\frac{L_{\rm BL}}{L_{\rm disc}}$	$T_{\rm BL}$ $[10^5\ {\rm K}]$	$\frac{L_{\rm tot}}{L_{\rm Edd}}$	PSD	DP	$\dot{M}_{\rm wind}$ $[M_\odot\ {\rm yr}^{-1}]$	v_r $[{\rm km\ s}^{-1}]$
HK22D	**Fiducial Model**	$\pi\times10^{-8}$	**Shakura-Sunyaev**	**self-consistent**	**0**	**0**	1×10^{-3}	**3**	**B**	4.6×10^{-14}	**1700**
HK22Df	No RT & ionization	$\pi\times10^{-8}$	Shakura-Sunyaev	fixed k and α	0	0	1×10^{-3}	3	B	1.6×10^{-11}	4000

Why is the wind weaker than found in previous simulations?

- **higher ionization state → lower force multipliers**

Higginbottom, Scepi, Knigge et al. 2023



Kitchen-Sink

Approximate Ionization & RT

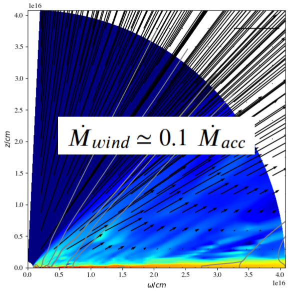
(How) does this translate to QSOs and AGN?

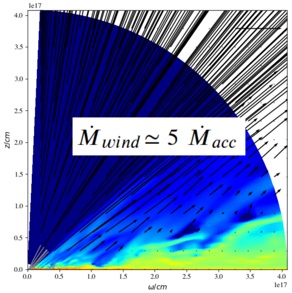
- This is hot off the press -- enjoy with caution!
- First results will be published "soon" in Scepi, Knigge et al. (2024)

Pure Shakura-Sunyaev Disks — $L/L_{Edd} \simeq 0.8$ – no separate X-ray source

$M_{BH} = 10^8 M_\odot$

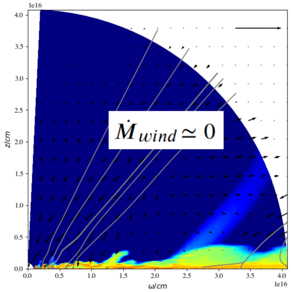
$M_{BH} = 10^9 M_\odot$


$\dot{M}_{wind} \simeq 0.1\ \dot{M}_{acc}$


$\dot{M}_{wind} \simeq 5\ \dot{M}_{acc}$

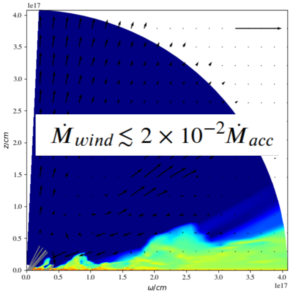
Pure Shakura-Sunyaev Disks — $L/L_{Edd} \simeq 0.8$ – with (weak) X-ray source

$M_{BH} = 10^8 M_\odot$ --
$L_X/L_{disk} \simeq 1\%$



$\dot{M}_{wind} \simeq 0$

$M_{BH} = 10^9 M_\odot$--
$L_X/L_{disk} \simeq 2\%$



$\dot{M}_{wind} \lesssim 2 \times 10^{-2} \dot{M}_{acc}$

Summary

- Line-driven winds are awesome
- The underlying physics is pretty well understood, ...
- ... but they are ***really*** difficult to simulate in > 1-D, ...
- But we **must** face this if we want to have a *physical* understanding of feedback
- First results:
  - X-ray weak QSOs can **definitely** produce powerful feedback
  - But what about lower-M_{BH}, lower-$\dot{M}$, higher L_x AGN?