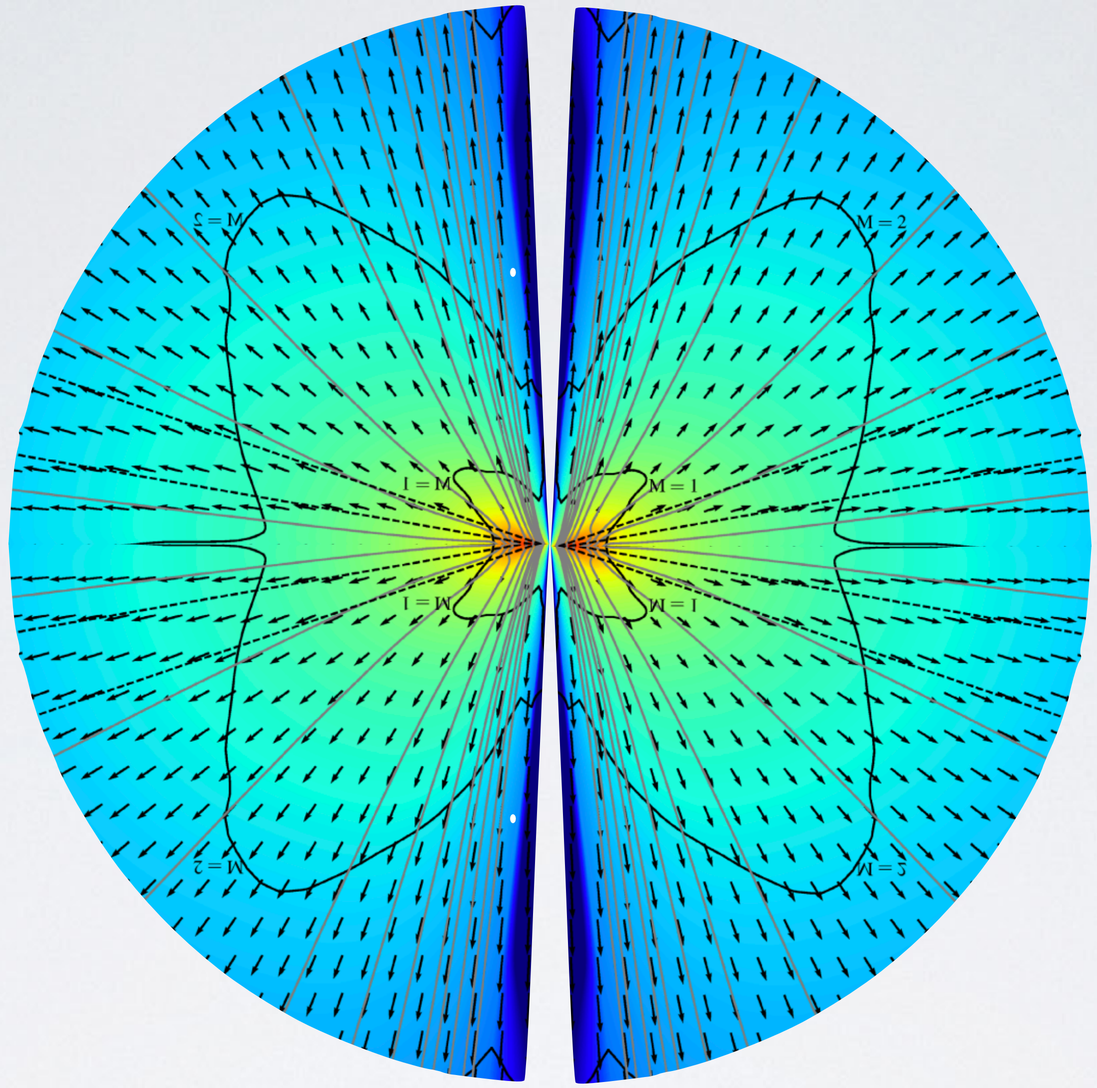
The Disc-Wind Connection in XRBs



James Matthews (University of Oxford)

Christian Knigge, **Phil Charles**, Noel Castro Segura, **Nick Higginbottom**, John Paice, Poshak Gandhi, Maria Georganti, Nicolas Scepi (Southampton), Knox Long (Eureka, STScI), **Karri Koljonen** (Turku University)
Jaco Brink, David Buckley, Enrico Kotze (Cape Town)
Stuart Sim (Queen's Belfast)

Plus thanks to: Teo Munoz-Darias, Nathalie Degenaar.

