Reverberation Mapping of Accretion Disk Winds in AGN

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Disk wind modelling:

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Knox Long (STScI)

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Stuart Sim (QUB)

James Matthews (Oxford)

MEMEcho:

Keith Horne (St Andrews)

CARAMEL:

Peter Williams (CfA)

Anna Pancoast (CfA)

Reverberation Mapping of Accretion Disk Winds in AGN

- Introduction
  - Ionization and radiative transfer modelling of AGN disk winds
- The physics of emission line reverberation
  - Clouds vs accretion disk winds
- The reverberation signatures of rotating accretion disk winds
  - Self-consistent response functions for QSOs and Seyferts
- A blind test of reverberation mapping methods
  - Are we recovering correct BLR properties from RM campaigns?

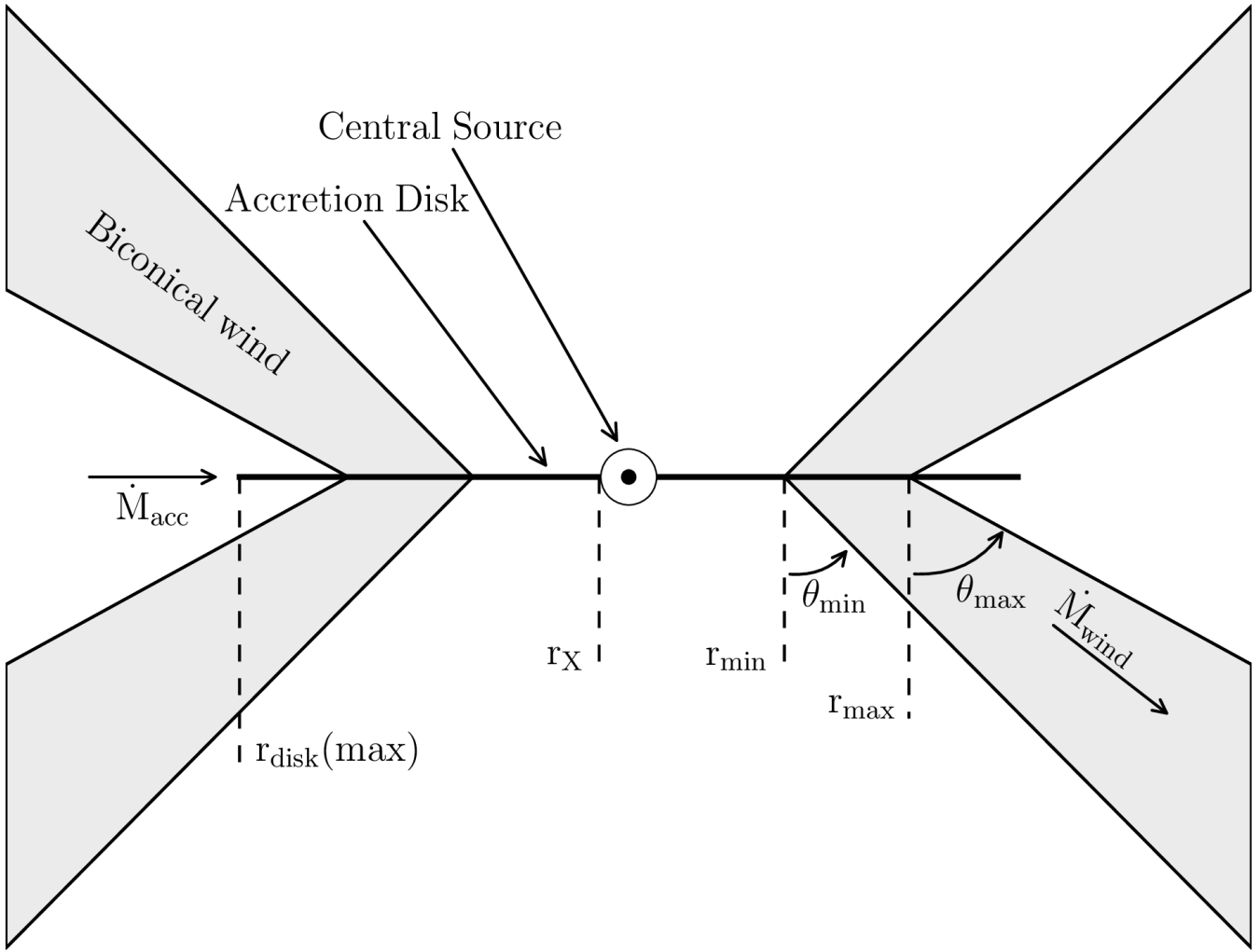
Introduction

Ionization and radiative transfer modelling of AGN disk winds

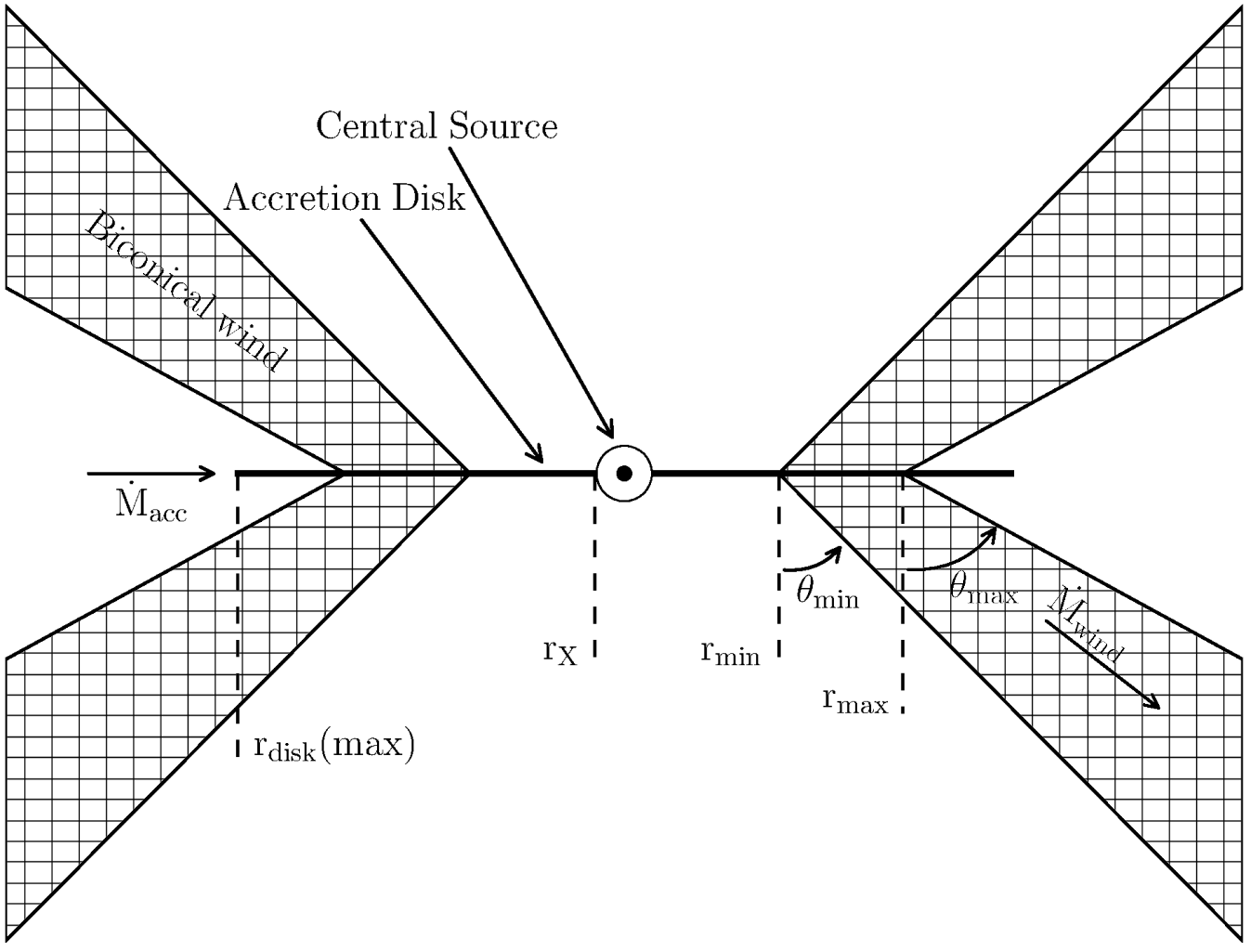
PYTHON: A 3-D MC ionization and radiative transfer code

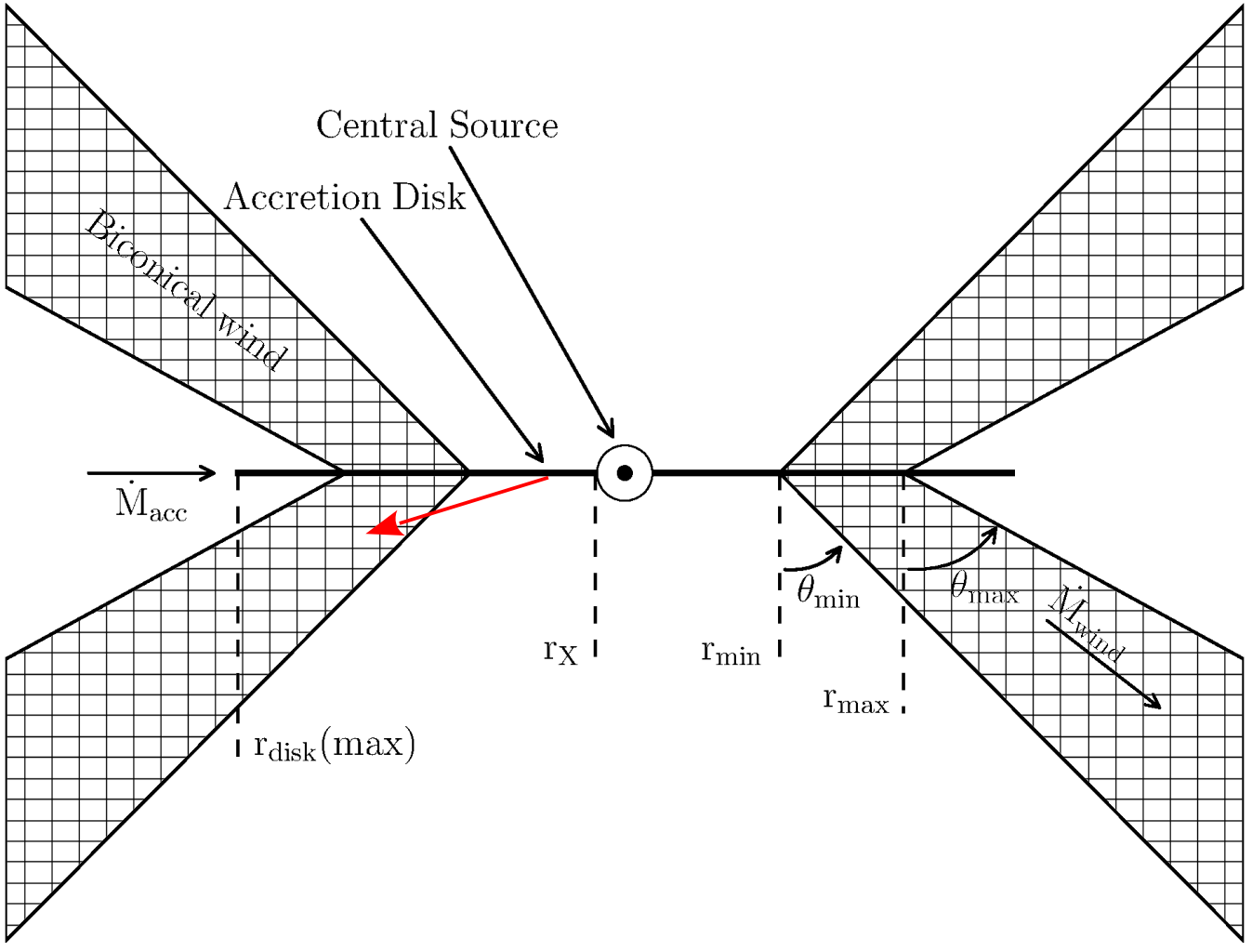
(Long & Knigge 2002; Higginbottom+13+14; Matthews+15+16, Mangham+17+19)

- Specifically designed for astrophysical outflows
- Arbitrary geometry and velocity fields
  - Built-in kinematic models (e.g. bi-conical rotating disk wind)
  - Read in external dynamical models (e.g. from hydro codes)
- Arbitrary type and number of radiation sources, including
  - Optically thick accretion disk (BB or stellar atmosphere)
  - X-ray emitting corona (PL)
- Allows for clumping via a filling factor f (“micro-clumping”)
- Solves for temperature and ionization state through the outflow
  - Thermal equilibrium (radiative and adiabatic processes)
  - Ionization equilibrium (radiative and collisional processes)
- **Predicts emergent spectra, line profiles, transfer functions**



Higginbottom+13


Central Source
Accretion Disk
Biconical wind
$\dot{M}_{acc}$
r_X
r_{min}
r_{max}
$r_{disk}(max)$
θ_{min}
θ_{max}
$\dot{M}_{wind}$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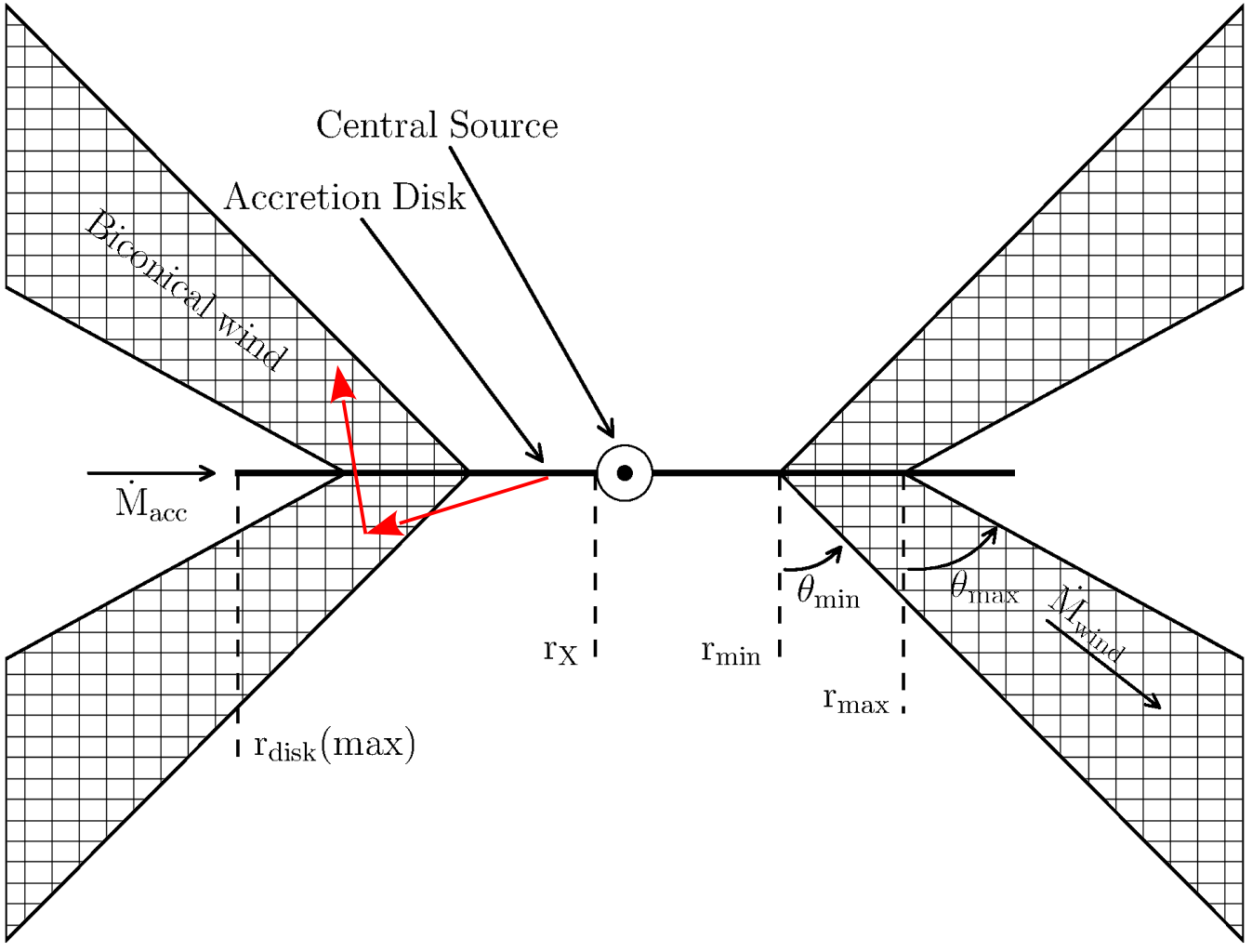
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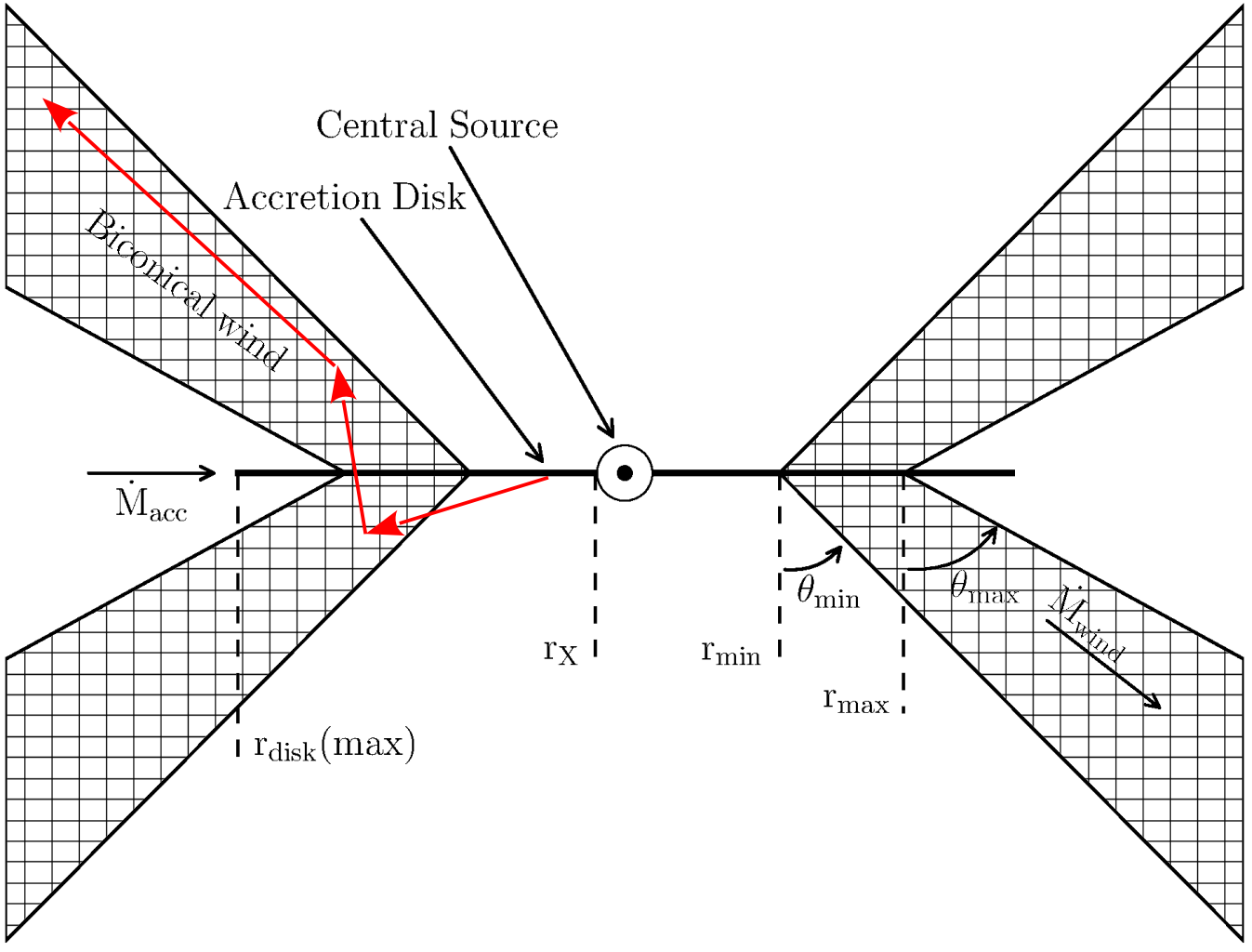
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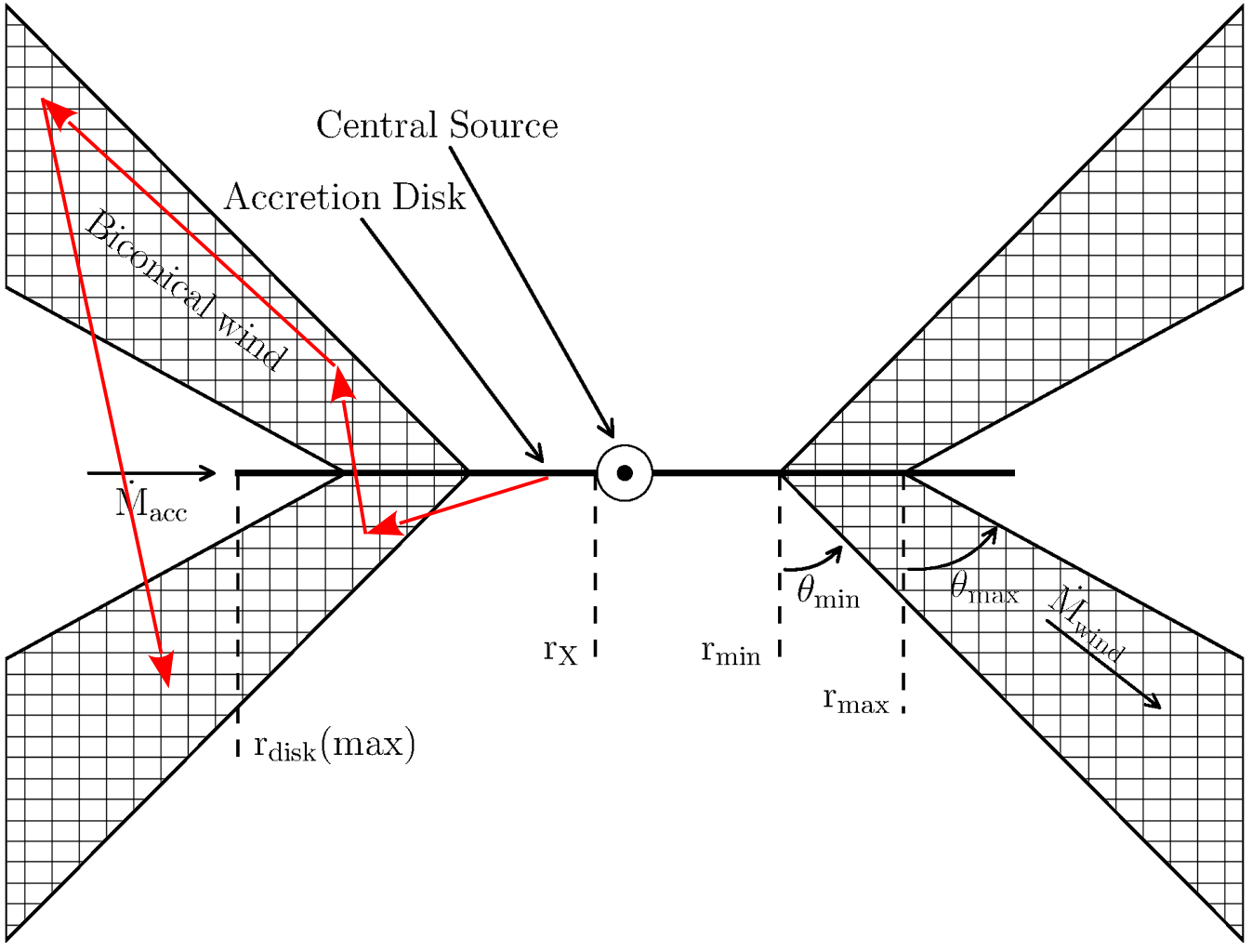
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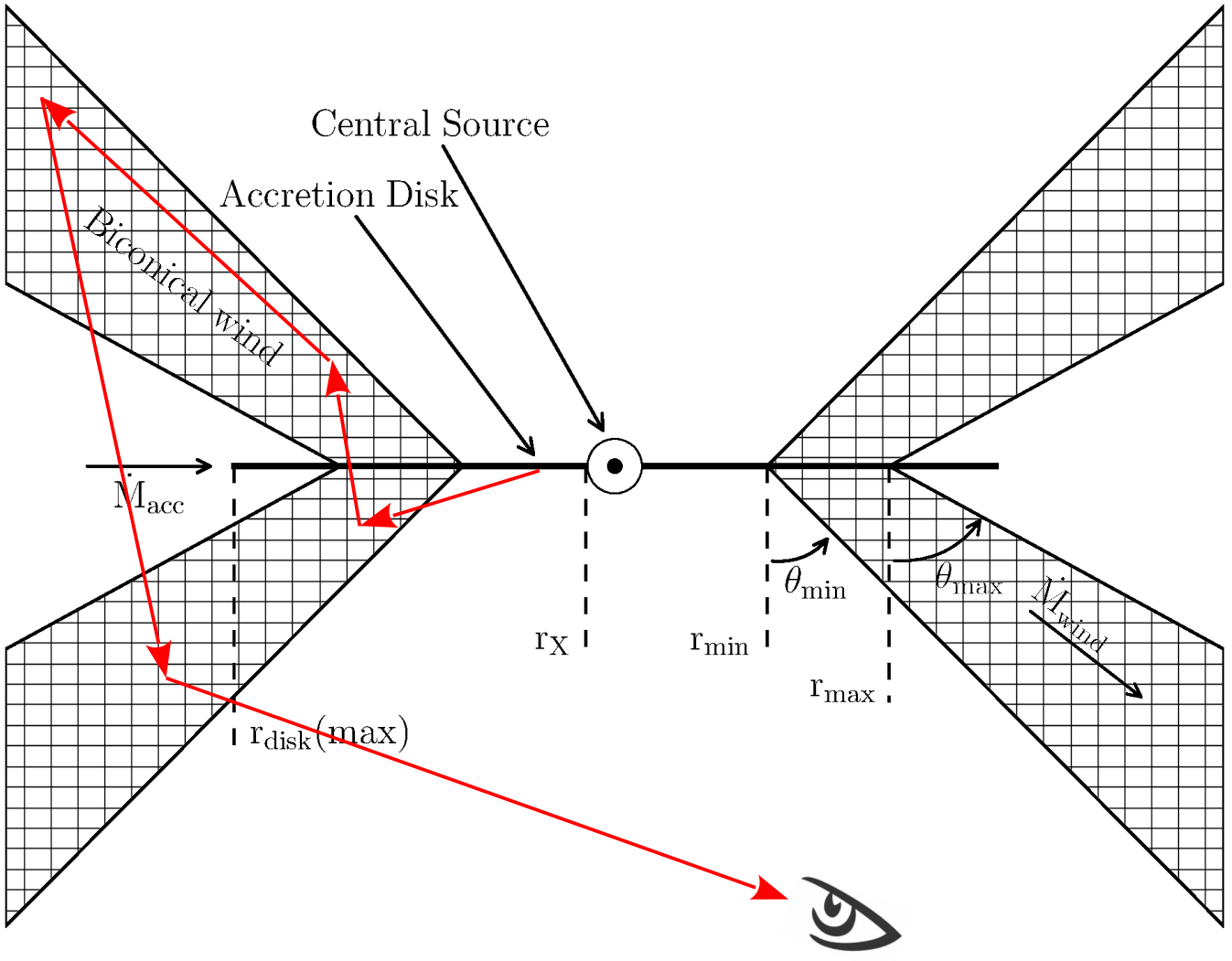
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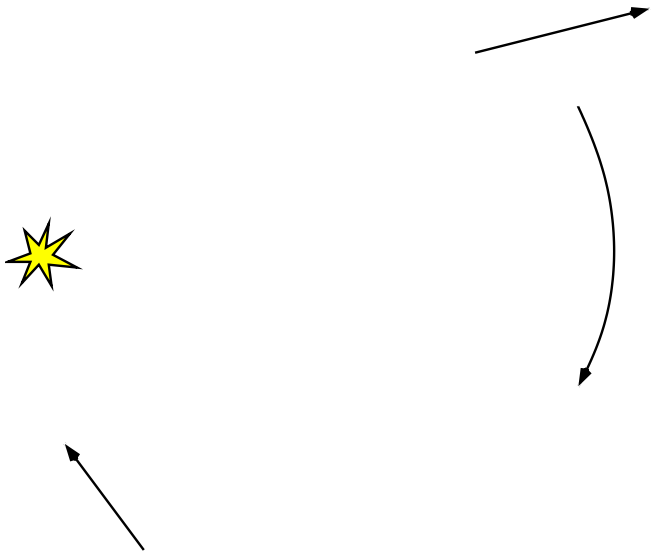
θ_{max}
$\dot{M}_{wind}$