UNIVERSITY OF OXFORD

THE ROYAL SOCIETY

Take-home Messages

Rich, varied multiphase phenomenology of optical-UV disc winds

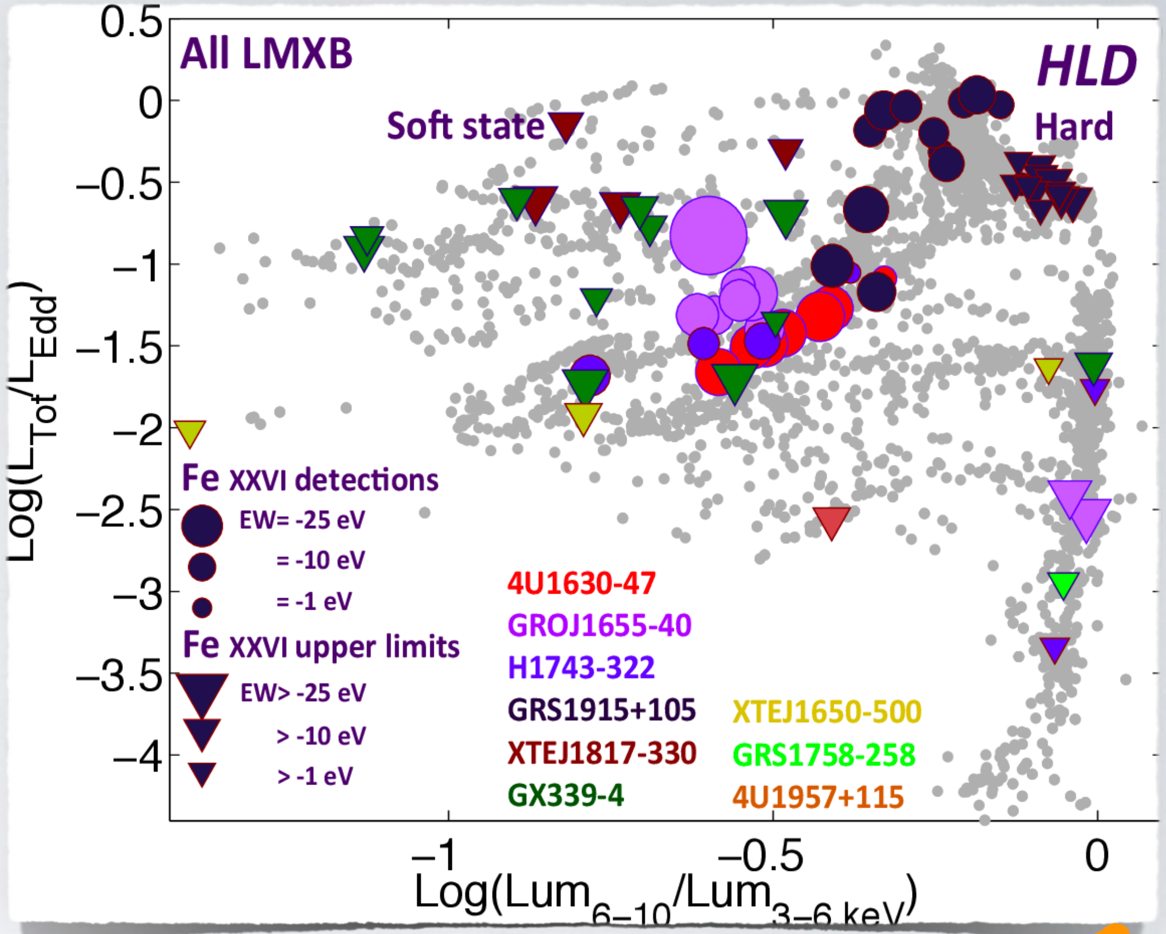
Radiative transfer and hydrodynamics matters: Full suite of computational tools must be leveraged