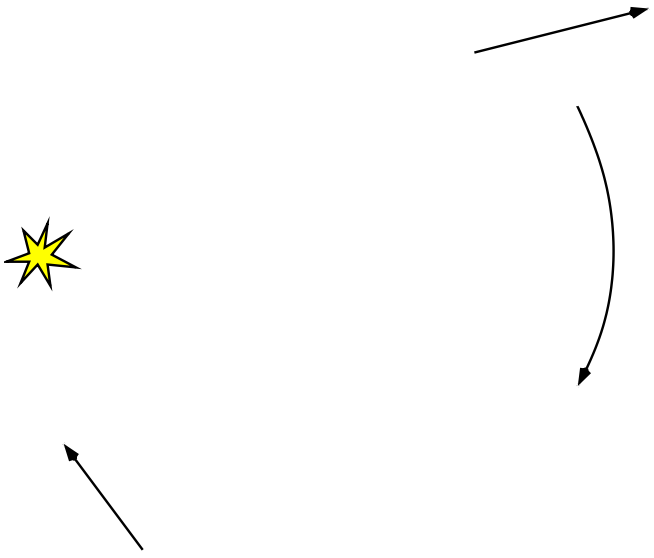
Take-home points

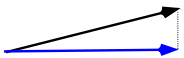
- **What would a disk wind model predict for *<insert your favourite observable>*? → PYTHON!**
  - X-ray, UV, optical, IR
  - spectra, line profiles, reverberation signatures, polarization, photocentres

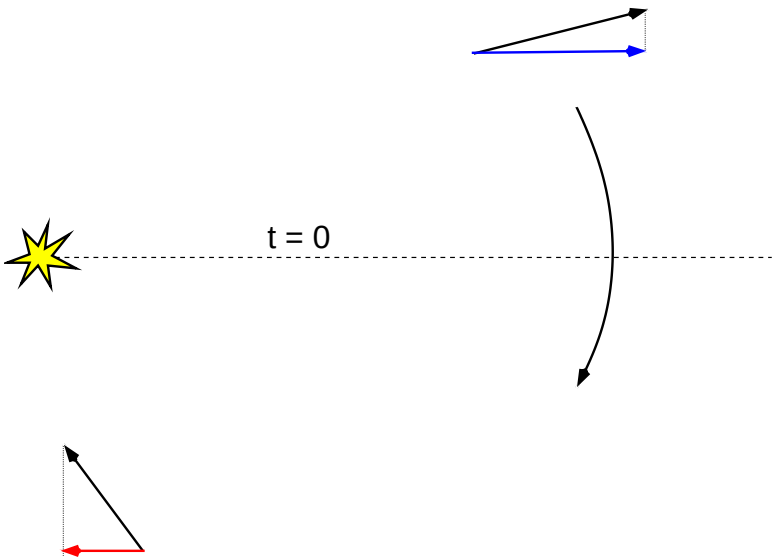
The physics of emission line reverberation