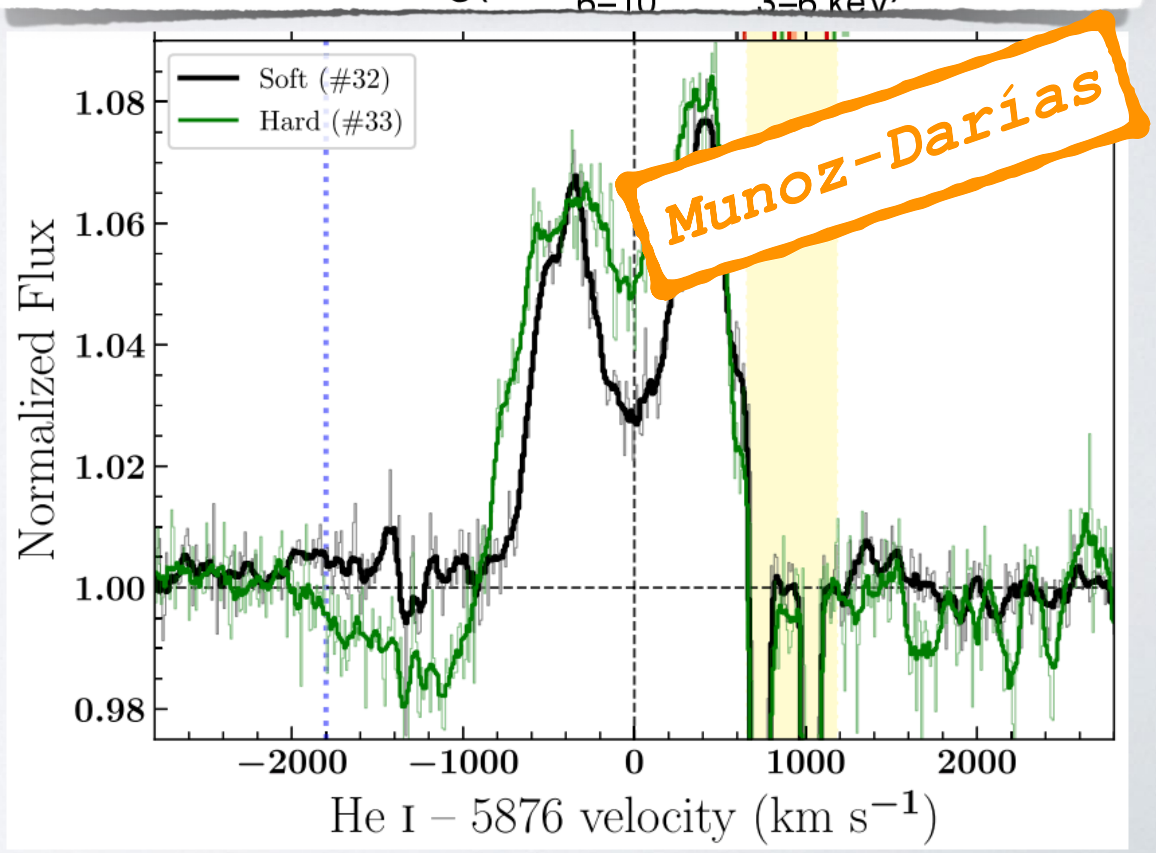
It's not just lines: Winds and atmospheres are "continuum reprocessors"

Physics of optical winds is unclear

A potted history of XRB winds

- Picture in ~2015: Winds seen in X-rays, equatorial viewing angles, soft states only (Ponti+2012; right)
- Debate over MHD v Thermal Winds, partly driven by GRO 1655-040
- 2015 onwards: winds in XRBs can be cool (optical lines) and found in hard states (Munoz-Darias+ 2015,2019)



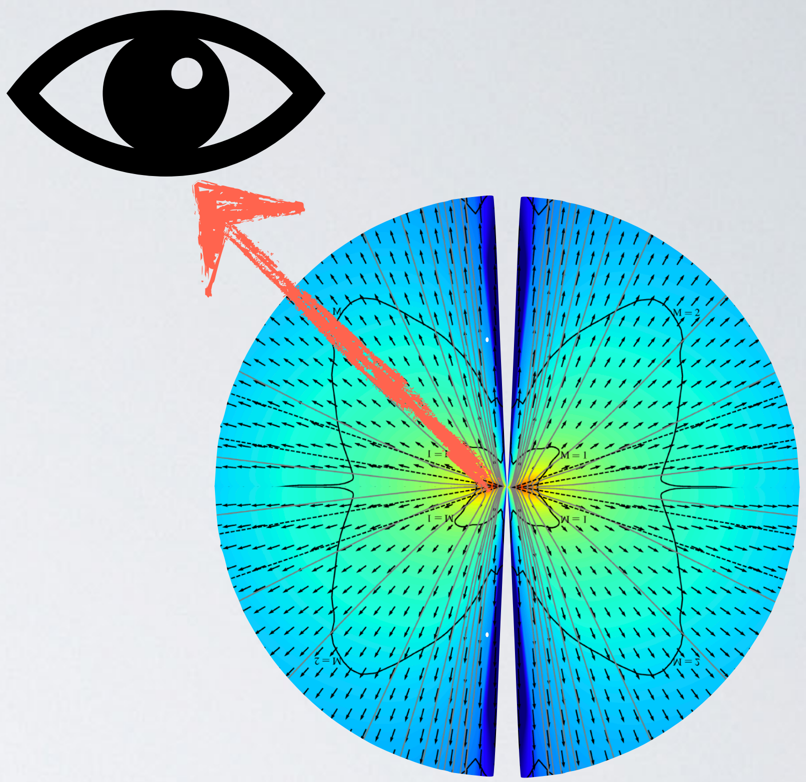


Radiative transfer: Why?