The standard cloud picture





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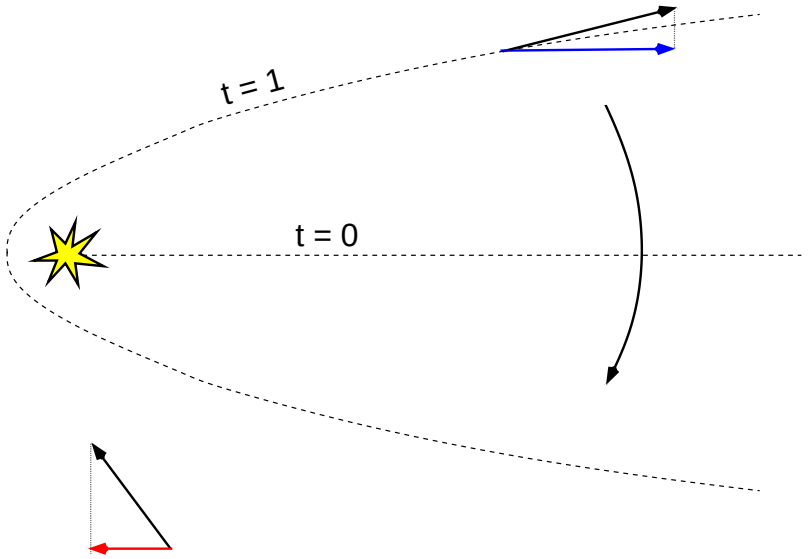
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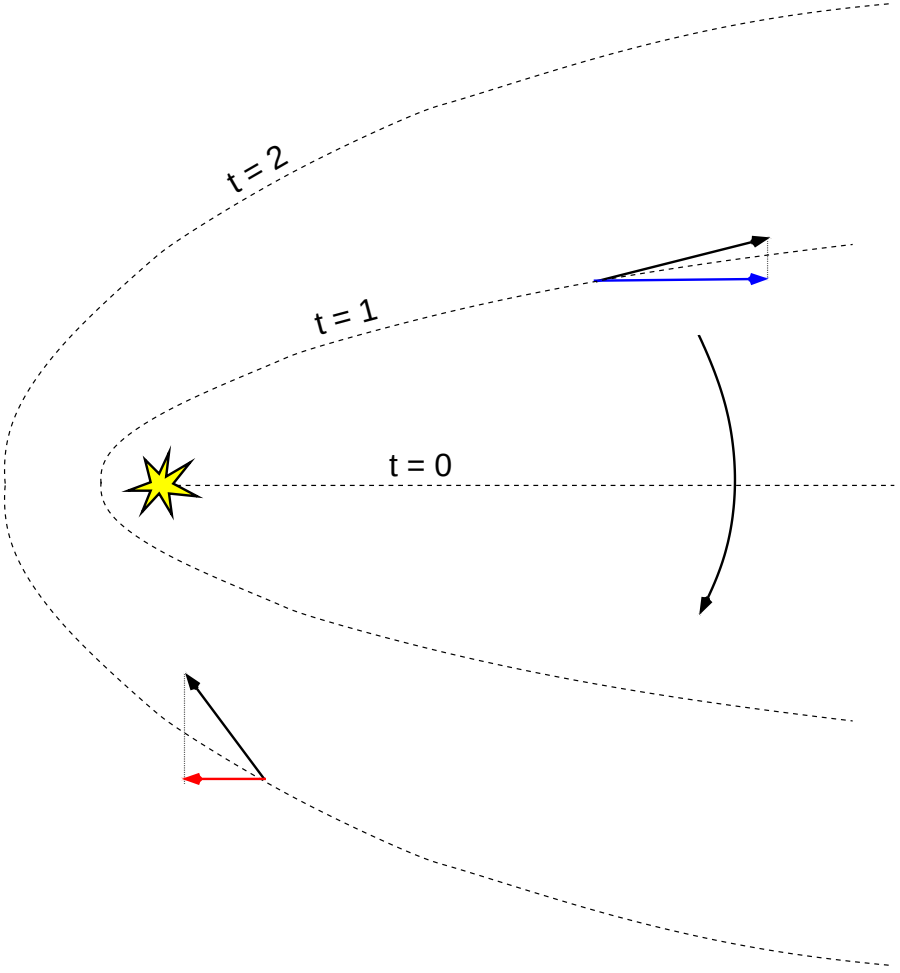
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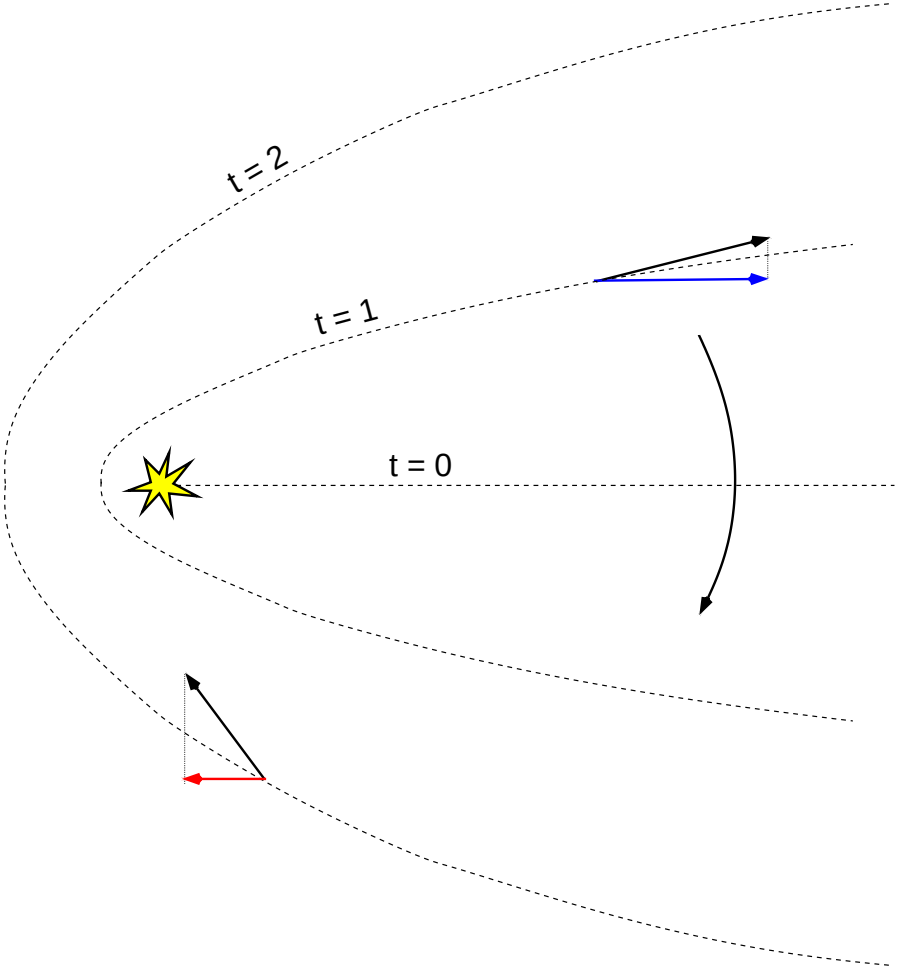
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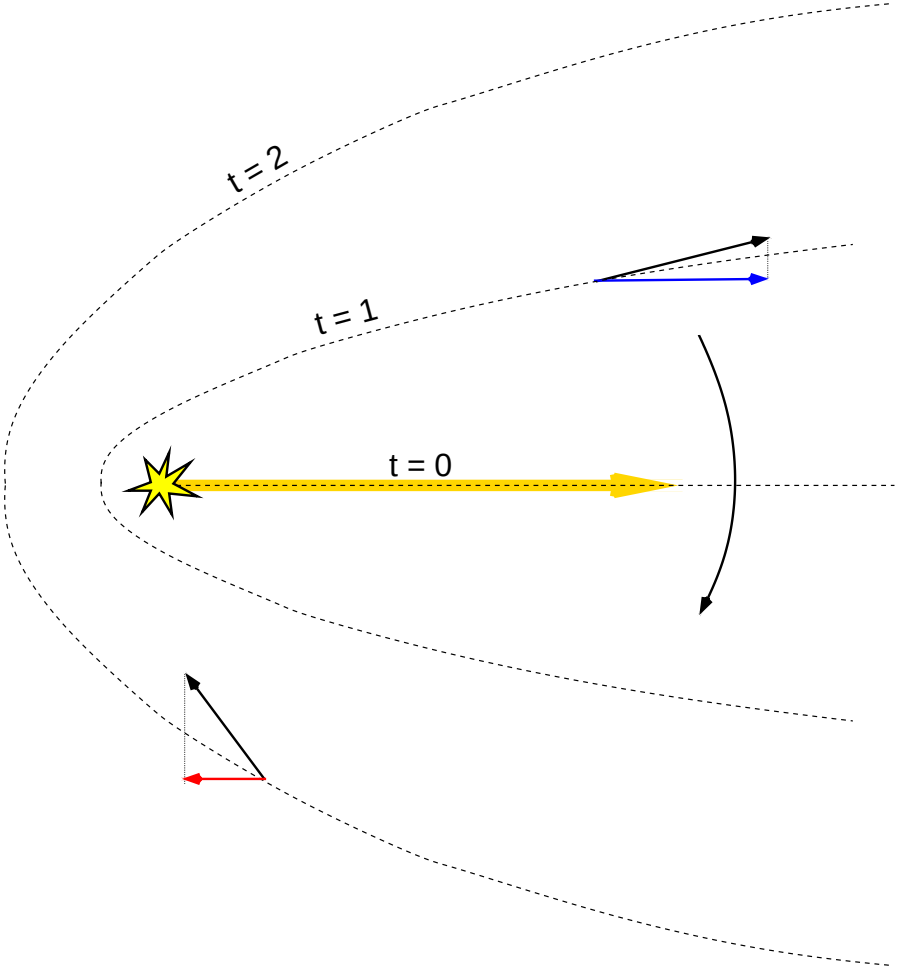
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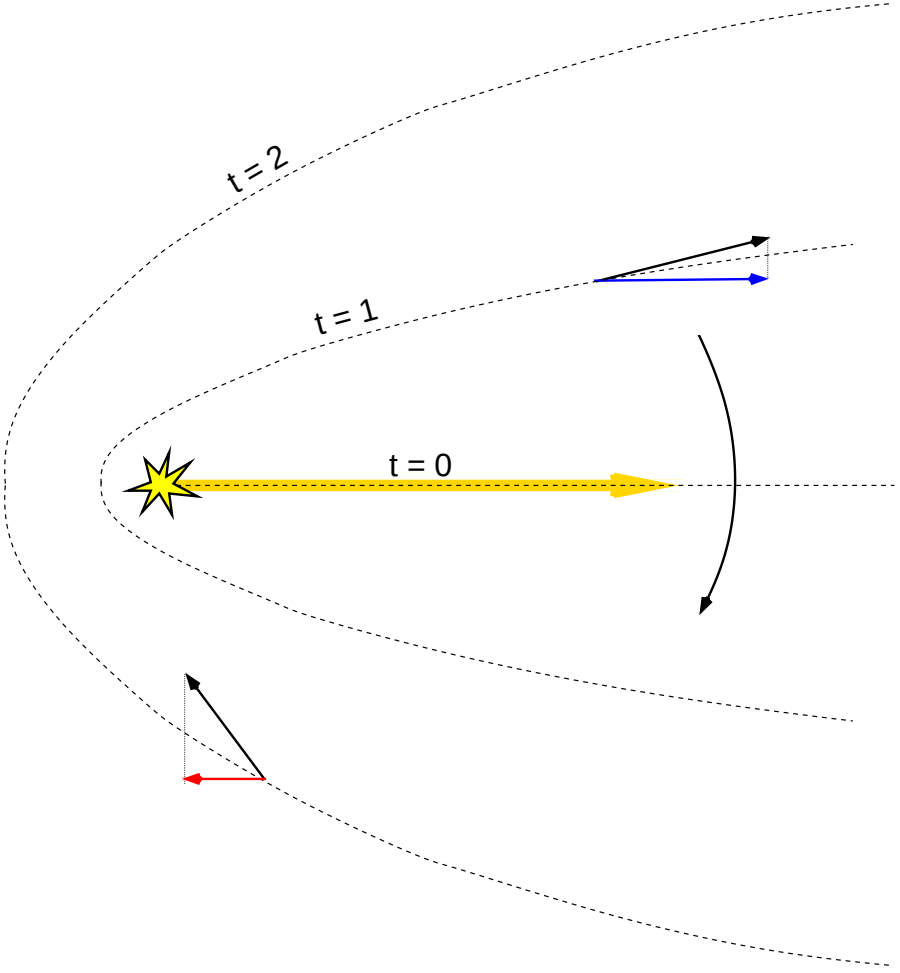
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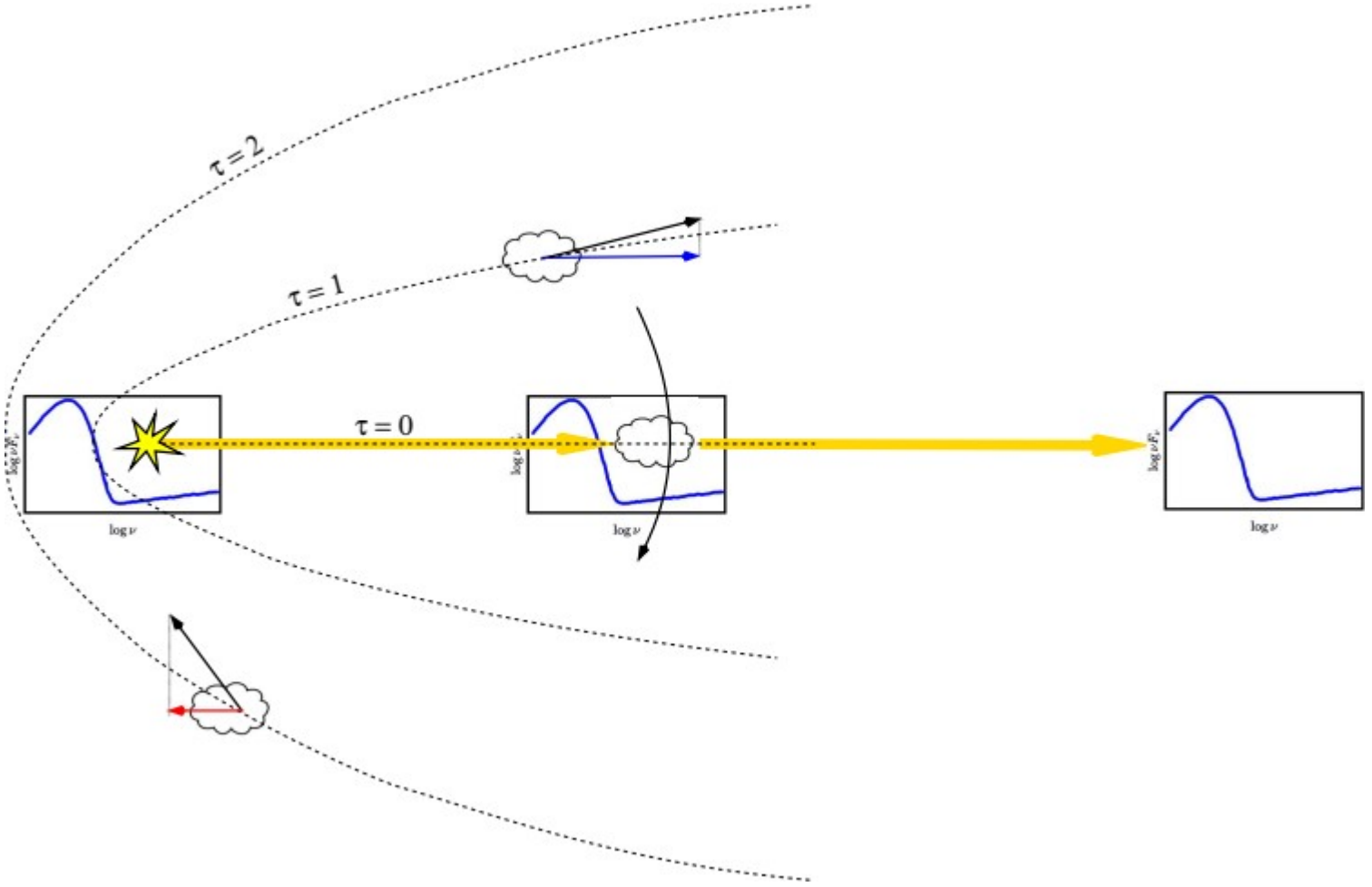
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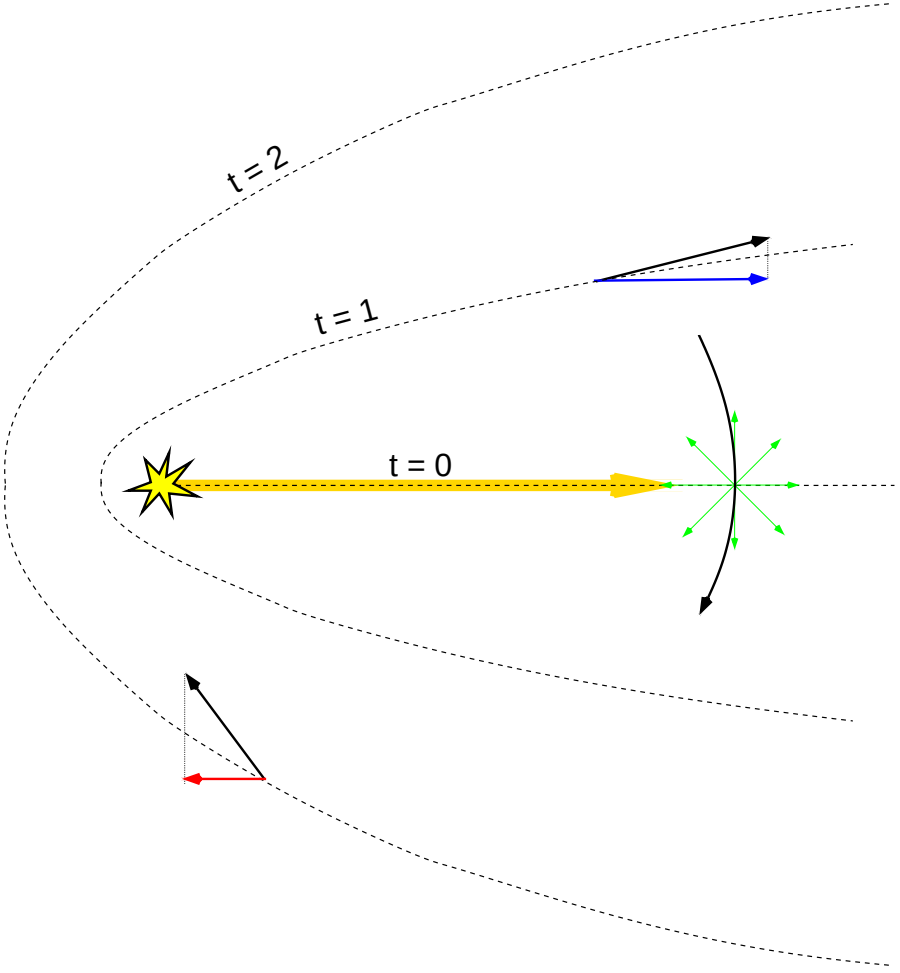
log ν
log νF_ν
log ν
log νF_ν
log ν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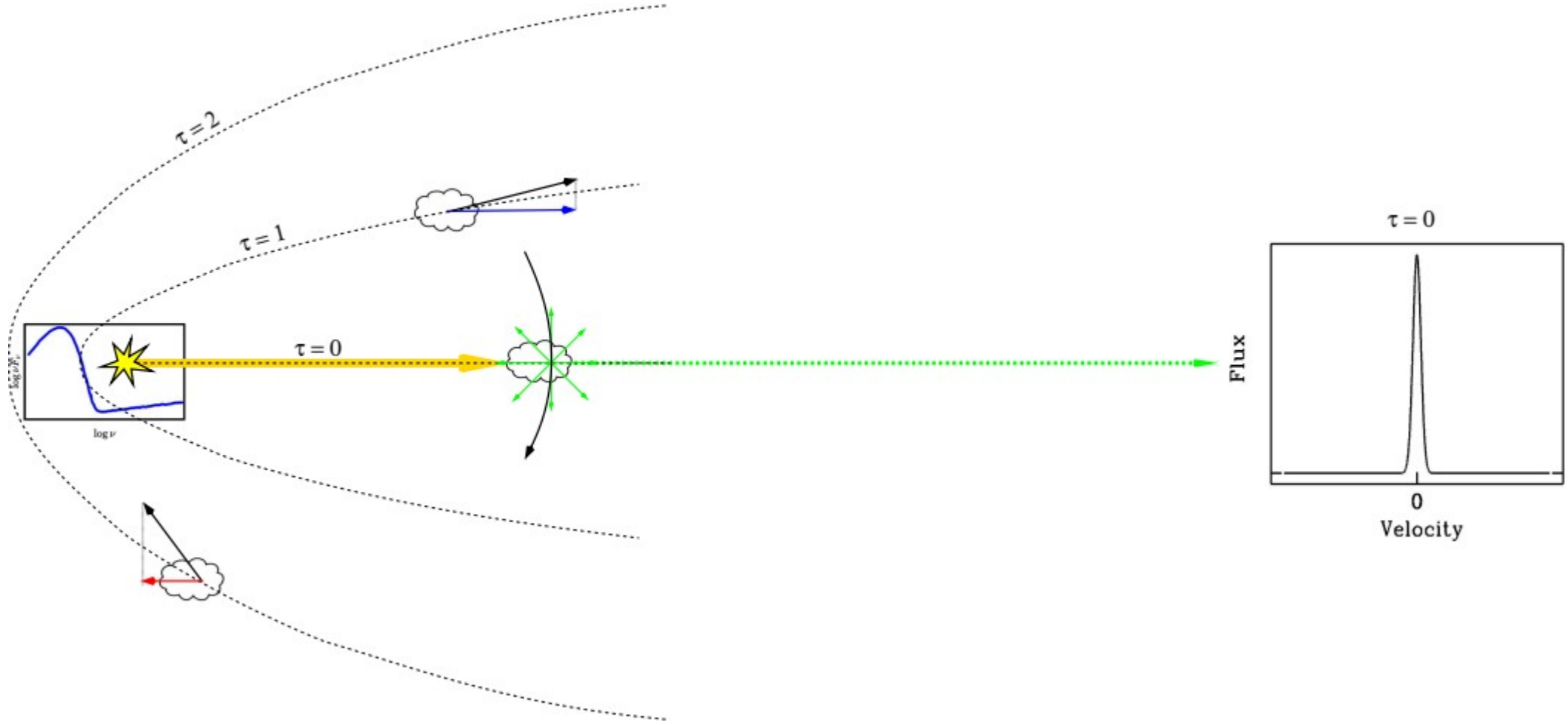
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Flux
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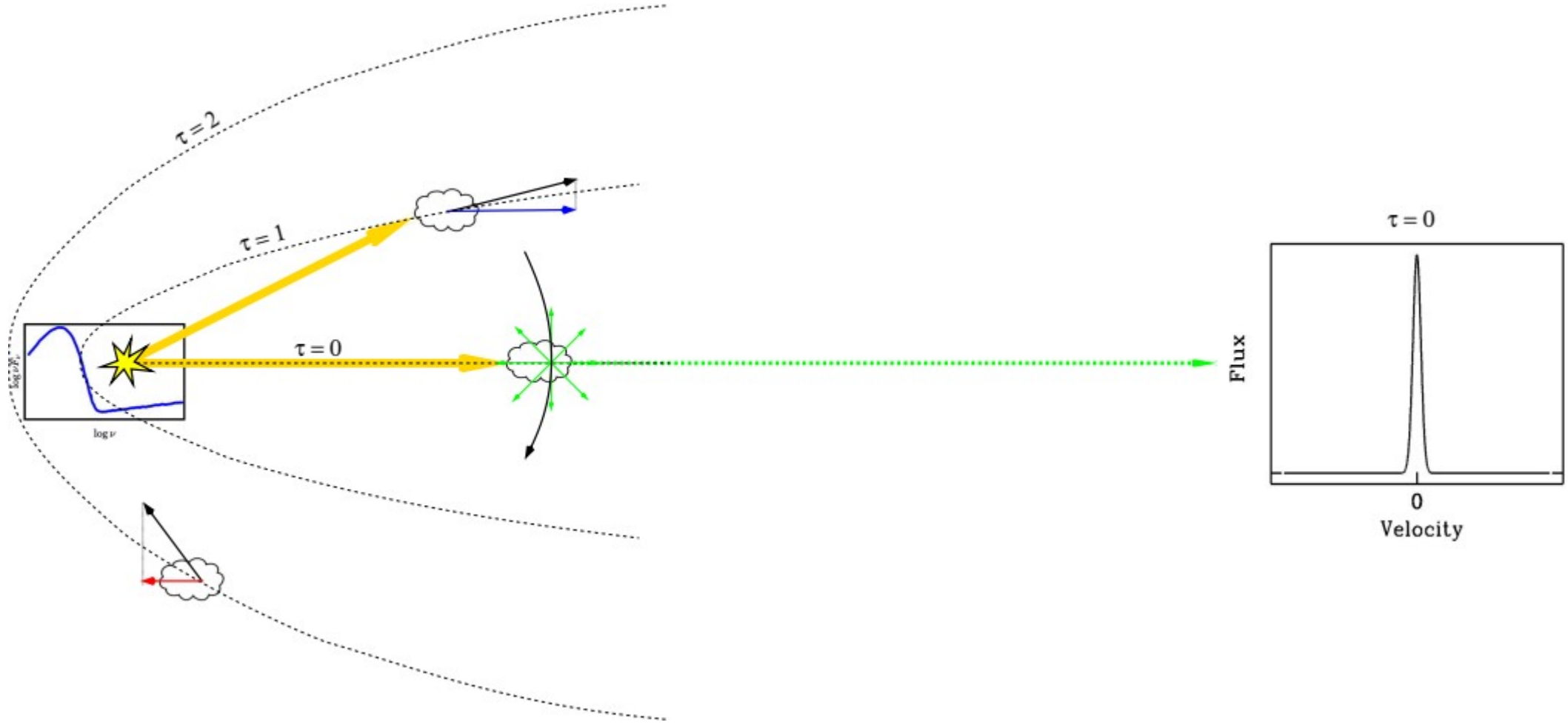
Velocity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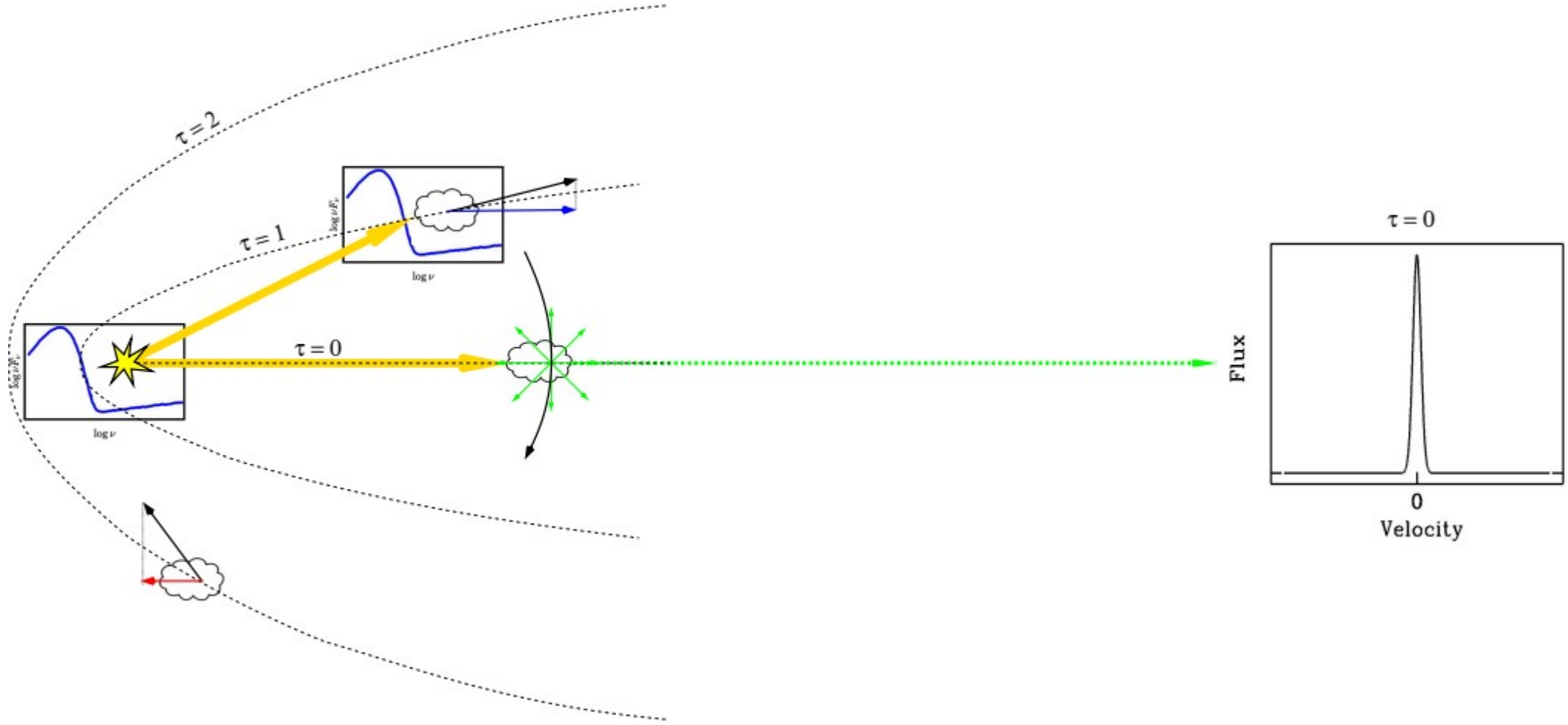
Velocity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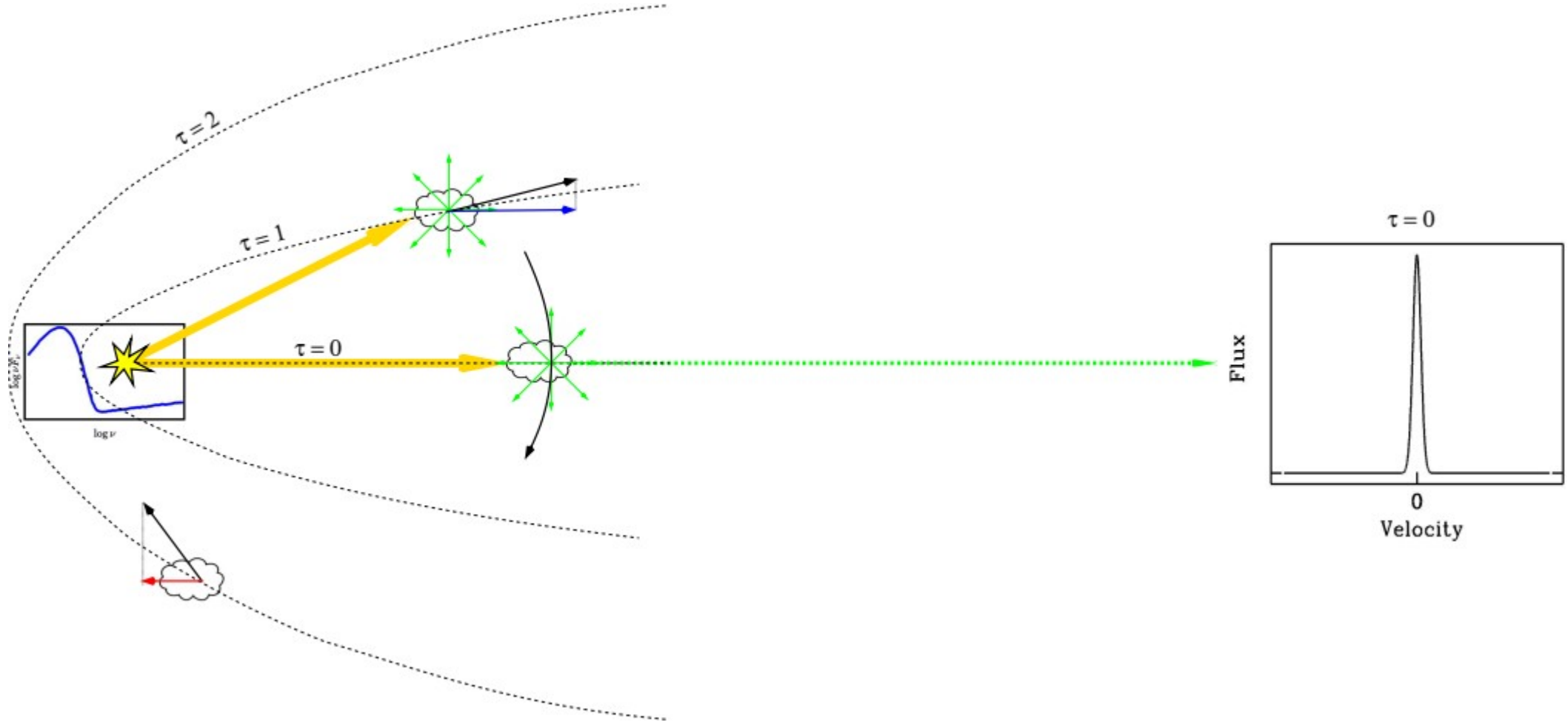
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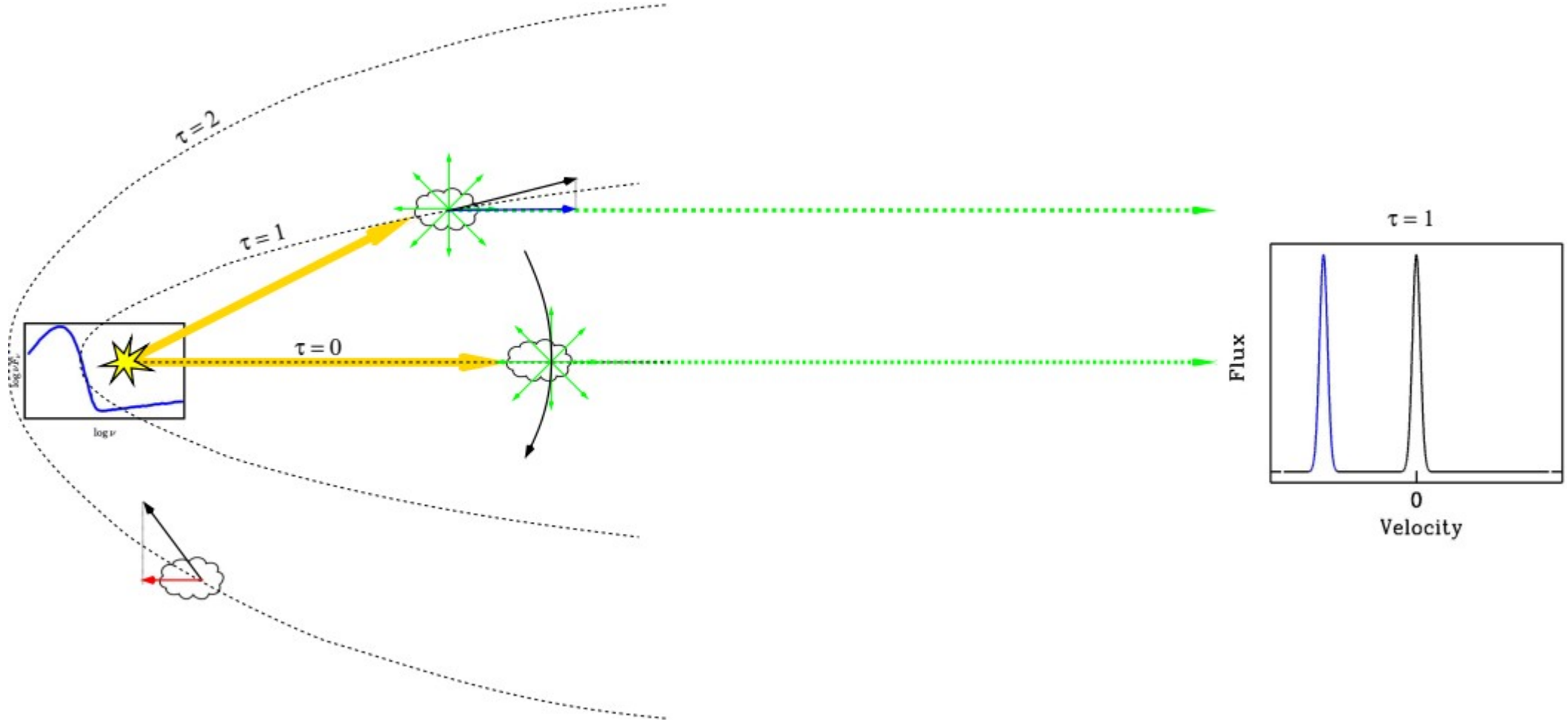
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Flux
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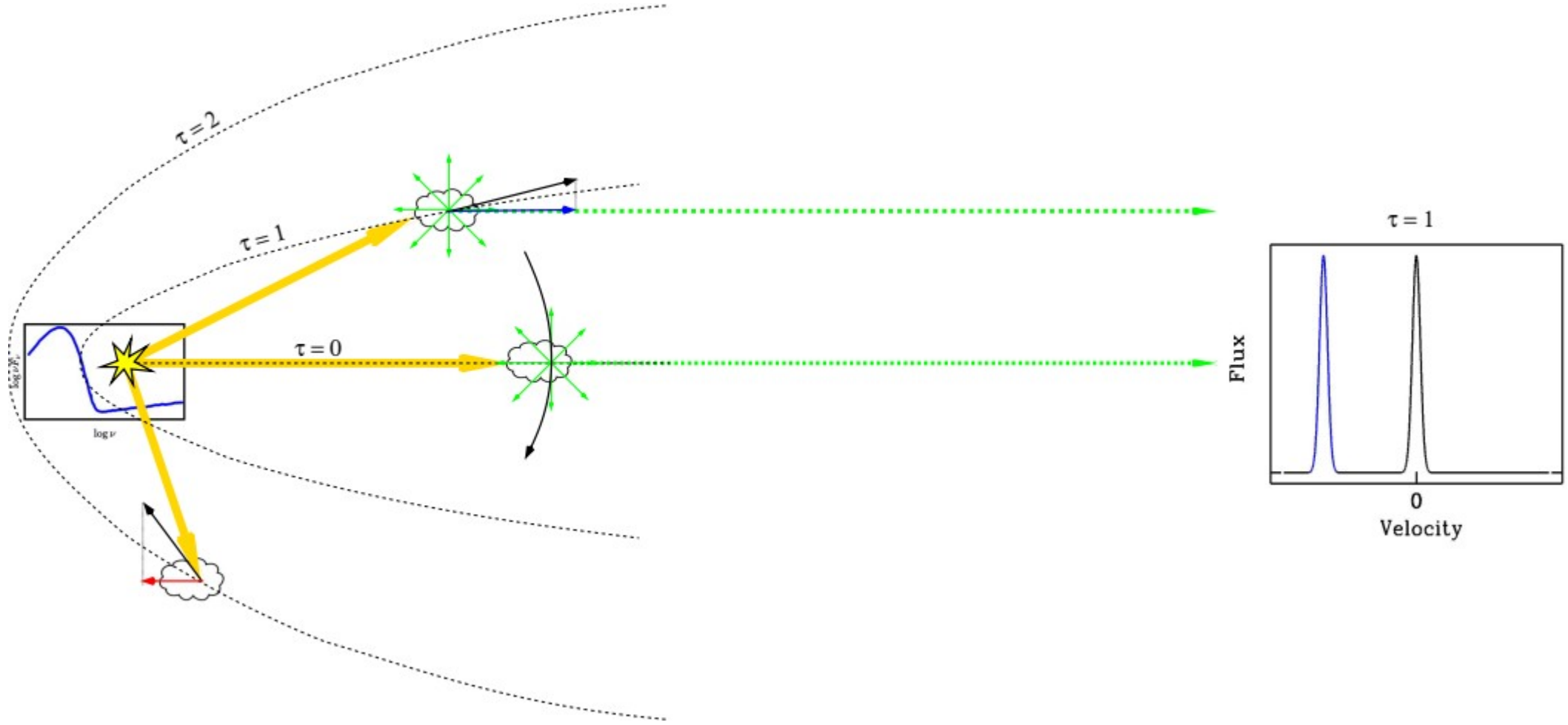
Velocity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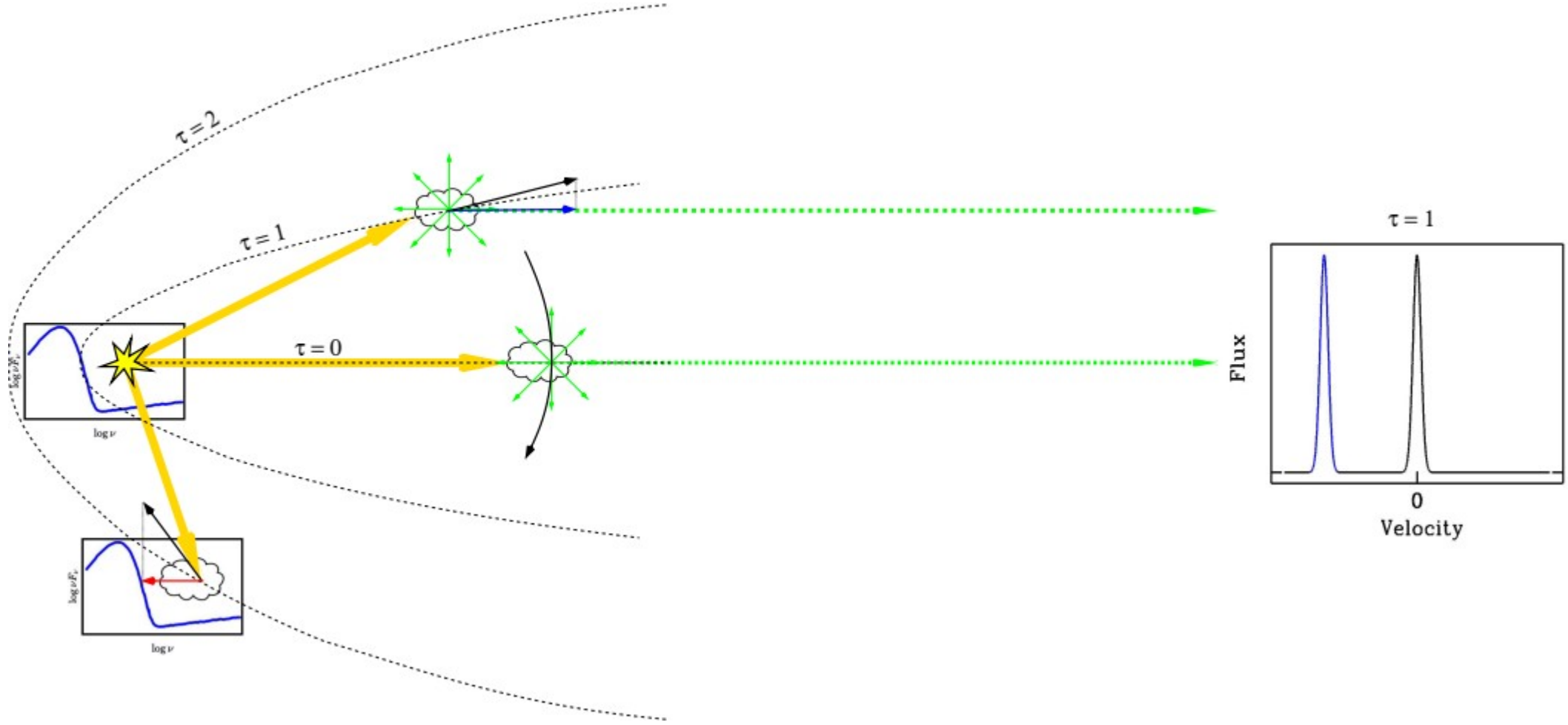
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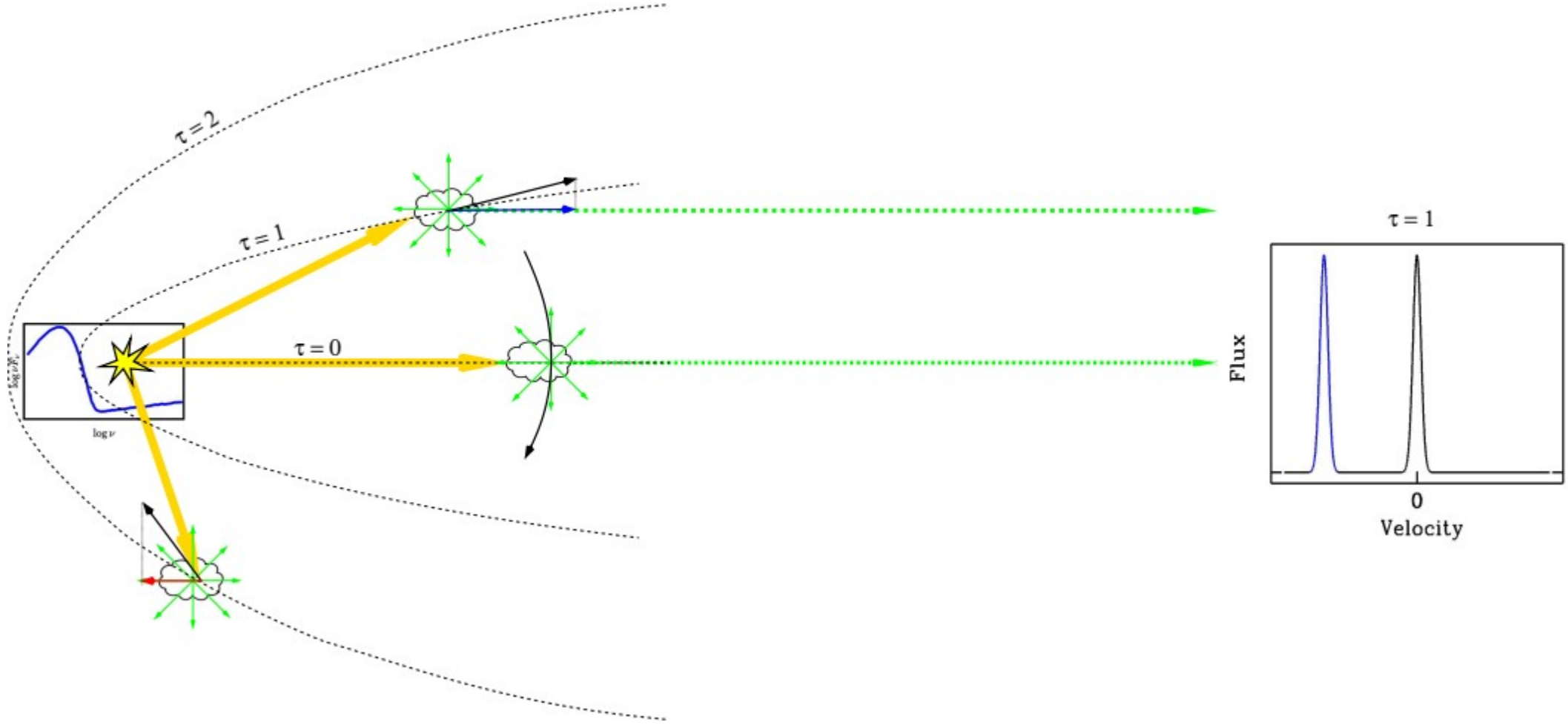
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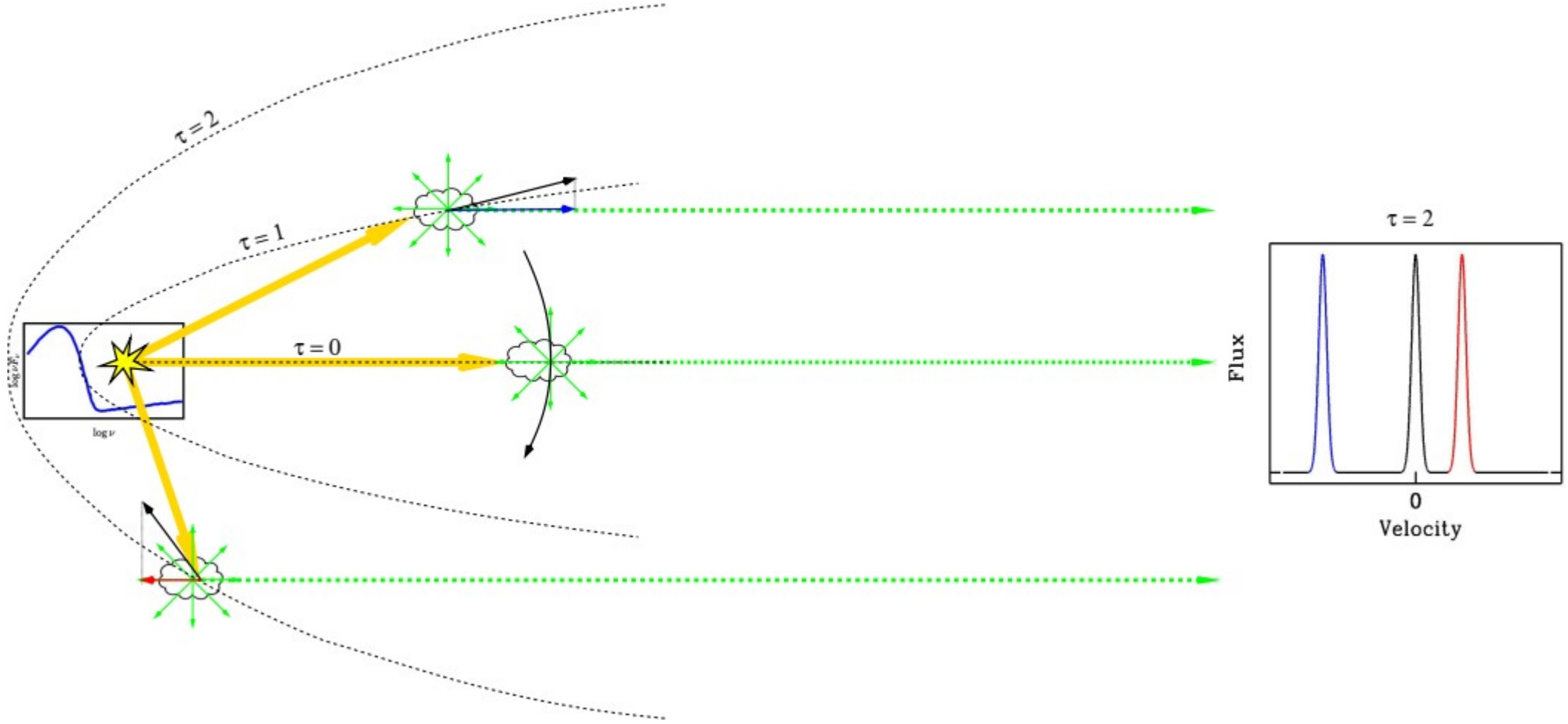
Velocity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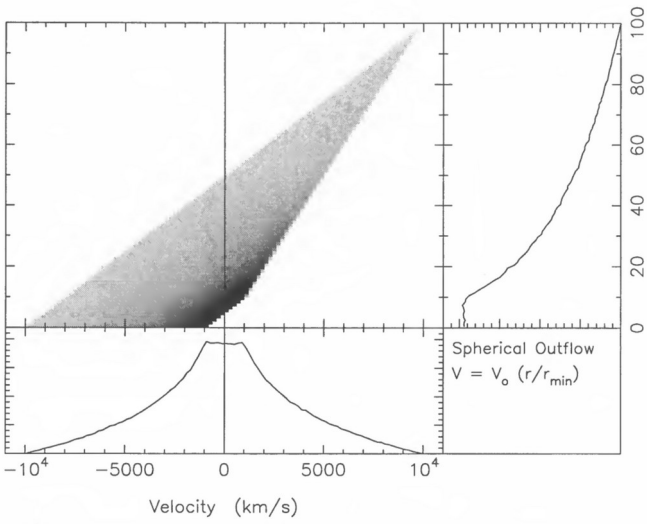
log ν
τ = 2
Flux
0
Velocity

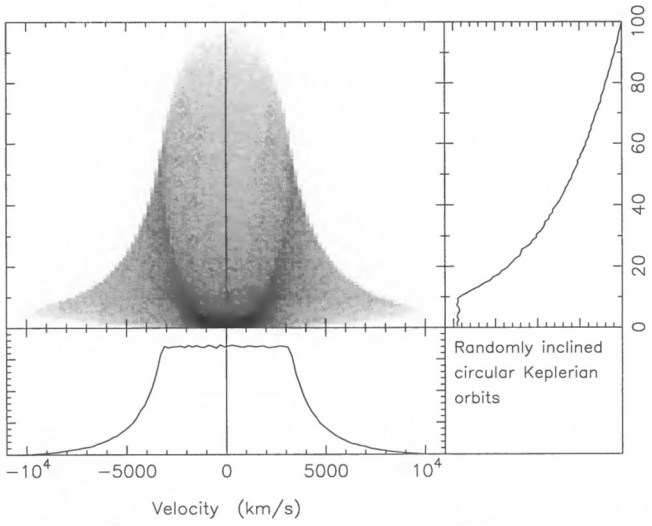
Outflow

blue-leads-red



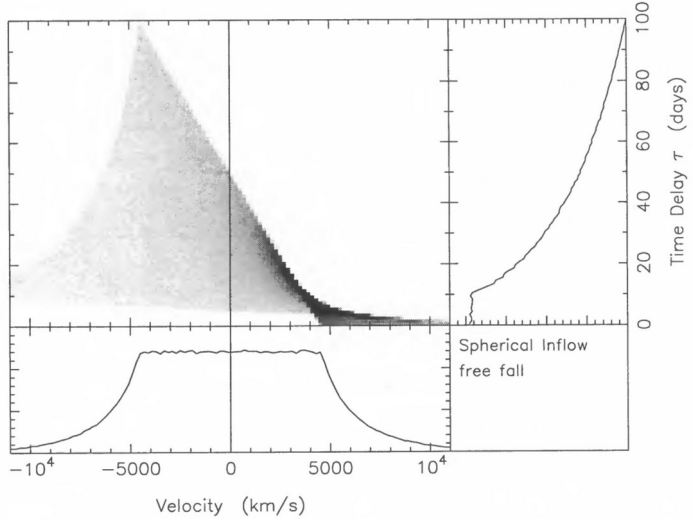
Disk

Symmetric



Inflow

red-leads-blue



Welsh & Horne 1991

(Typical) assumptions

- Linear and/or positive response

- All BLR material sees the same SED (as do we)

- Isotropic line (re-)emission

- Optical tracks driving continuum

- Global BLR properties do not respond to continuum variations

- Linear and/or positive response

  X OBS: non-linear and anomalous line responses

  PHYS: photo-ionization, radiative transfer

- All BLR material sees the same SED (as do we)

  X OBS: BLR “holiday”

  PHYS: (self-)shielding, disk fore-shortening, limb-darkening

- Isotropic line (re-)emission

  X OBS: Strong lines, doubles, black BAL profiles

  PHYS: BLR conditions suggest $\tau \gg 1$

- Optical tracks driving continuum

  X OBS: continuum reverberation time-scales

  PHYS: (self-)shielding, multiple components (disk vs corona, soft X-ray excess)

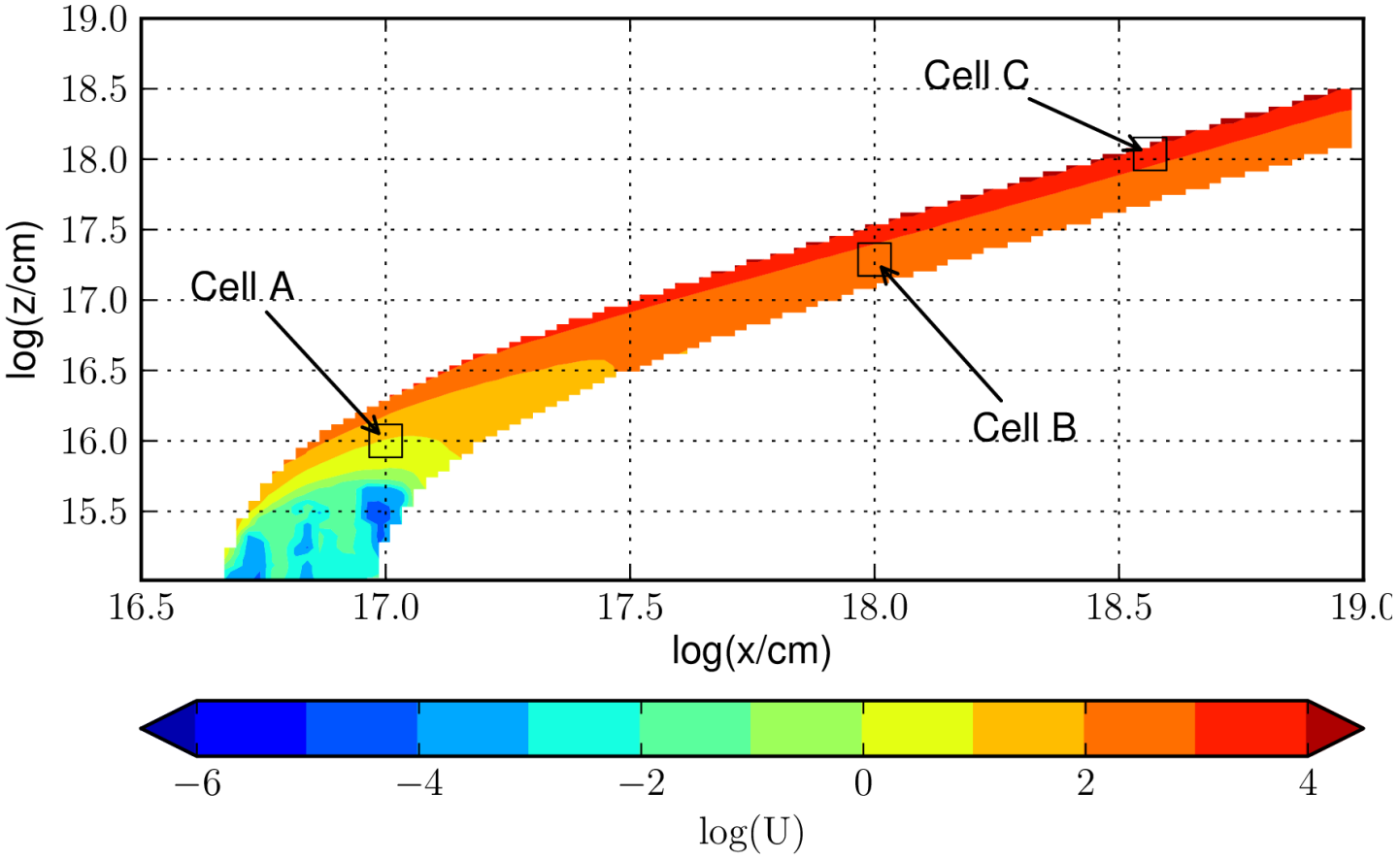
- Global BLR properties do not respond to continuum variations

  X OBS: line-locking, ghost of Lyman alpha

  PHYS: radiation pressure

Assumptions are made to be broken

Example: the SED in rotating disk winds



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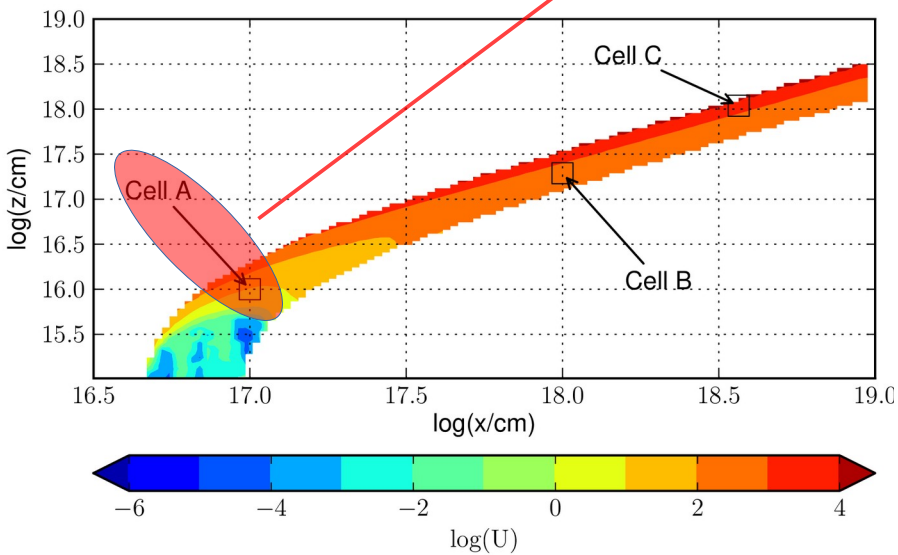

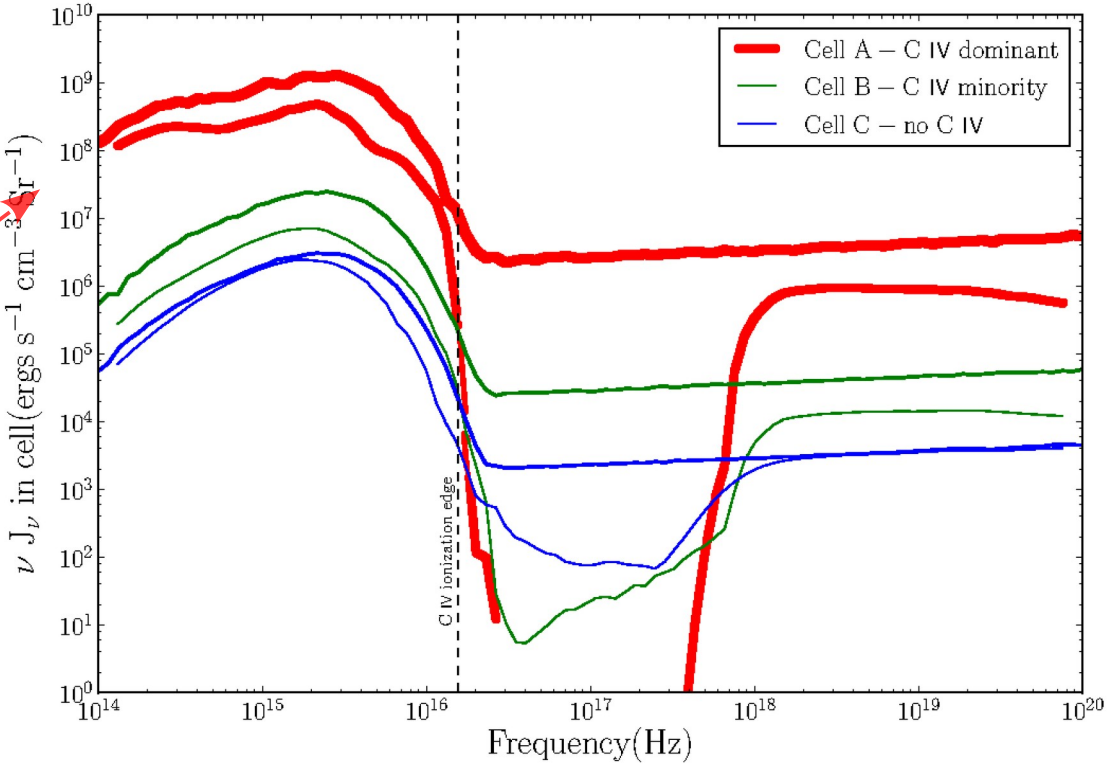

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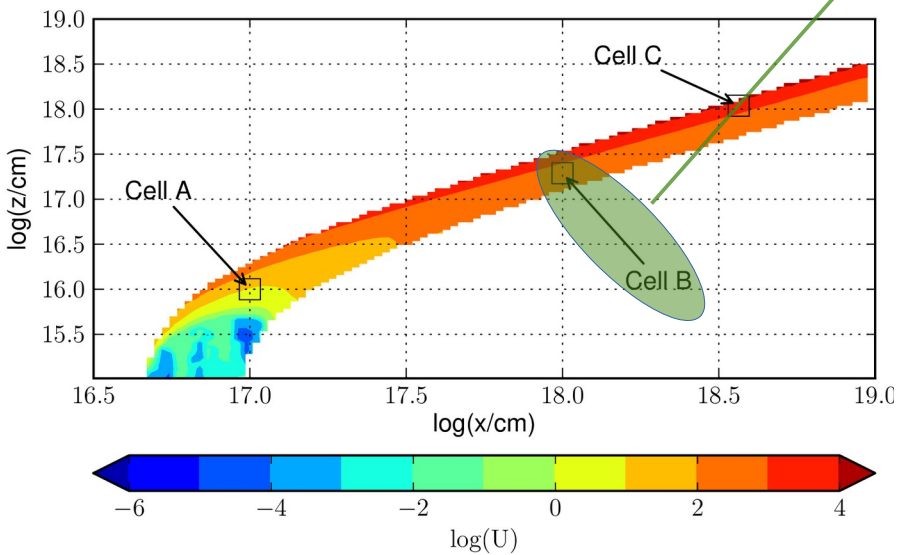