$$F_\lambda$$

$$\theta_i$$

$$\dot{M}_w, v_w, T_e, R_0$$

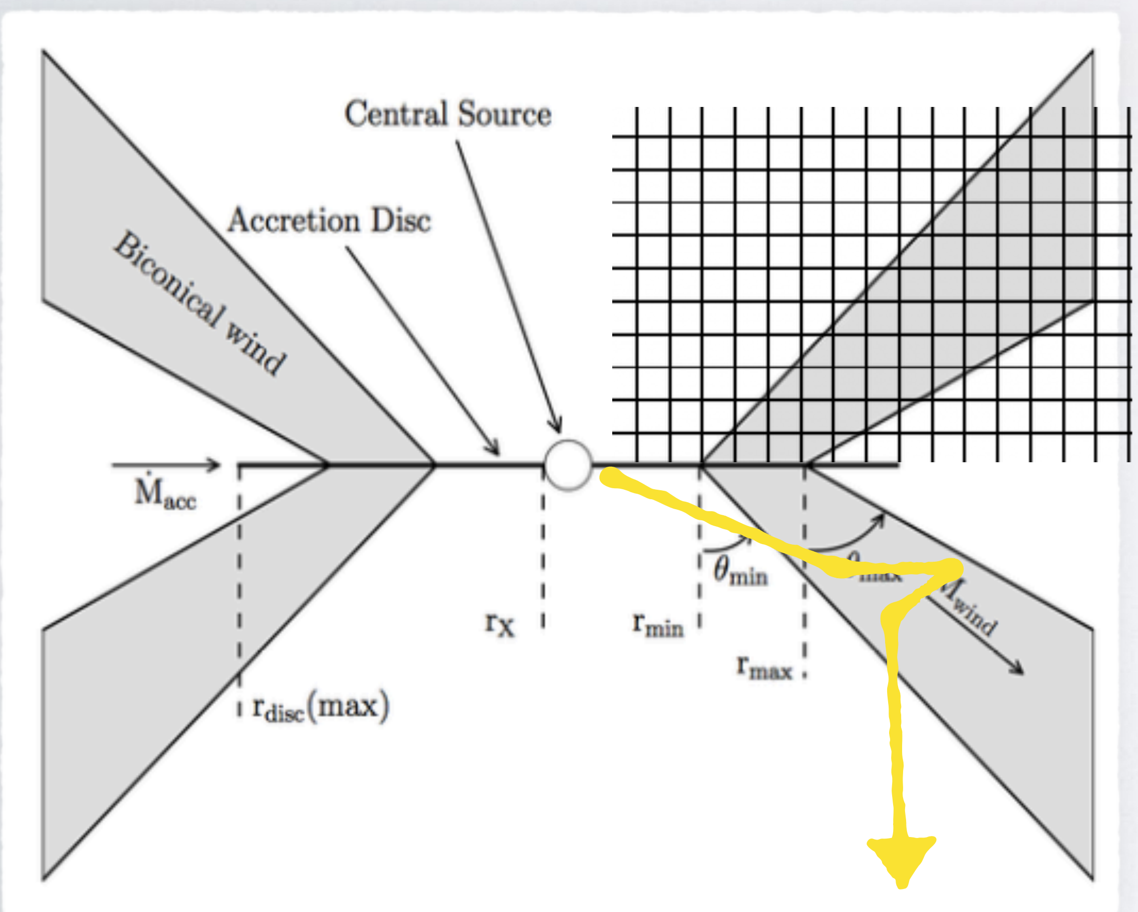


We want to know the physics of the winds:

- How much energy, mass, momentum and AM do they transport?
- What mechanism drives them?
- How do they affect disc/states/hysteresis?

Radiative transfer: How?