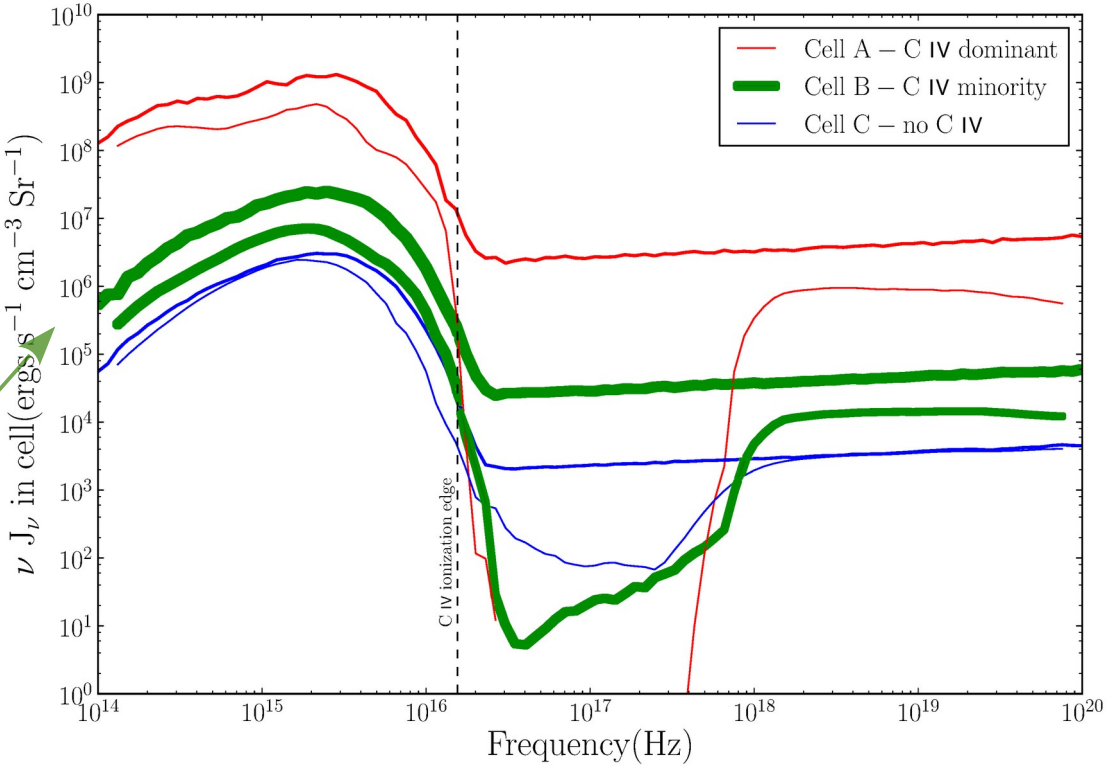

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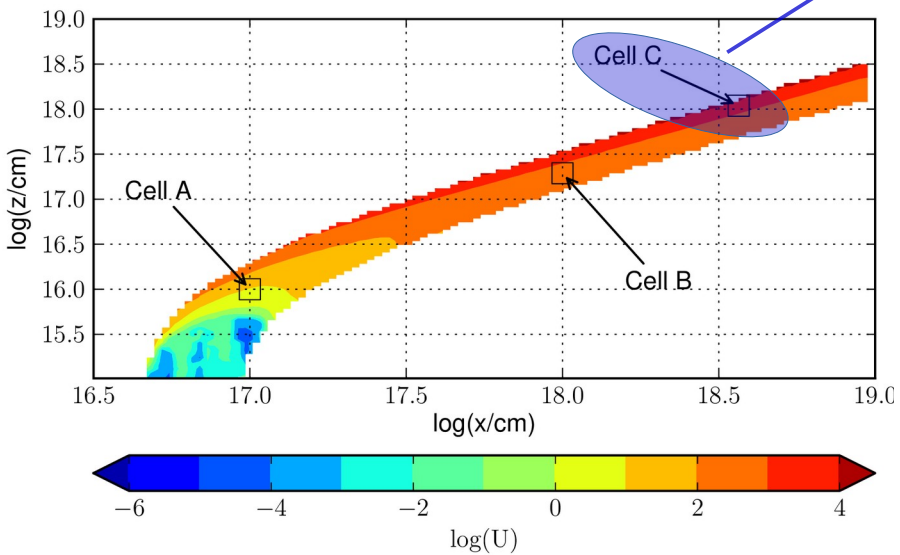
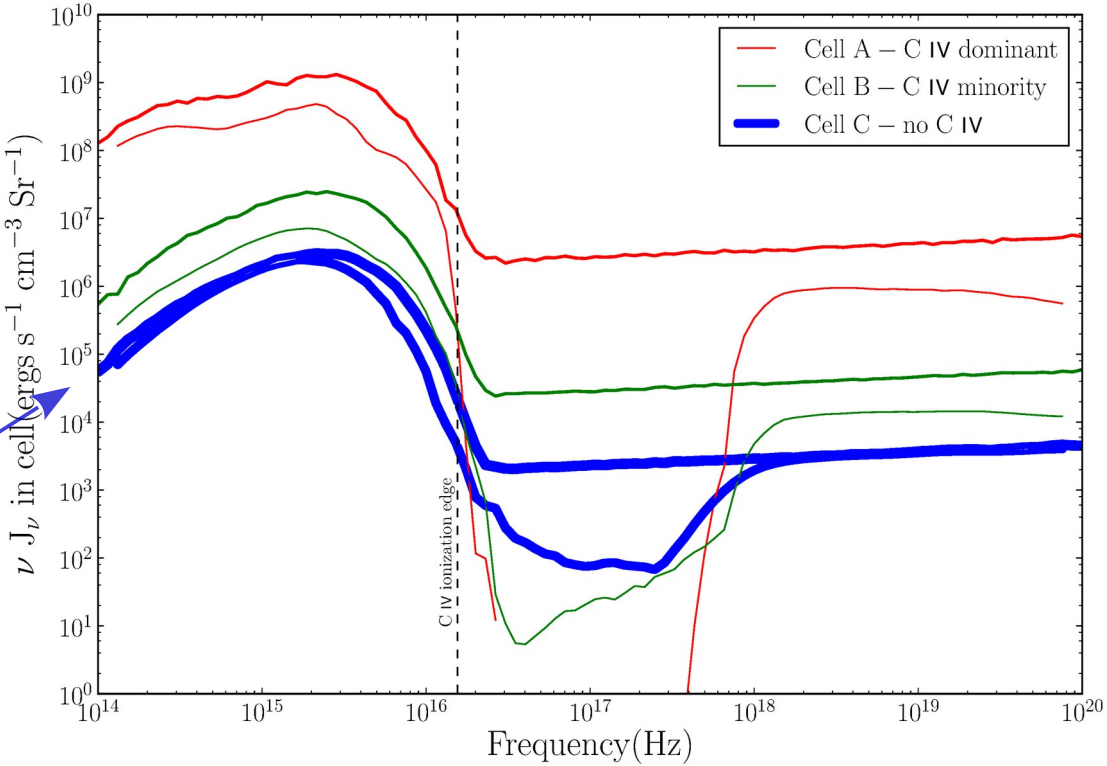




Higginbottom+13

The reverberation signatures of rotating disk winds

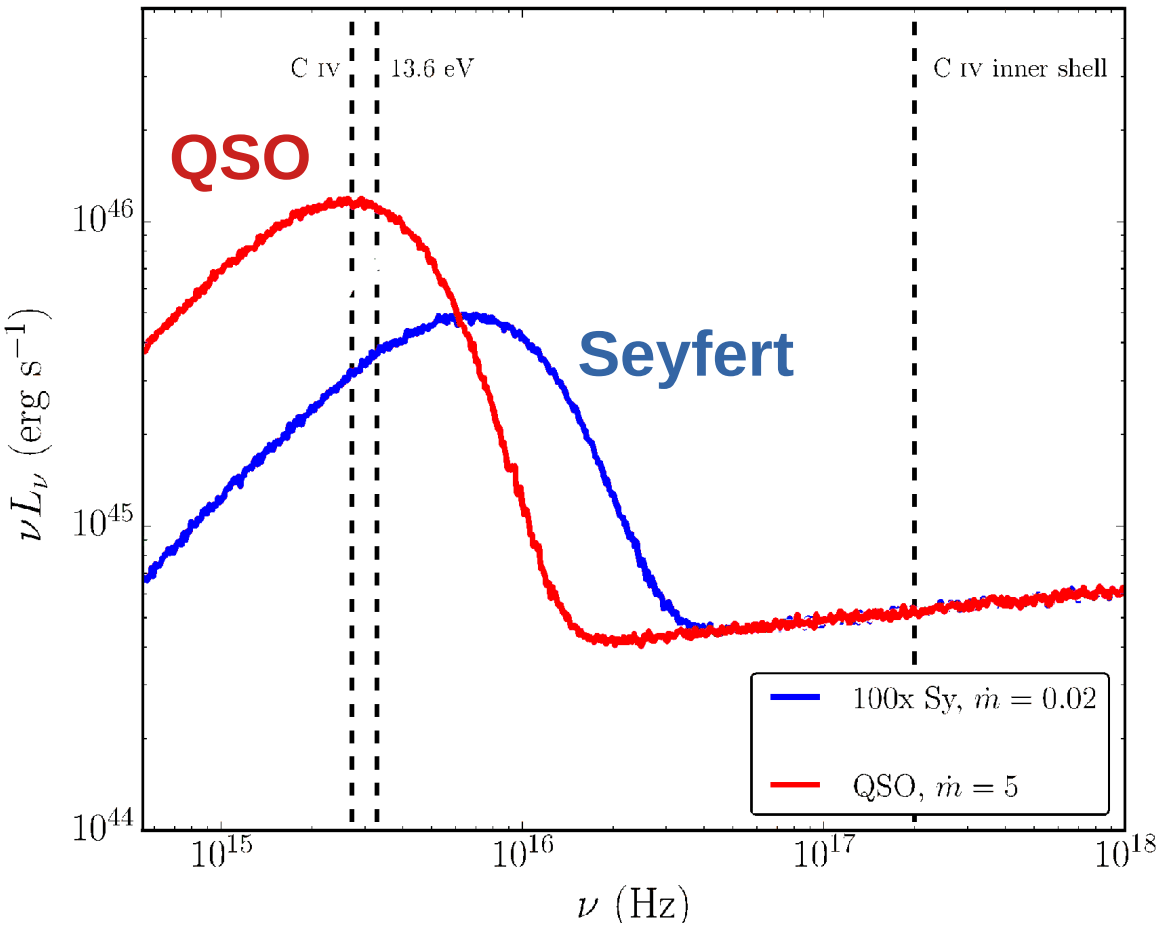
Self-consistent response functions for QSOs and Seyferts

Parameter	Symbol, units	Seyfert	QSO
SMBH mass	$M_{\rm BH}$, $M_\odot$	10^7	10^9
Accretion rate	$\dot{M}_{\rm acc}$, $M_\odot\ yr^{-1}$	0.02	5
	$\dot{m}_{\rm acc}$, $\dot{M}_{\rm Edd}$	≈ 0.1	≈ 0.2

Mangham+17

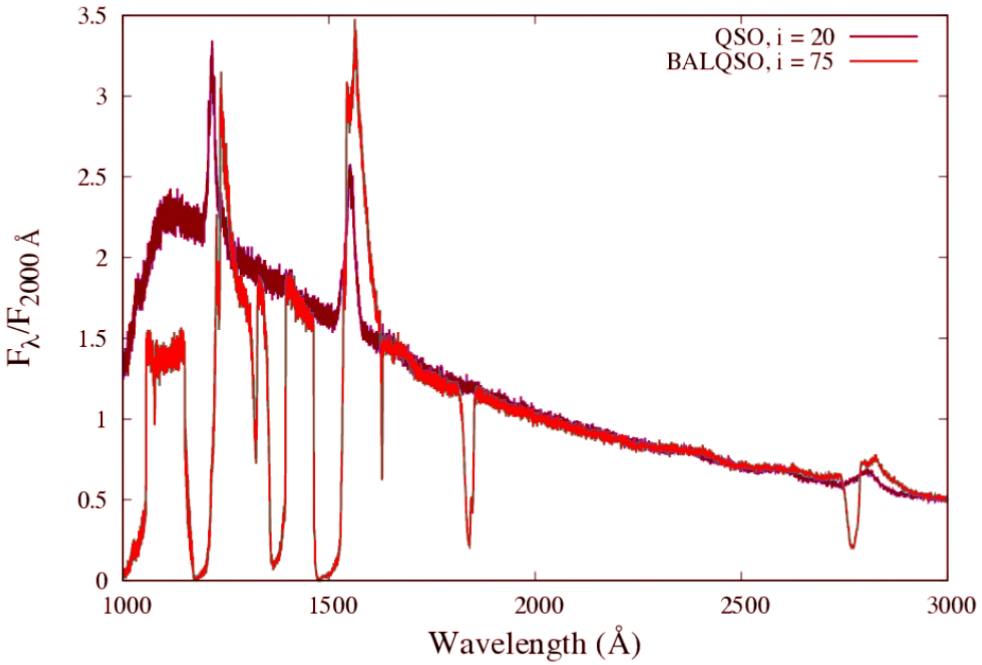
Parameter	Symbol, units	Seyfert	QSO
SMBH mass	$M_{\rm BH}$, $M_\odot$	10^7	10^9
Accretion rate	$\dot{M}_{\rm acc}$, $M_\odot\ yr^{-1}$	0.02	5
	$\dot{m}_{\rm acc}$, $\dot{M}_{\rm Edd}$	≈ 0.1	≈ 0.2
X-ray source radius	r_X, r_g	6	6
	r_X, cm	8.8×10^{12}	8.8×10^{14}
Accretion disc radii	$r_{\rm disc}$(min)	r_X	r_X
	$r_{\rm disc}$(max), r_g	3400	3400
	$r_{\rm disc}$(max), cm	5×10^{15}	5×10^{17}

Mangham+17

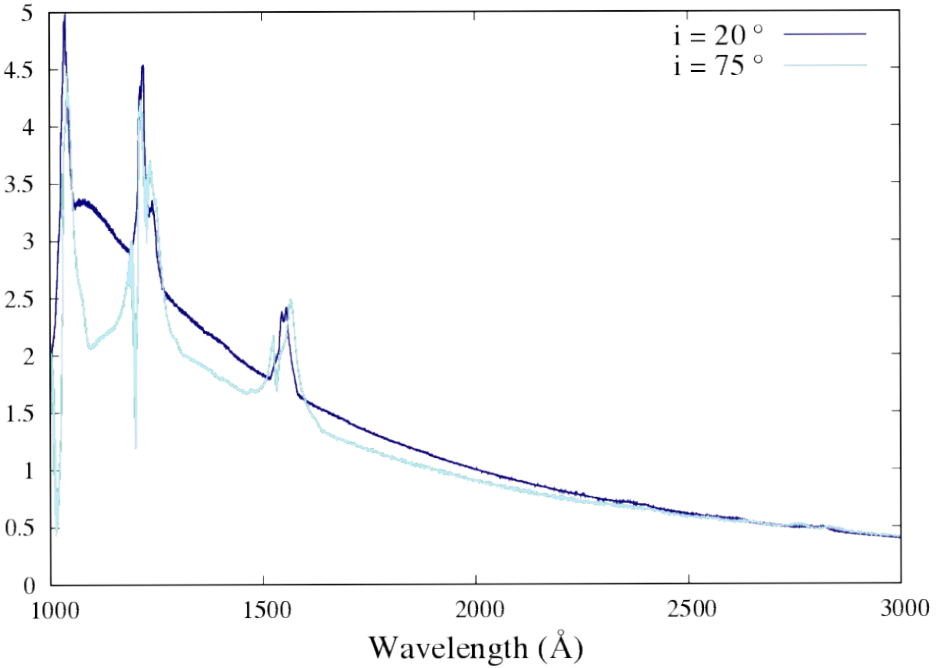

C IV
13.6 eV
C IV inner shell
QSO
Seyfert
10^{46}
10^{45}
10^{44}
νL_ν (erg s^{-1})
10^{15}
10^{16}
10^{17}
10^{18}
ν (Hz)
100x Sy, $\dot{m} = 0.02$
QSO, $\dot{m} = 5$

Mangham+17

QSO



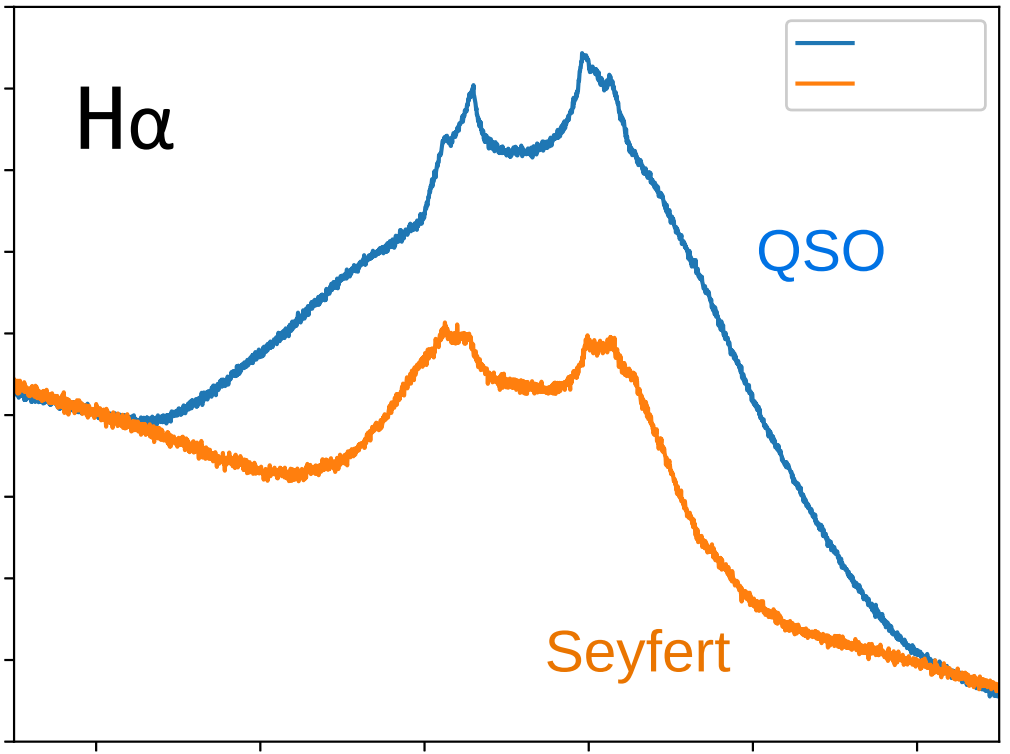
Seyfert



Mangham+17

Take-home points

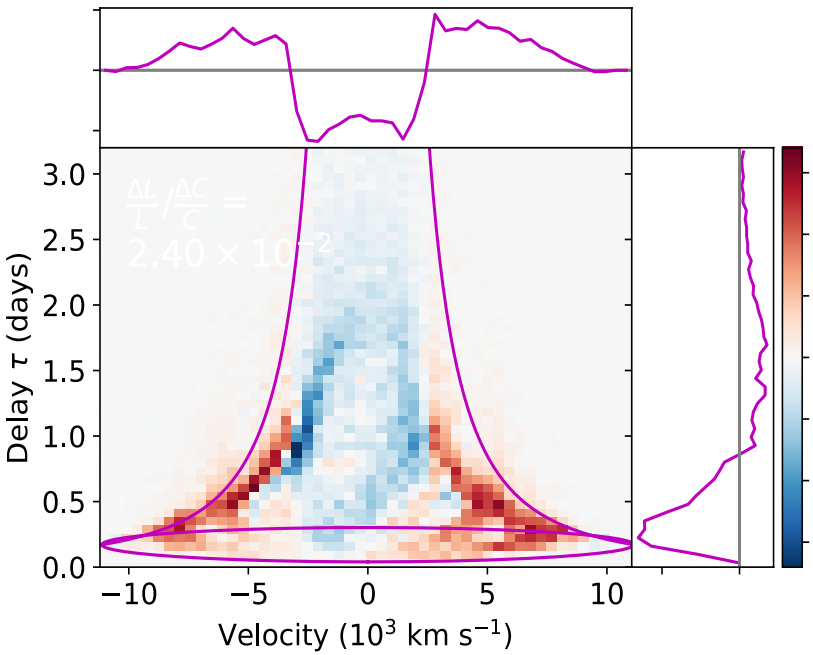
- What would a disk wind model predict for *<insert your favourite observable>*? → PYTHON!
- **Disk winds may naturally explain the (near) absence of BALs in Seyferts**



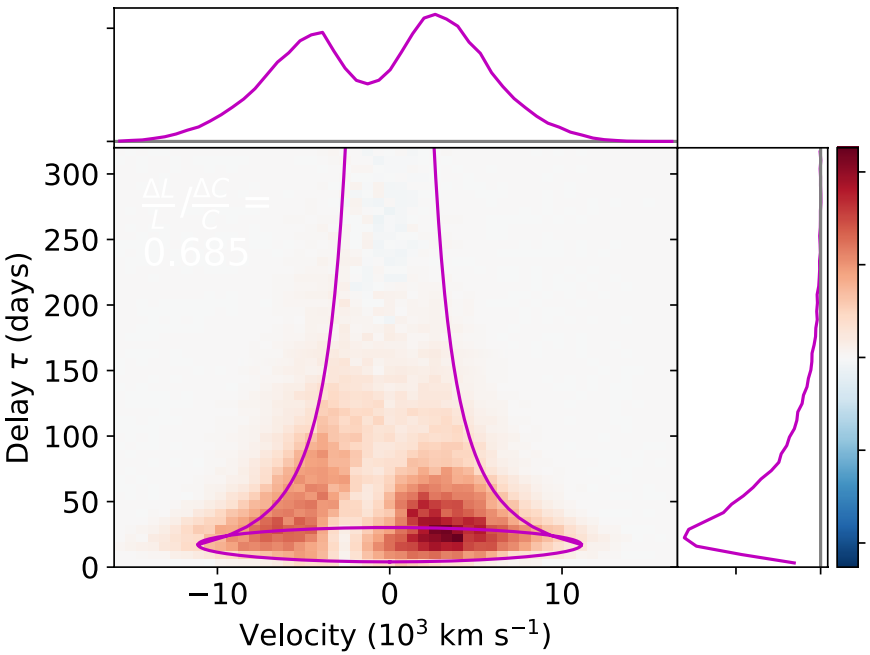
Mangham+17

Predicted response functions

Seyfert

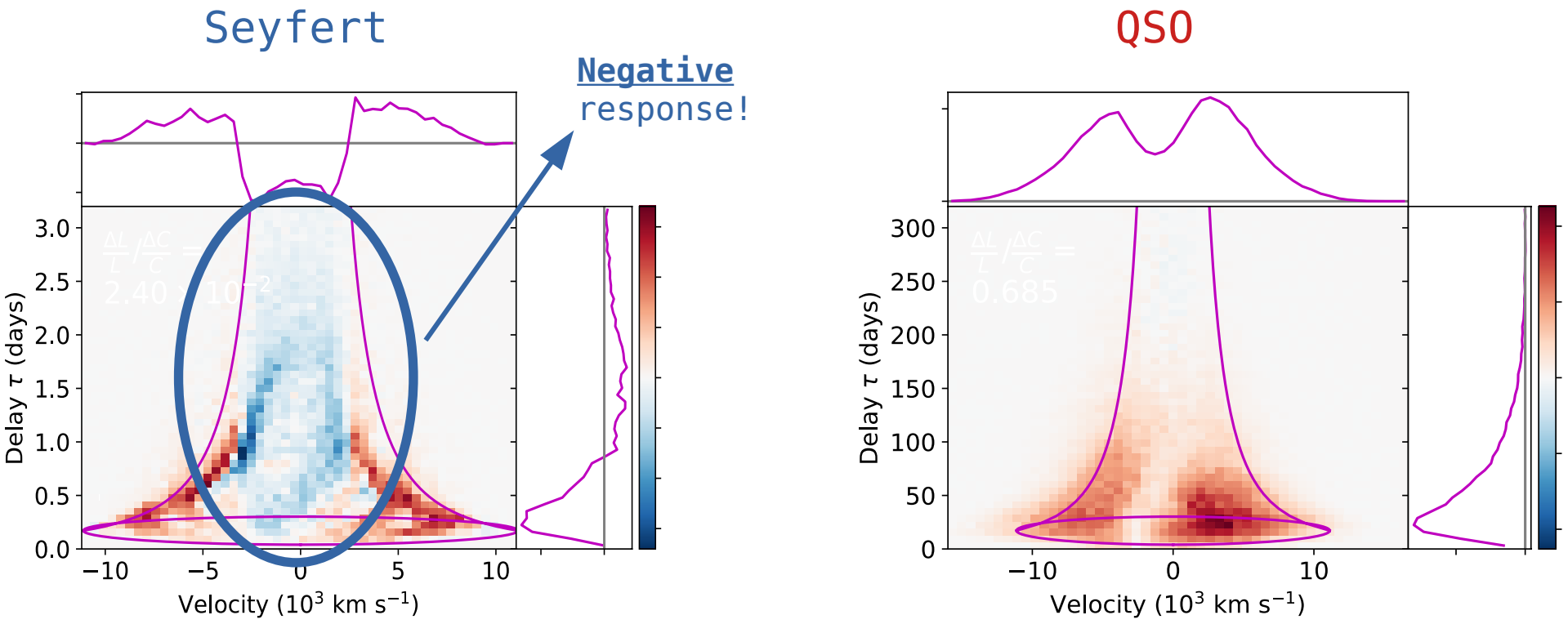


QSO



Mangham+17

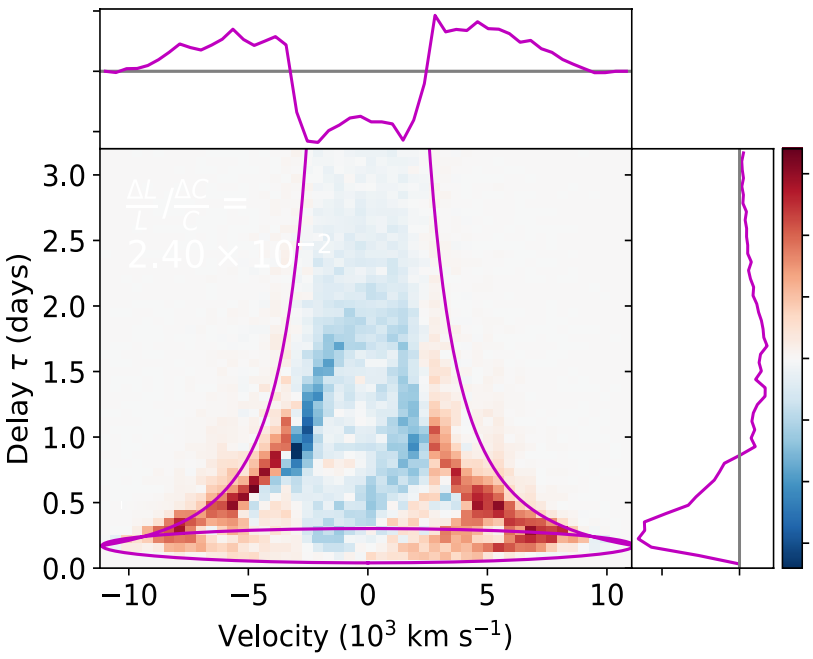
Predicted response functions



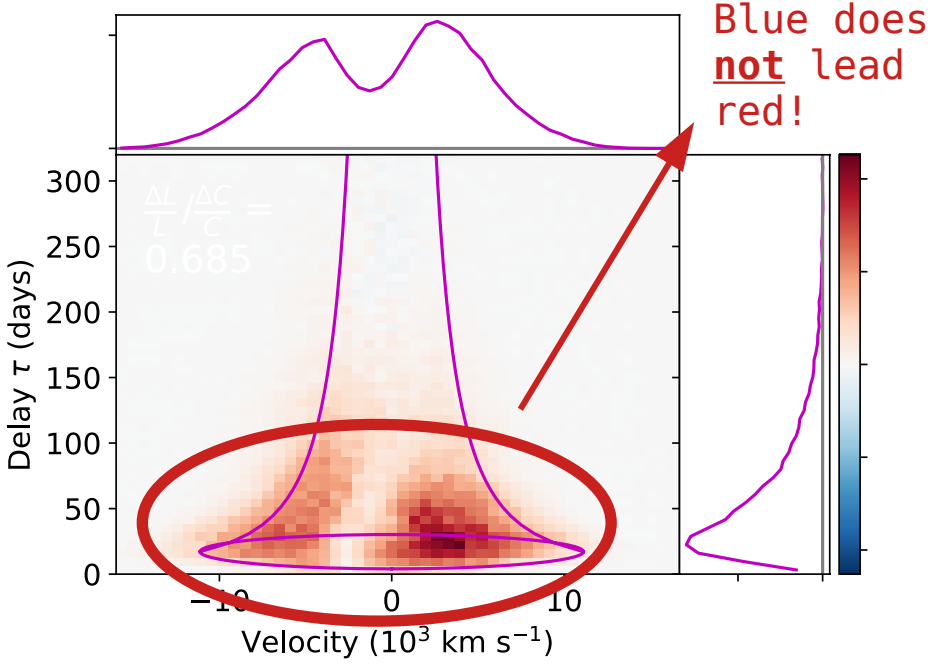
Mangham+17

Predicted response functions

Seyfert



QSO



Mangham+17

Take-home points

- What would a disk wind model predict for *<insert your favourite observable>*? → PYTHON!
- Disk winds may naturally explain the (near) absence of BALs in Seyferts
- **Disk wind response functions do <u>not</u> always show blue-leads-red signatures**
- **Line response can be <u>negative</u> across significant parts of τ-v space**

A blind test of reverberation mapping methods

Are we recovering correct BLR properties from RM campaigns?

All plots from Mangham+19

= Mangham, Knigge, Williams, Horne, Pancoast, Matthews, Long, Sim & Higginbottom 2019, MNRAS 488 2780

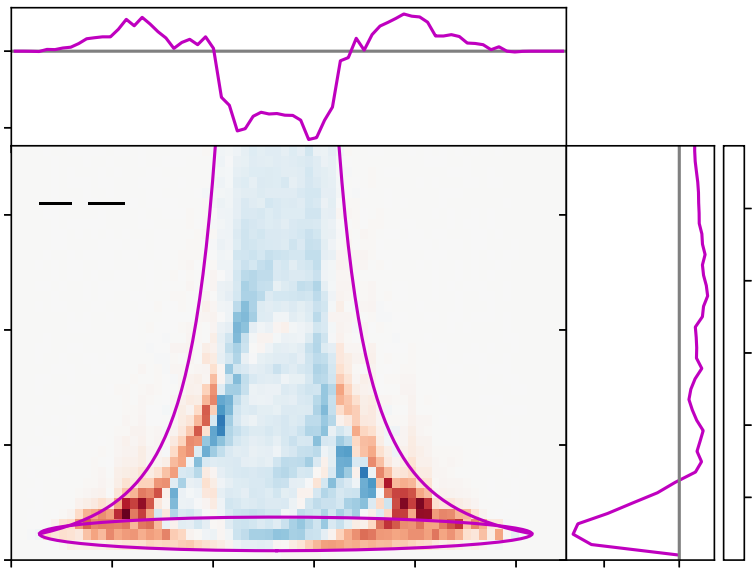
ArXiv:1906.11272

Generating mock data

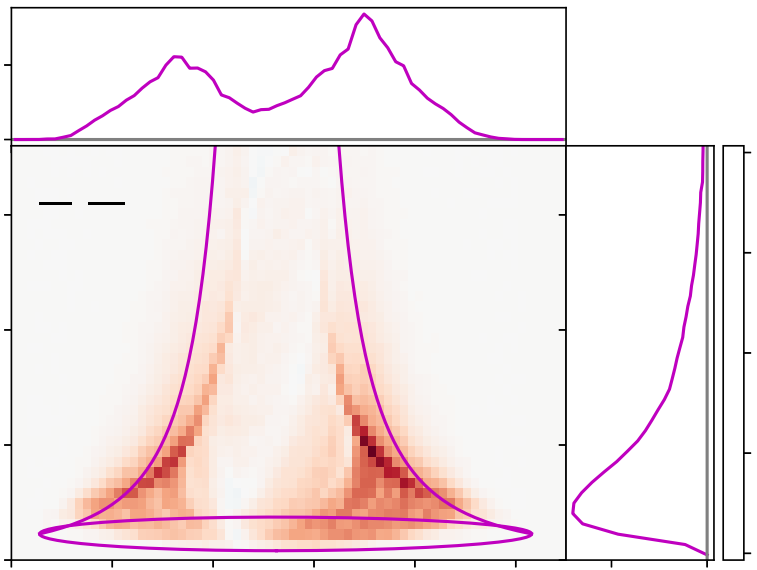
Input #1:

(Rescaled) Seyfert and QSO response functions

Seyfert

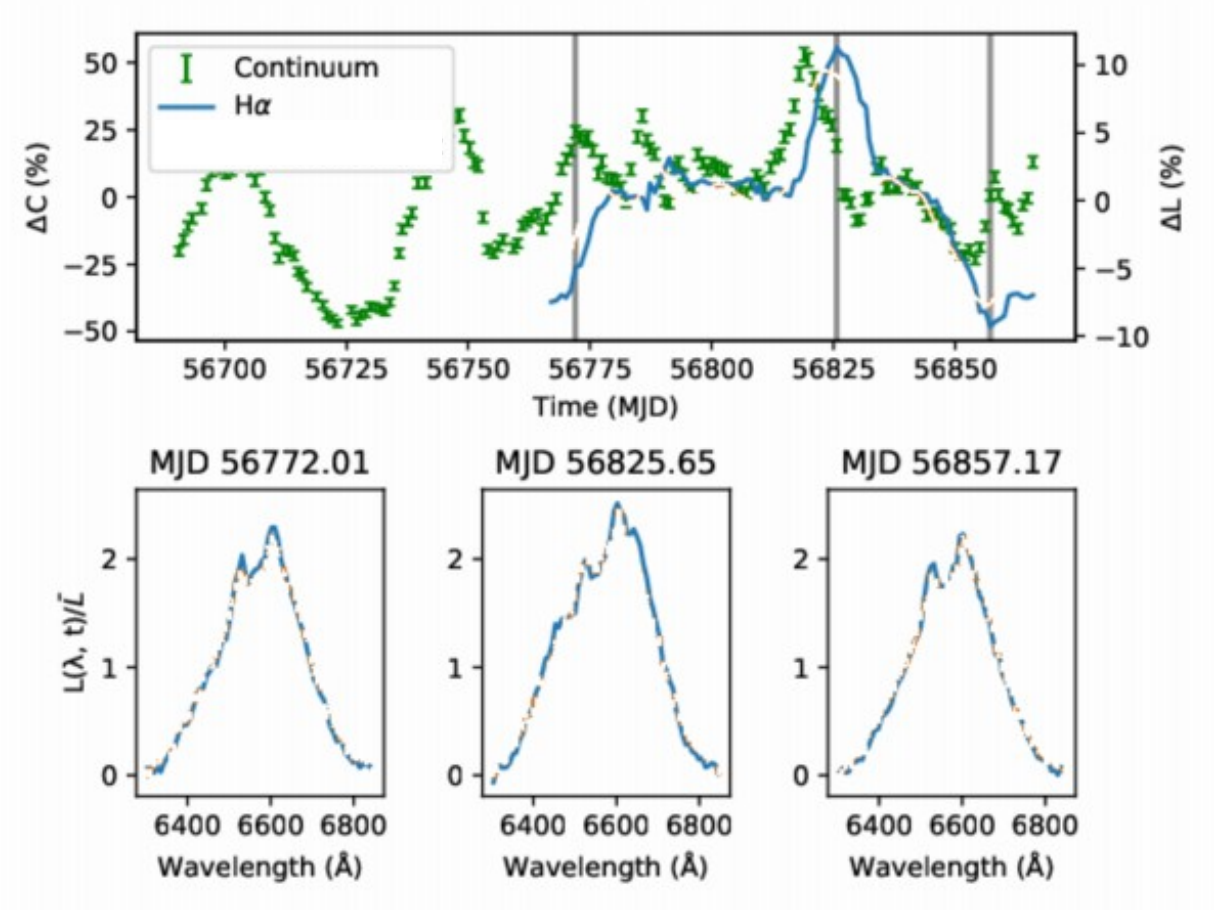


QSO



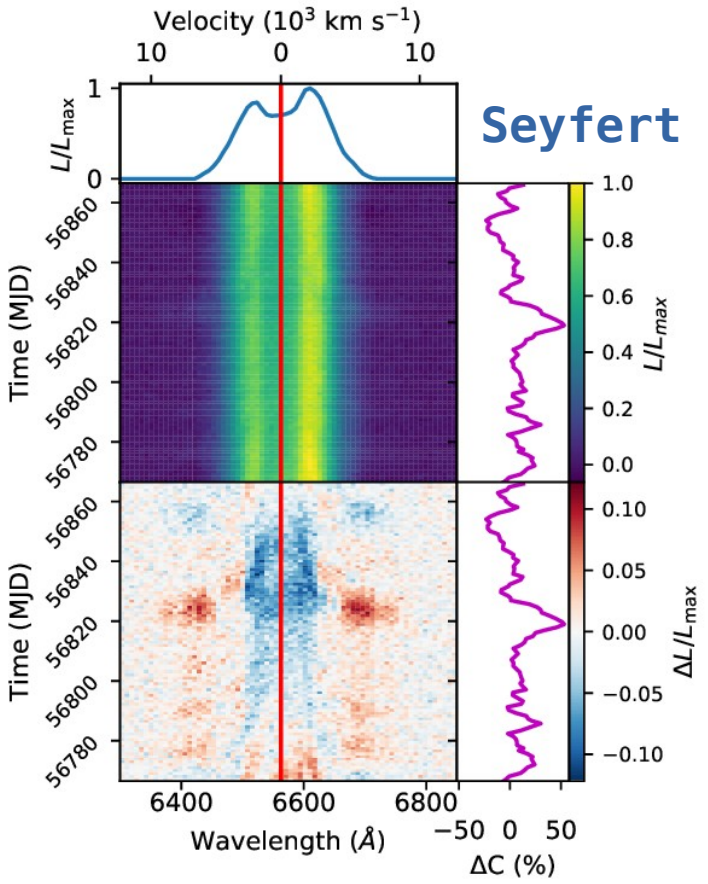
Input #2:

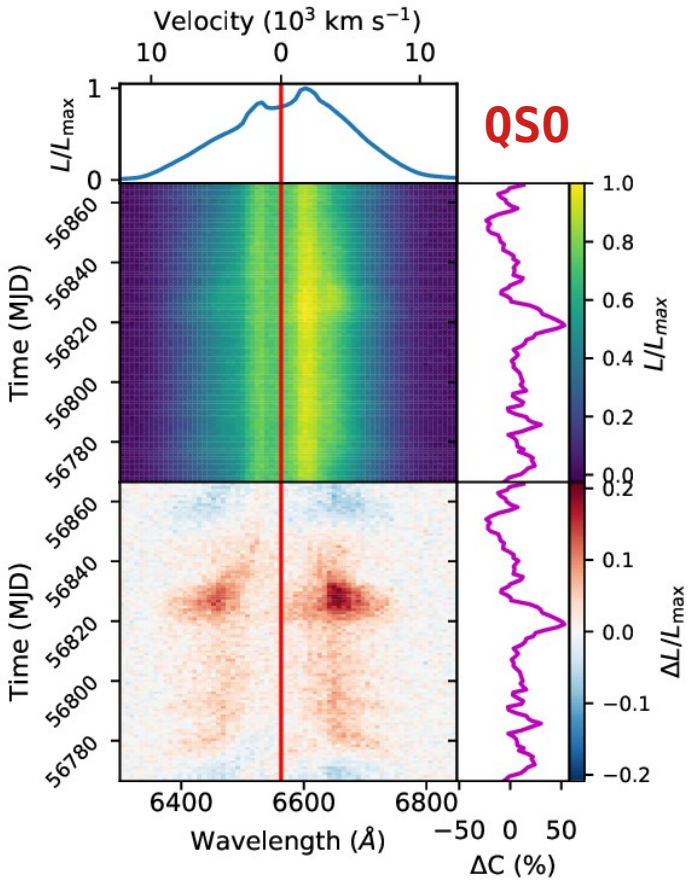
AGNStorm continuum (driving) light curve



Output:

Predicted spectroscopic time series (+noise)





Recovery methods

- MEMEcho
  - Developers:
    - Keith Horne
  - Approach:
    - Maximum entropy inversion
  - Output:
    - Velocity-delay map
  - Assumptions:
    - Linearized, positive response
    - Smoothness

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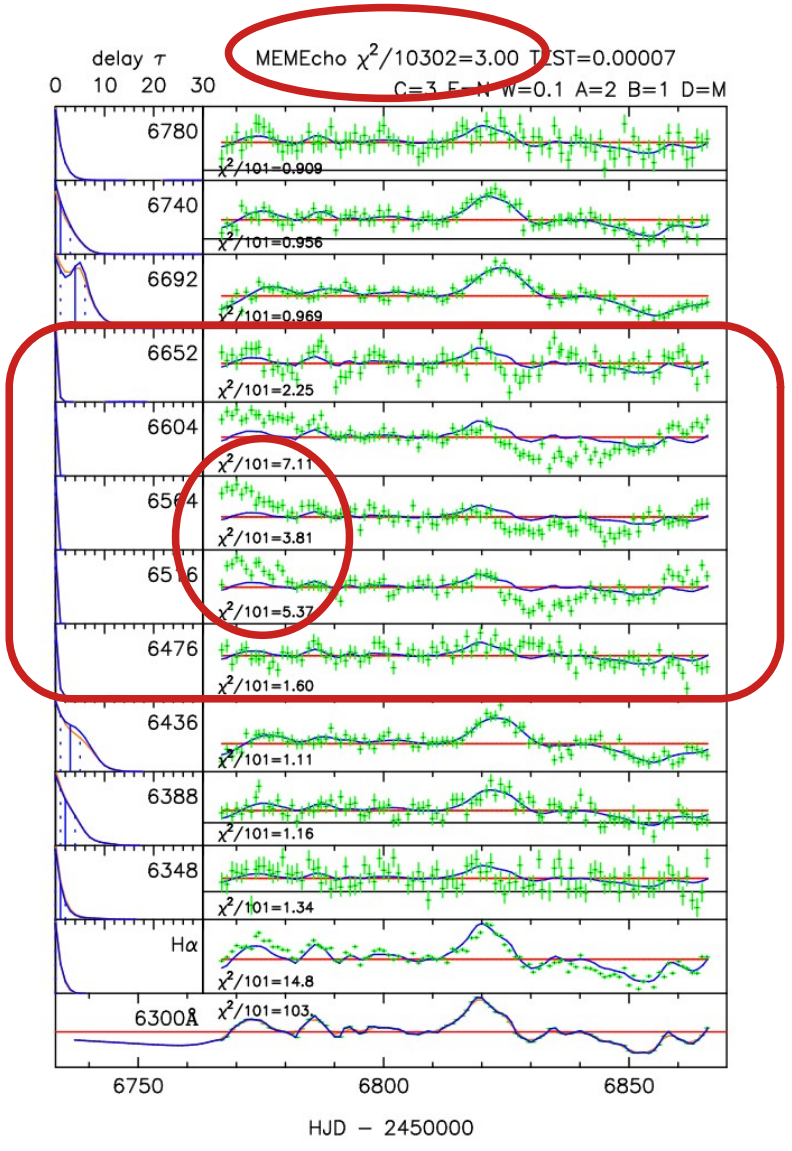
  - Developers:
    - Keith Horne
  - Approach:
    - Maximum entropy inversion
  - Output:
    - Velocity-delay map
  - Assumptions:
    - Linearized, positive response
    - Smoothness

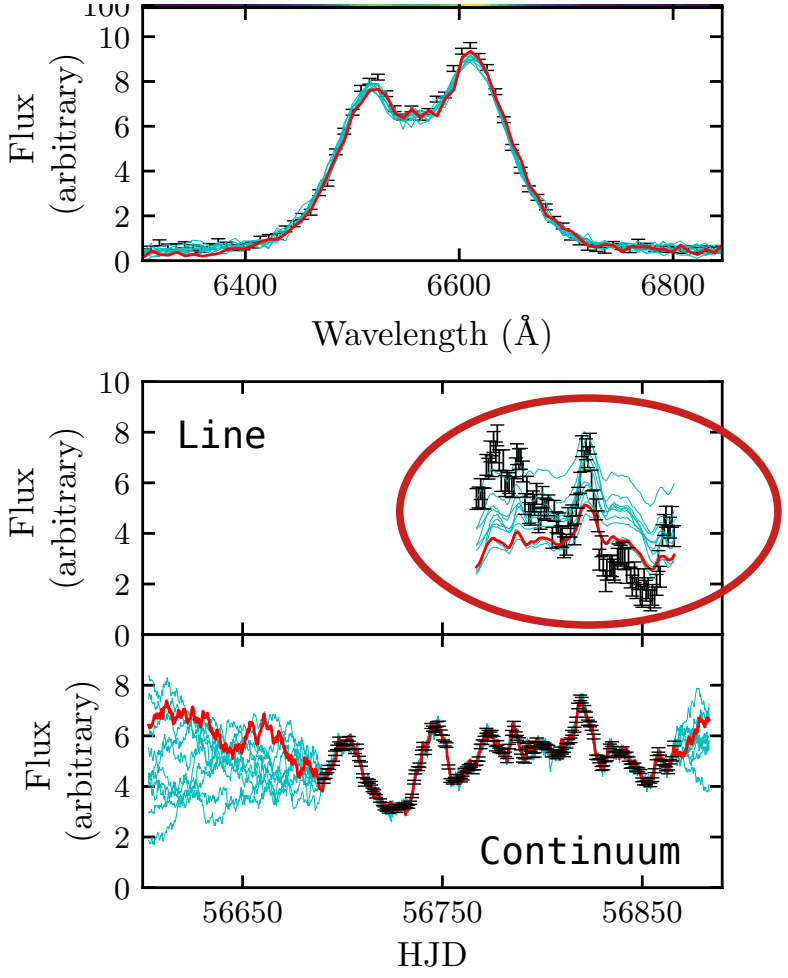
- CARAMEL
  - Developers:
    - Anna Pancoast & Peter Williams
  - Approach:
    - Cloud-based forward modelling
  - Output:
    - Model parameter distributions
  - Assumptions:
    - Linear, positive response
    - Geometric/kinematic framework

Results

The Seyfert model



- MEMEcho
  - No acceptable fits
  - Caused by negative line-centre response
  - “Graceful failure”
    - No incorrect inference



- CARAMEL
  - No acceptable fits
  - Caused by negative line-centre response
  - “Graceful failure”
    - No incorrect inference

Take-home points

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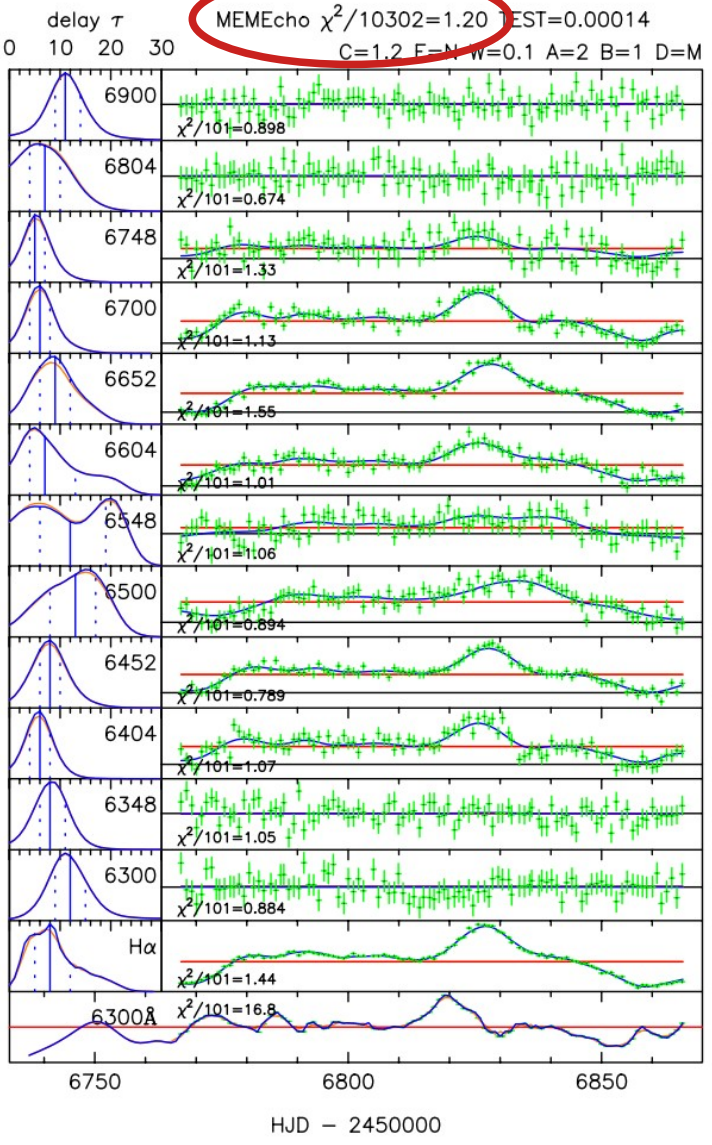
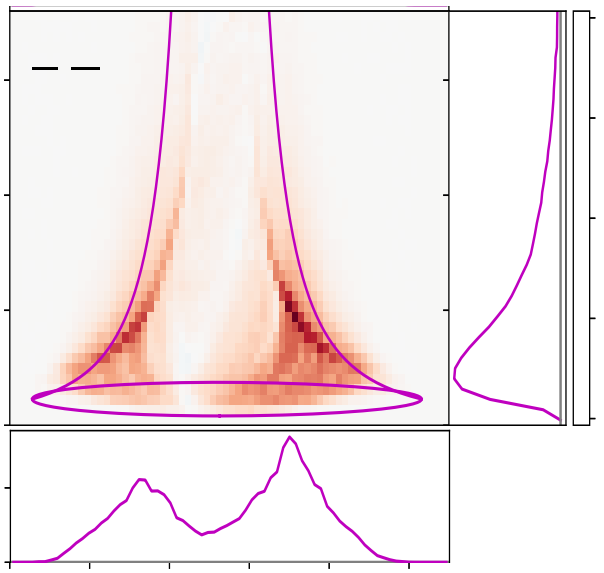
Results

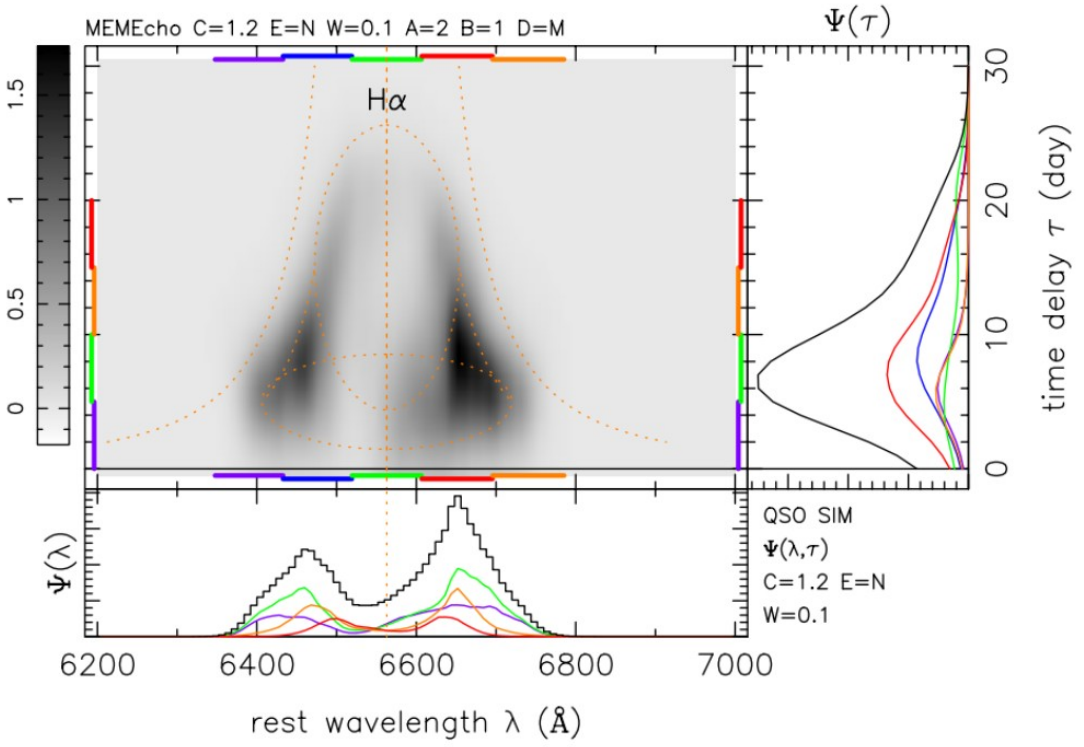
The QSO model with MEMEcho


delay τ
0 10 20 30
MEMEcho χ²/10302=1.20 TEST=0.00014
C=1.2 F=N W=0.1 A=2 B=1 D=M
6900
χ²/101=0.898
6804
χ²/101=0.674
6748
χ²/101=1.33
6700
χ²/101=1.13
6652
χ²/101=1.55
6604
χ²/101=1.01
6548
χ²/101=1.06
6500
χ²/101=0.894
6452
χ²/101=0.789
6404
χ²/101=1.07
6348
χ²/101=1.05
6300
χ²/101=0.884
Hα
χ²/101=1.44
6300Å
χ²/101=16.8
6750
6800
6850
HJD − 2450000

PYTHON ground truth

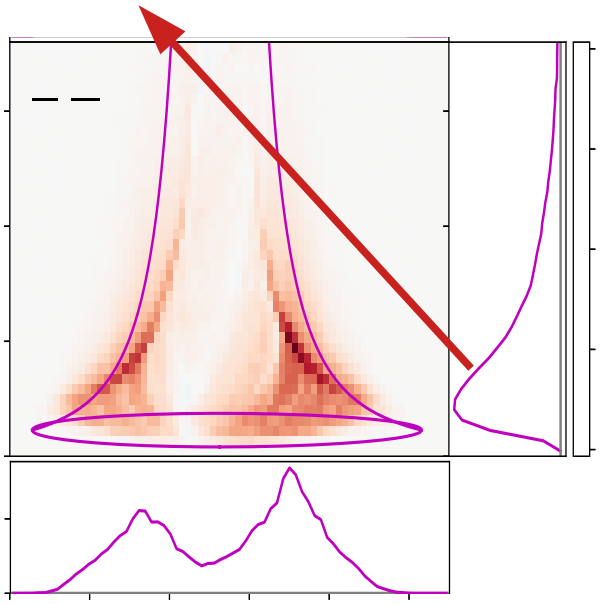


MEMEcho reconstruction



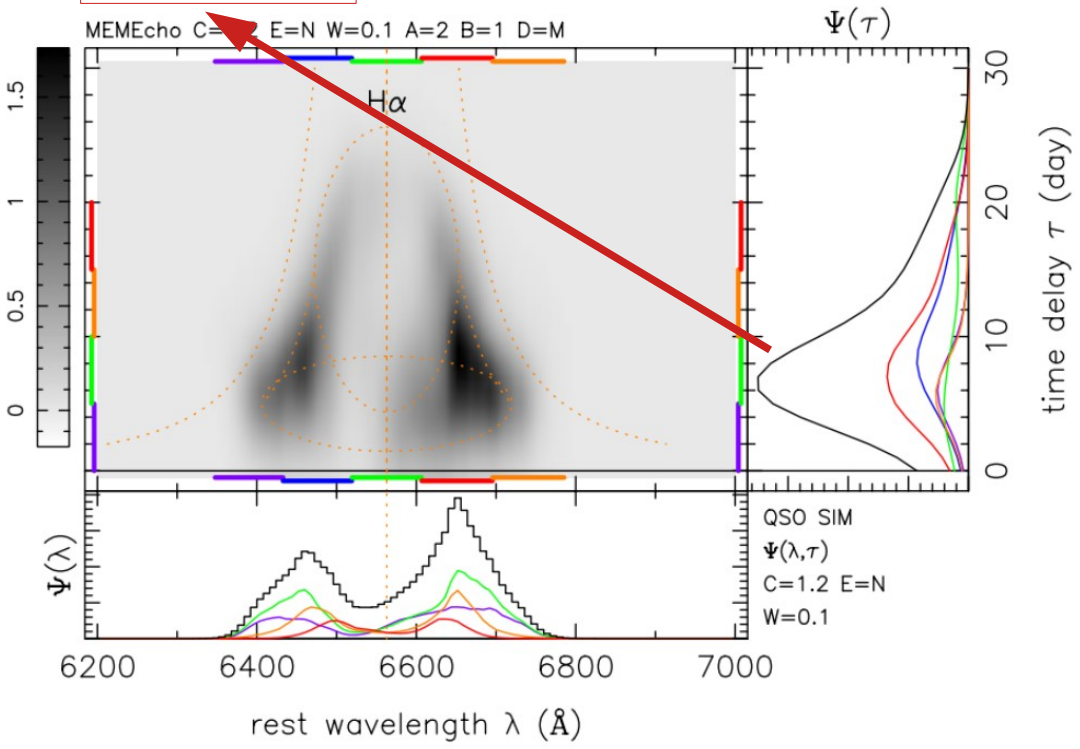
PYTHON ground truth

$\tau_{peak} \approx 4$ d

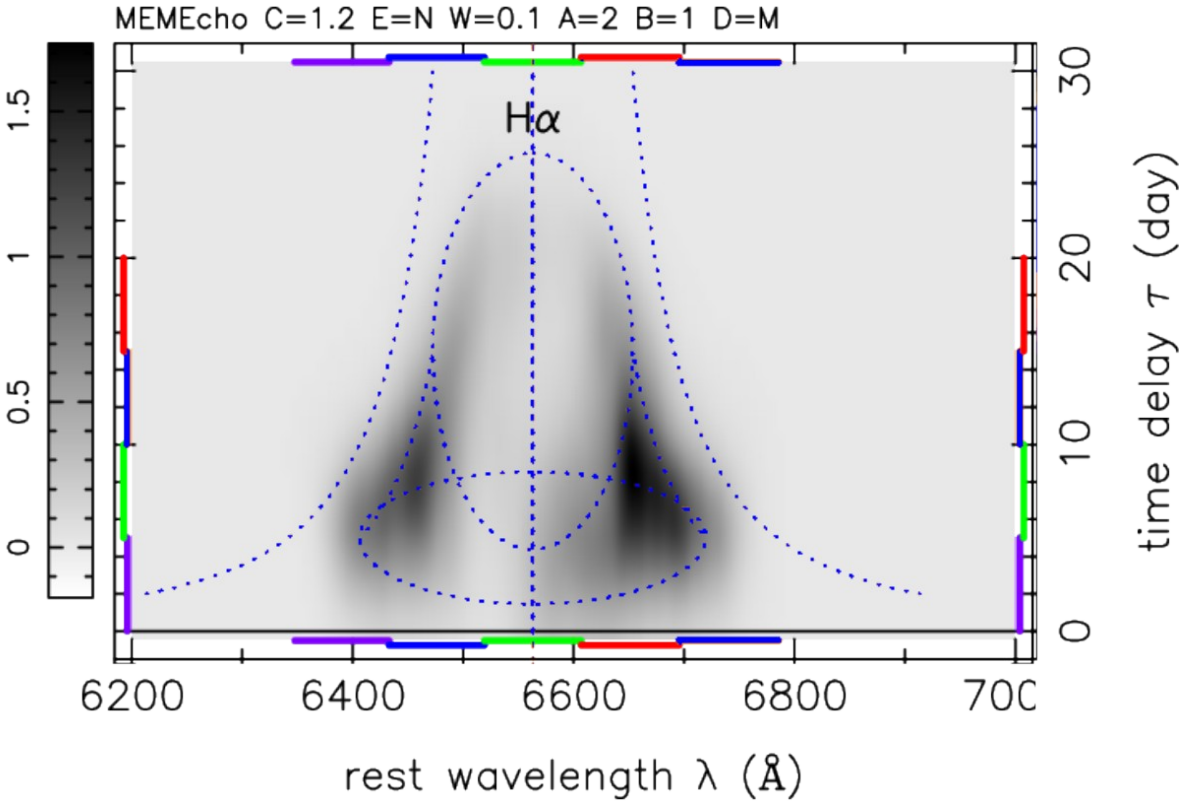


MEMEcho reconstruction

$\tau_{peak} \approx 6$ d



Inferences from the MEMEcho map



"For a $10^8\,M_\odot$ black hole, the dotted curves show the virial envelope for edge-on circular Keplerian orbits, and for 45° inclined orbits extending from 5 to 15 light days. This framework captures much of the structure evident in the velocity-delay map..."

- KH

Take-home points

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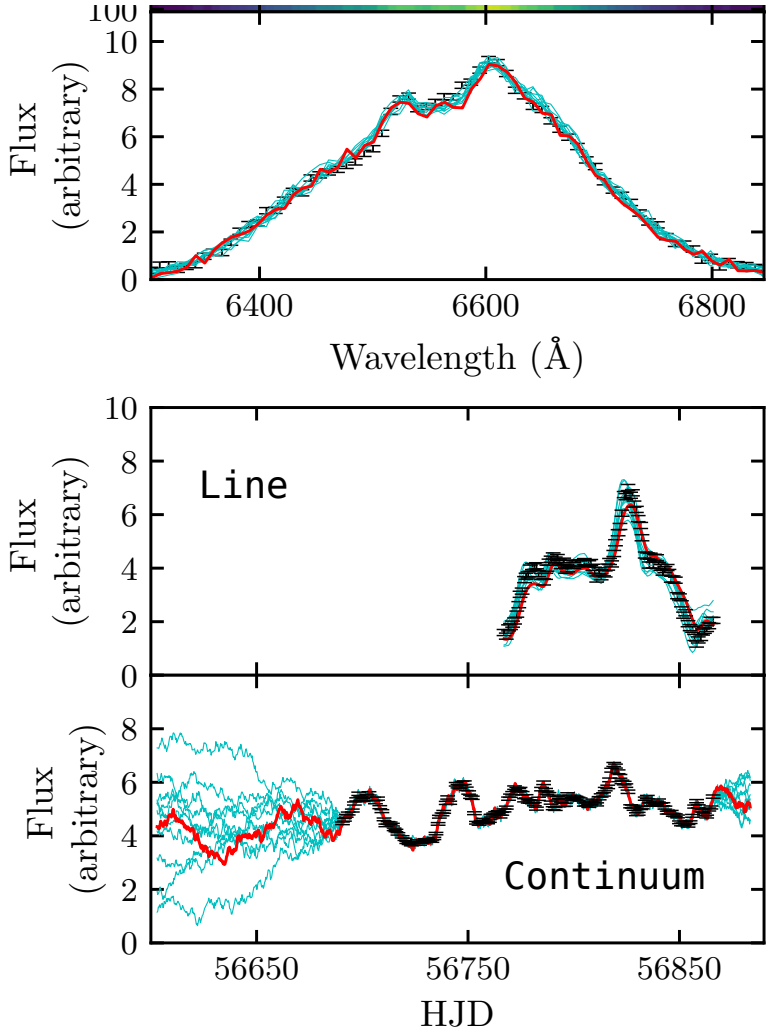
MEMEcho

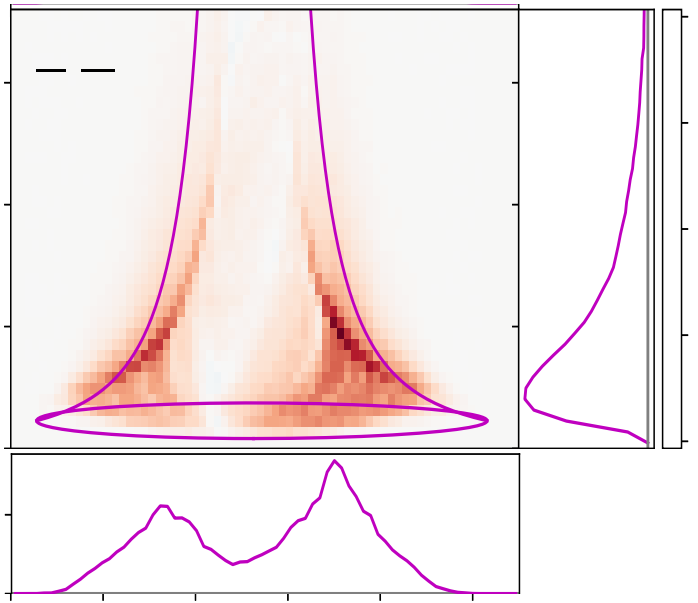
- **Correctly recovers (smoothed) response function**
- **Lag overestimated by 50%**
- **Expert interpretation yields correct**
  - **BH mass**
  - **Inclination**
  - **Geometry of line-forming region**

Results

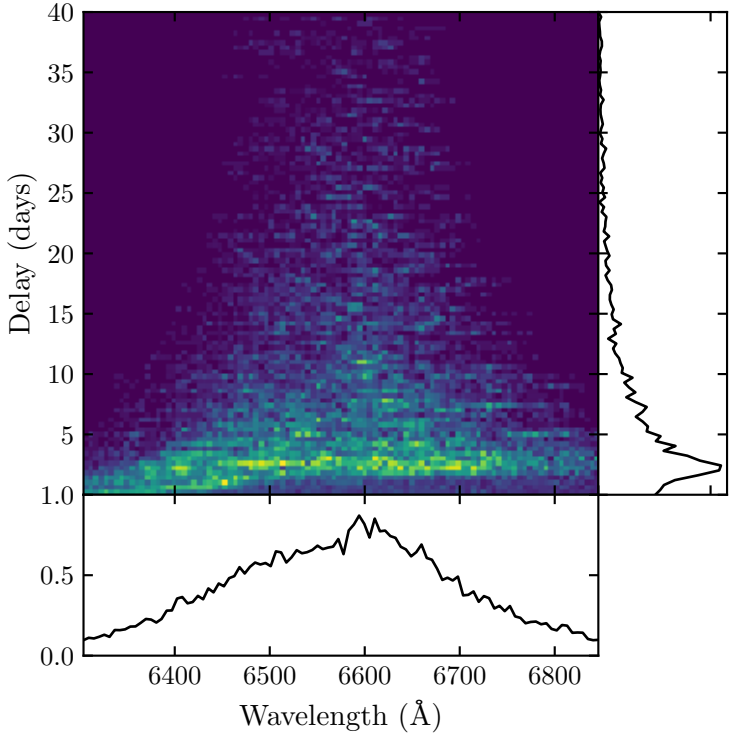
The QSO model with CARAMEL


Flux
(arbitrary)
Wavelength (Å)
Line
Continuum
HJD

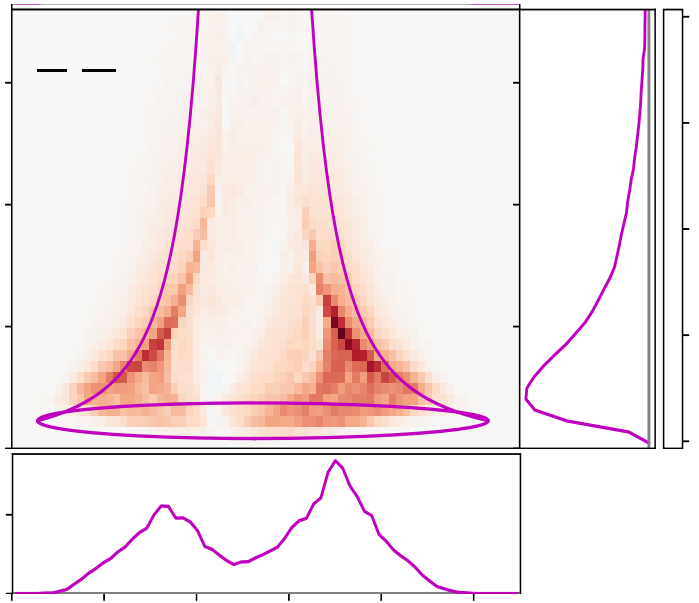
PYTHON ground truth



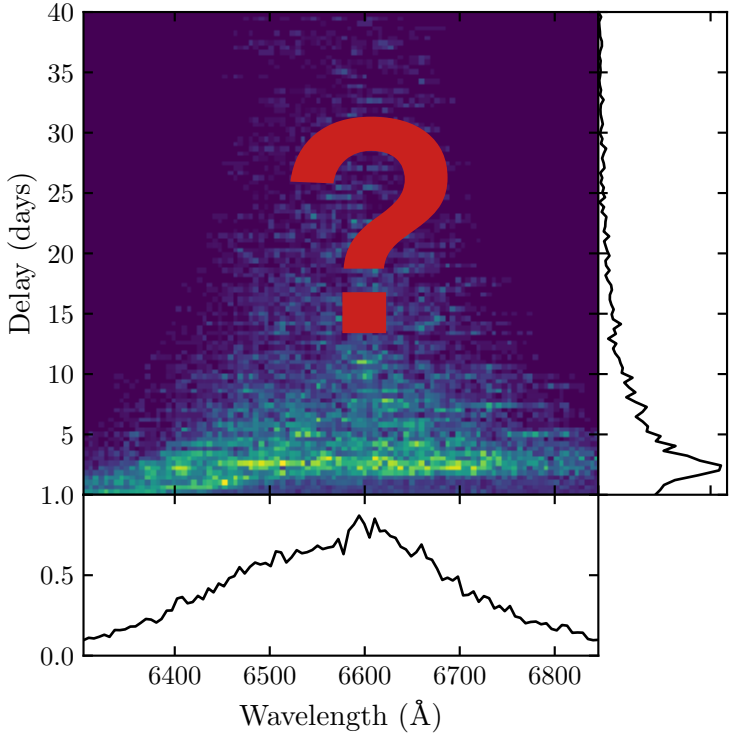
CARAMEL “reconstruction”



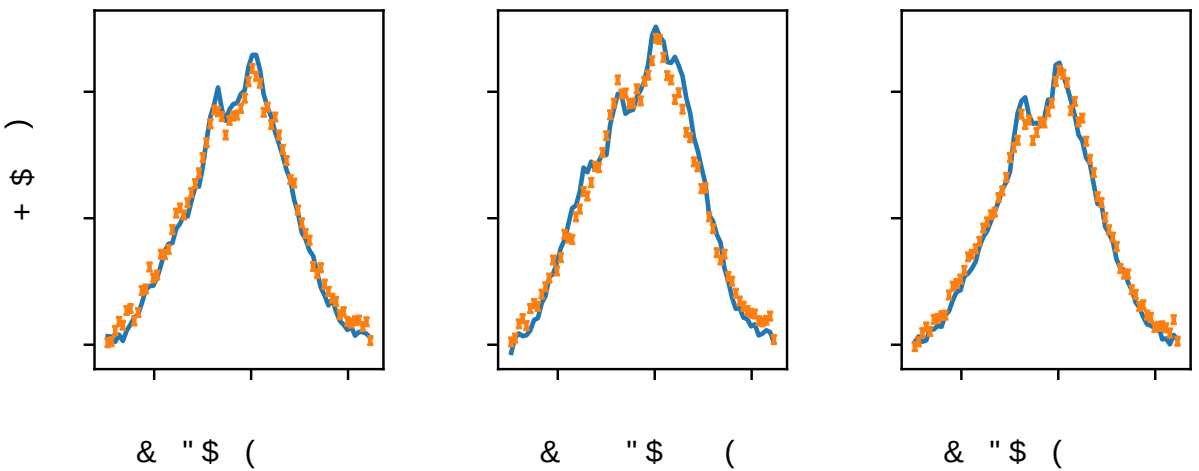
PYTHON ground truth



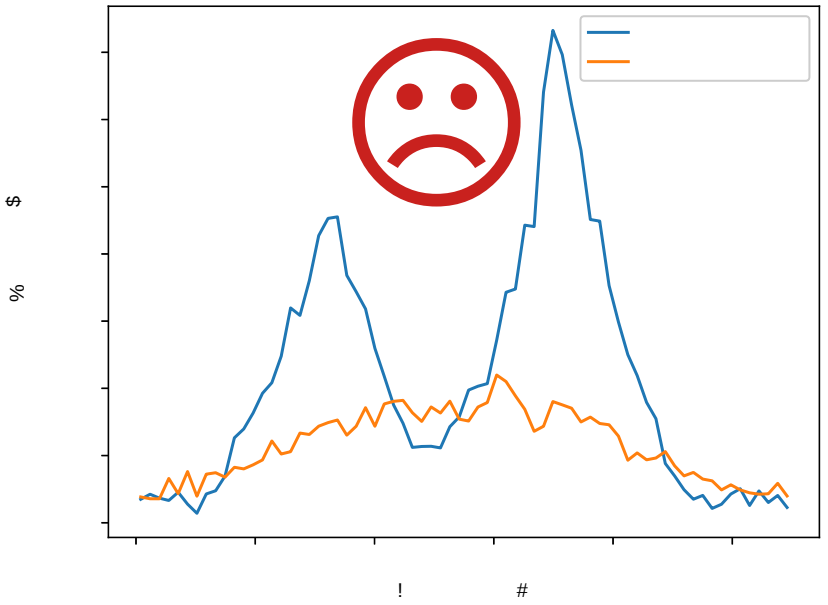
CARAMEL “reconstruction”



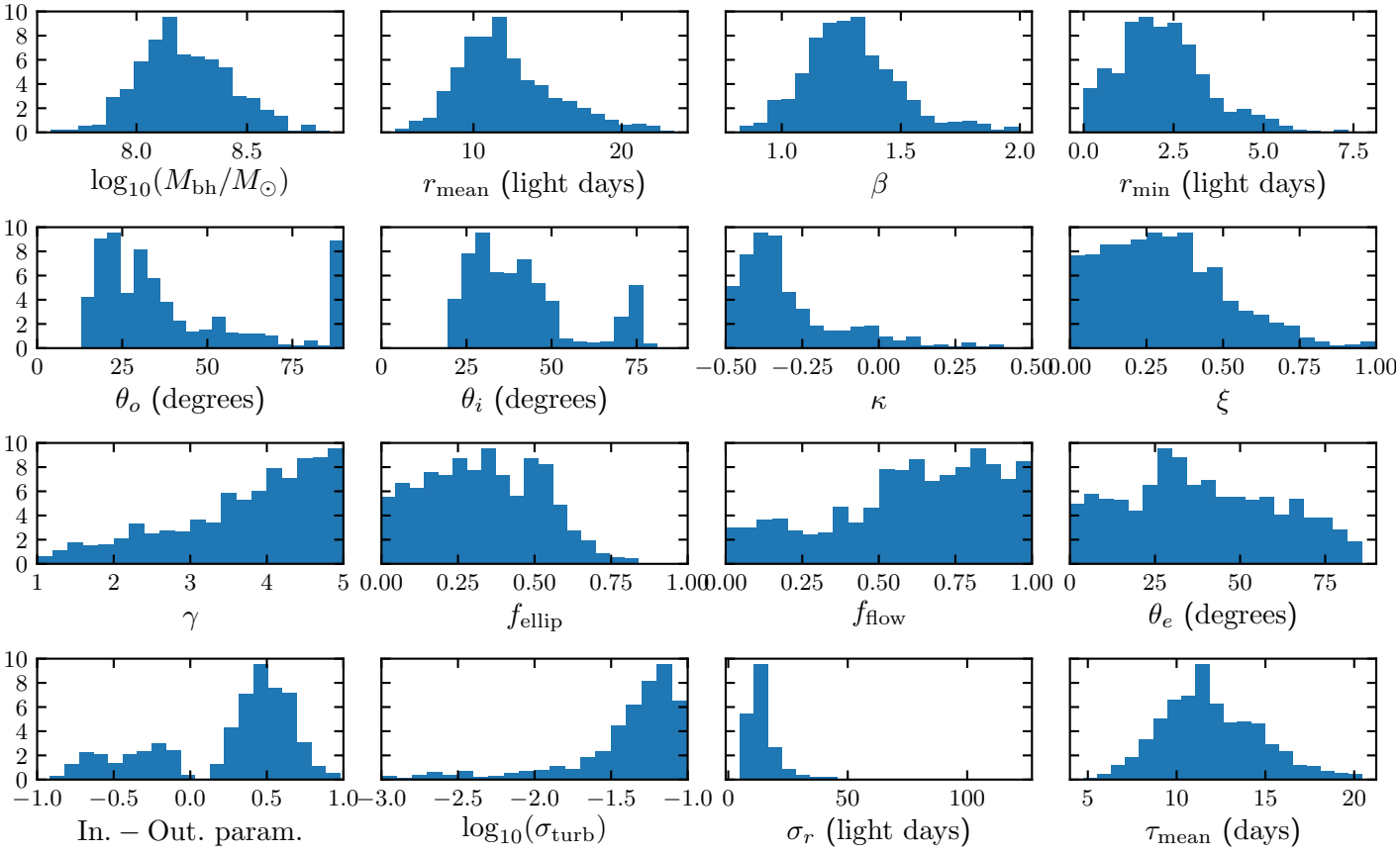
Individual line profiles are fit OK...



...but the RMS line profile is fit poorly

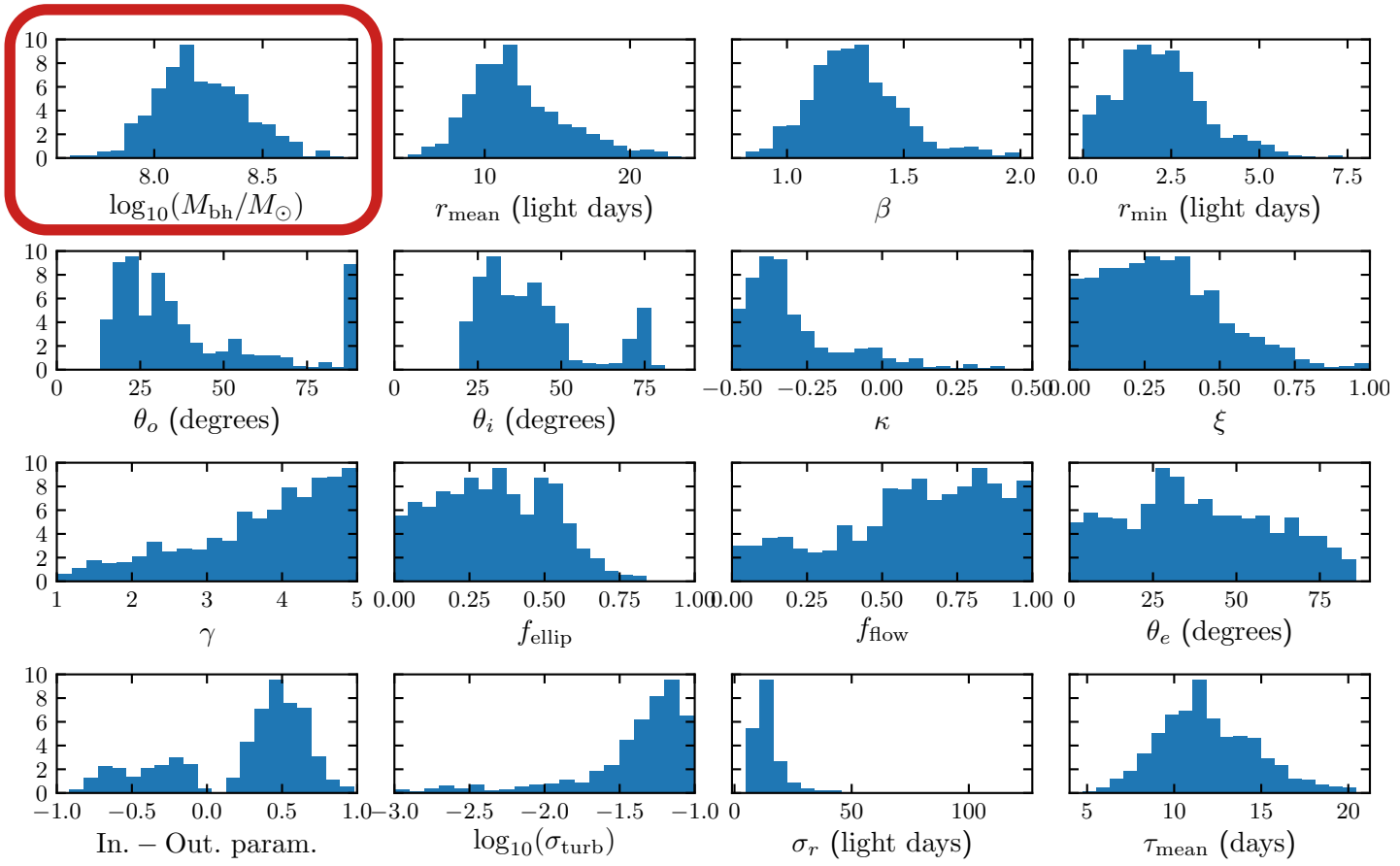


CARAMEL parameter distributions



CARAMEL parameter distributions

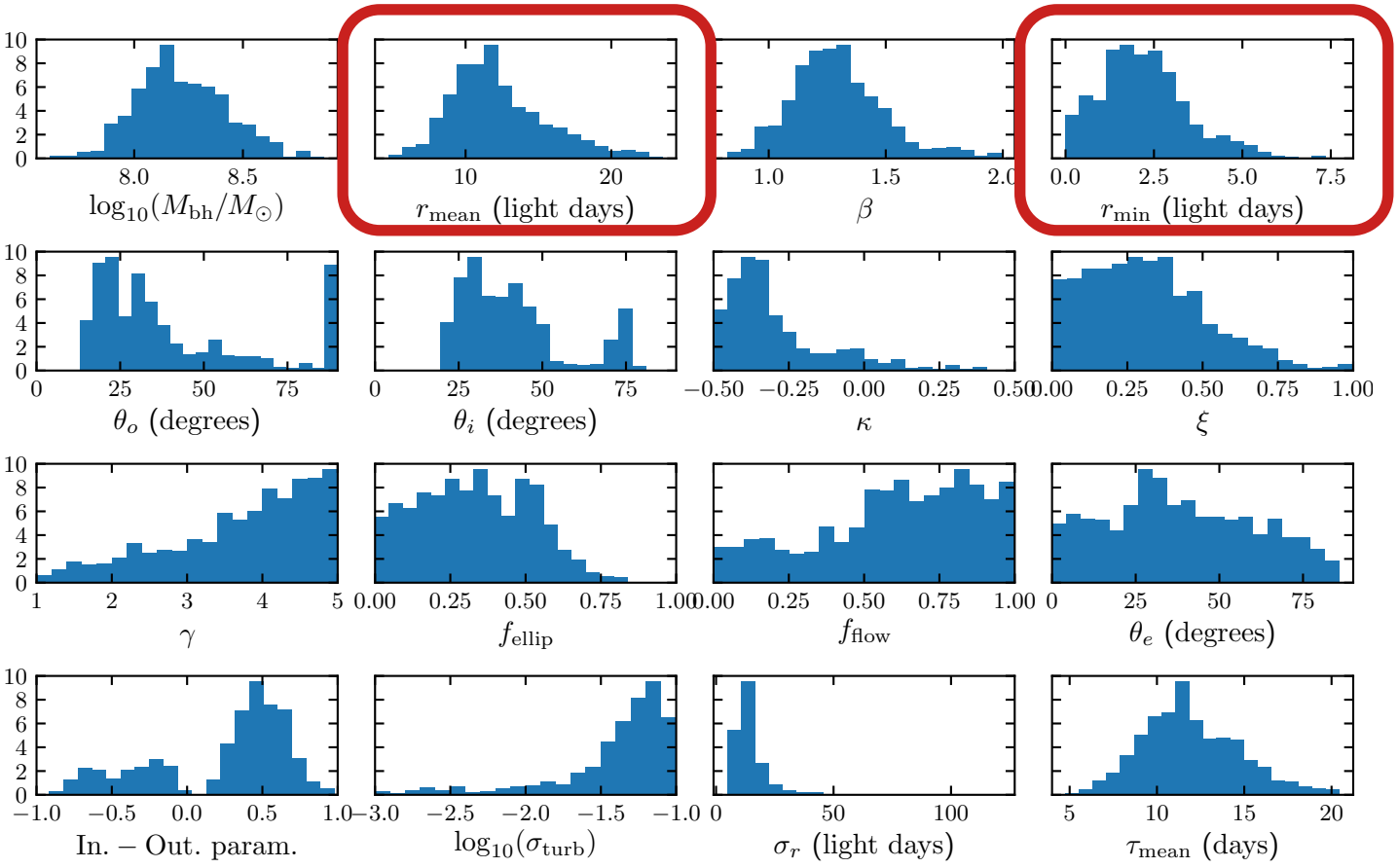
☺ BH mass



CARAMEL parameter distributions

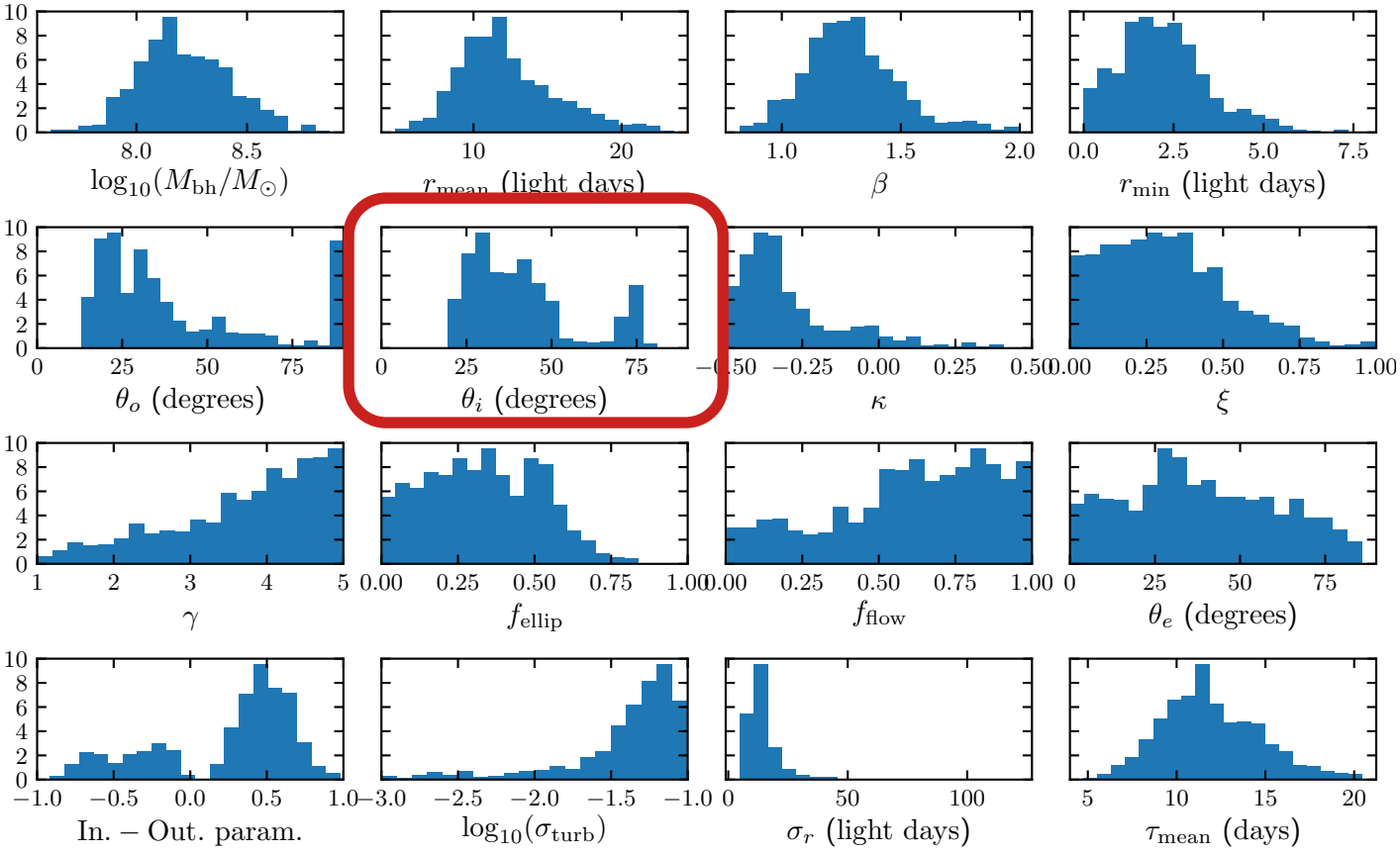
☺ BH mass

☺ BLR size



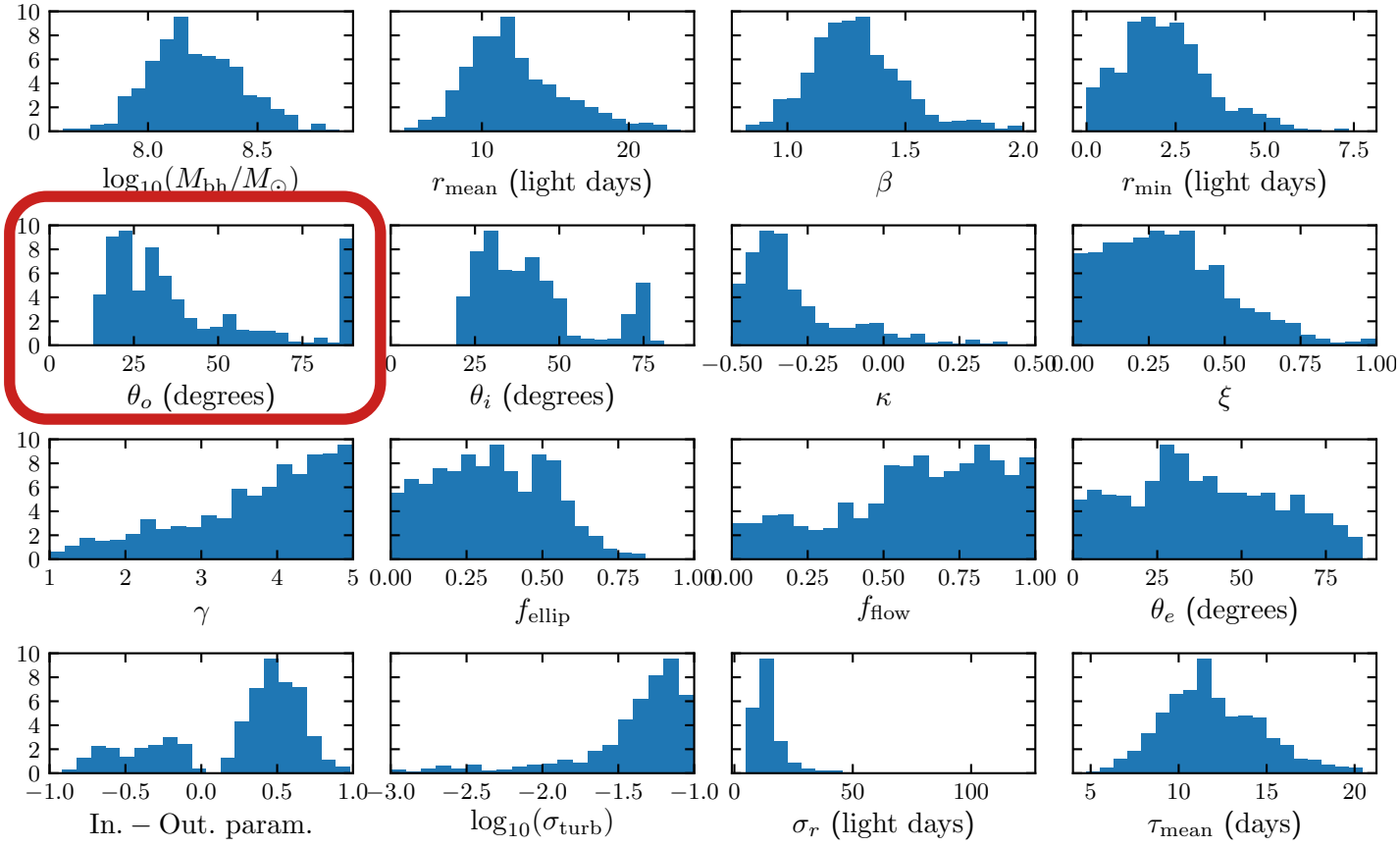
CARAMEL parameter distributions

- BH mass
- BLR size
- inclination



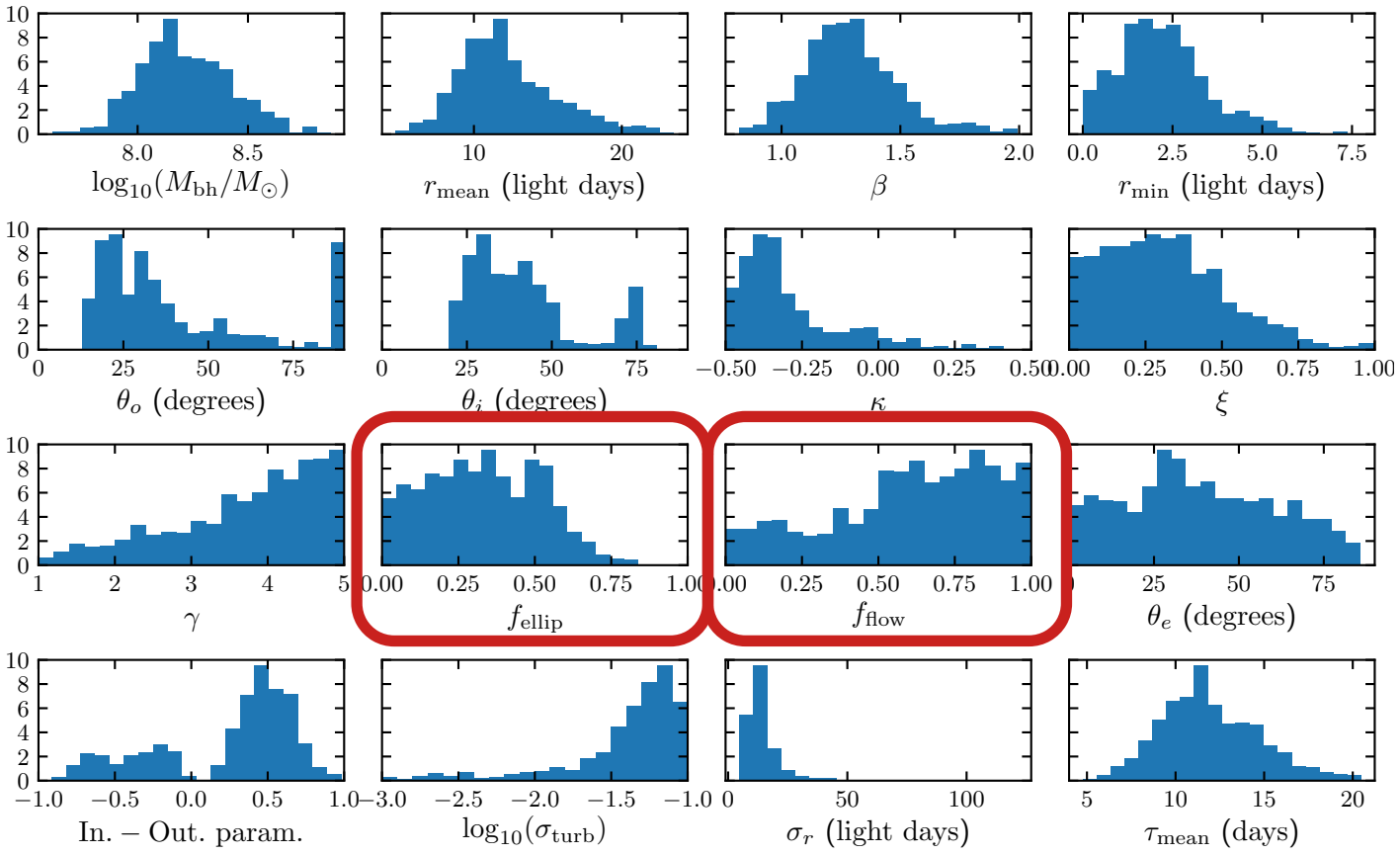
CARAMEL parameter distributions

- BH mass
- BLR size
- inclination
- geometry



CARAMEL parameter distributions

- ☺ BH mass
- ☺ BLR size
- ☺ inclination
- ☺ geometry
- 😐 kinematics



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  - **Lag**
  - **BH mass**
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- Problem with recovered response function
- Parameter distribution yield correct
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- **Neither method recovers disk wind kinematics (rotation-dominated LFR)**

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