- "Python" is a confusingly named code designed to model the spectra of objects with disc winds (Long & Knigge 2002; Higginbottom+ 2013; Matthews+ 2015)
  - I am hoping we will soon be renaming it to something like Mistral
- Monte Carlo radiative transfer and photoionisation code
- Flexible, powerful code with range of applications: AGN, XRBs, YSOs, WDs, Stars, TDE



1. Photon packets (~10^7) fly through wind grid
2. MC estimators recorded to characterise
3. Converge on ionization state and T

$$J_\nu \, d\nu = \frac{1}{4\pi}\frac{1}{V}\sum_{d\nu} w_i \Delta s$$

Mean intensity is calculated as a sum over photon trajectories (the Monte Carlo equivalent of an integral over "rays")

Hydrodynamics: why? (“Defying Gravity”)

Lagrangian rate of change of momentum

Gravity of compact object

$$\boxed{\rho \frac{d\overrightarrow{v}}{dt} = -\nabla P + \frac{1}{\mu_0}\overrightarrow{B} \times (\nabla \times \overrightarrow{B}) + \overrightarrow{F}_{\mathrm{rad}} - \rho\,\overrightarrow{g}}$$

Hydrodynamics: why? ("Defying Gravity")

Lagrangian rate of change of momentum

Gravity of compact object

$$\boxed{\rho \frac{d\vec{v}}{dt} = -\nabla P + \frac{1}{\mu_0}\vec{B} \times (\nabla \times \vec{B}) + \vec{F}_{\mathrm{rad}} - \rho \vec{g}}$$

Pressure gradient

Radiation force

Lorentz force + Ampere's law

Hydrodynamics: why? ("Defying Gravity")

Lagrangian rate of change of momentum

Gravity of compact object

$$\boxed{\rho \frac{d\vec{v}}{dt} = -\nabla P + \frac{1}{\mu_0}\vec{B}\times(\nabla\times\vec{B}) + \vec{F}_{\mathrm{rad}} - \rho\vec{g}}$$

Pressure gradient

Radiation force

Lorentz force + Ampere's law

Thermal Driving

Magnetic Driving

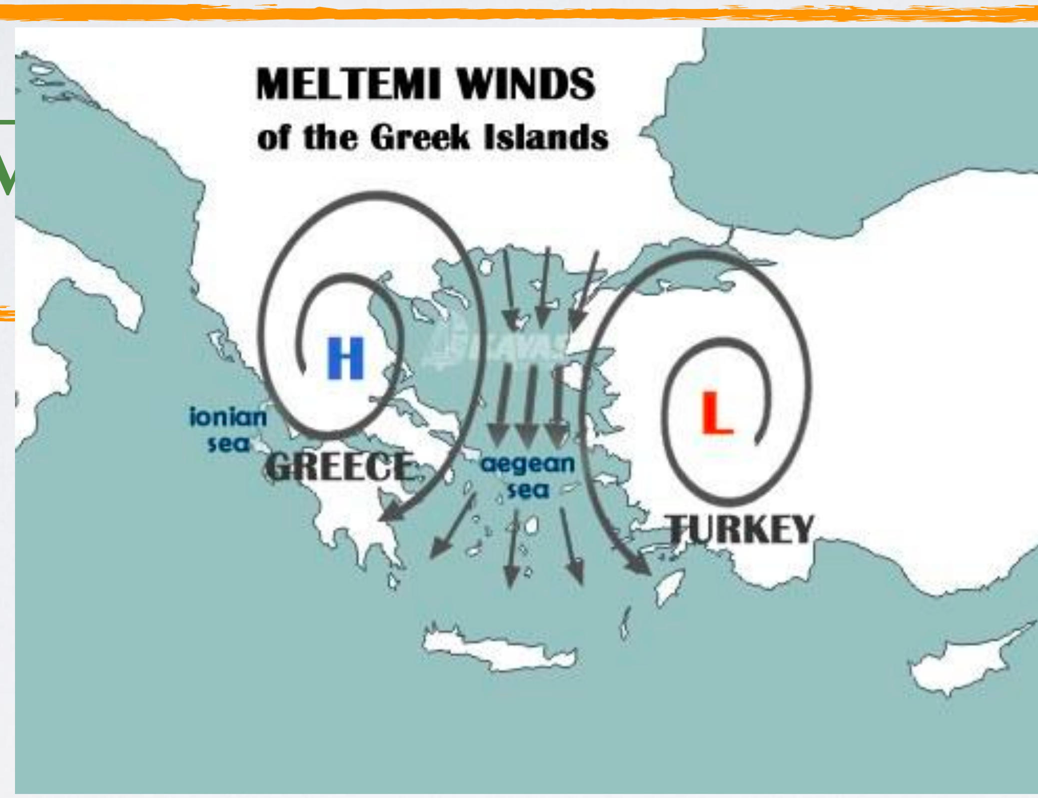
Radiative Driving

Hydrodynamics: why? ("Defying Gravity")

Lagrangian rate of change of momentum

Gravity of compact object

$$\rho \frac{d\vec{v}}{dt} = -\nabla$$



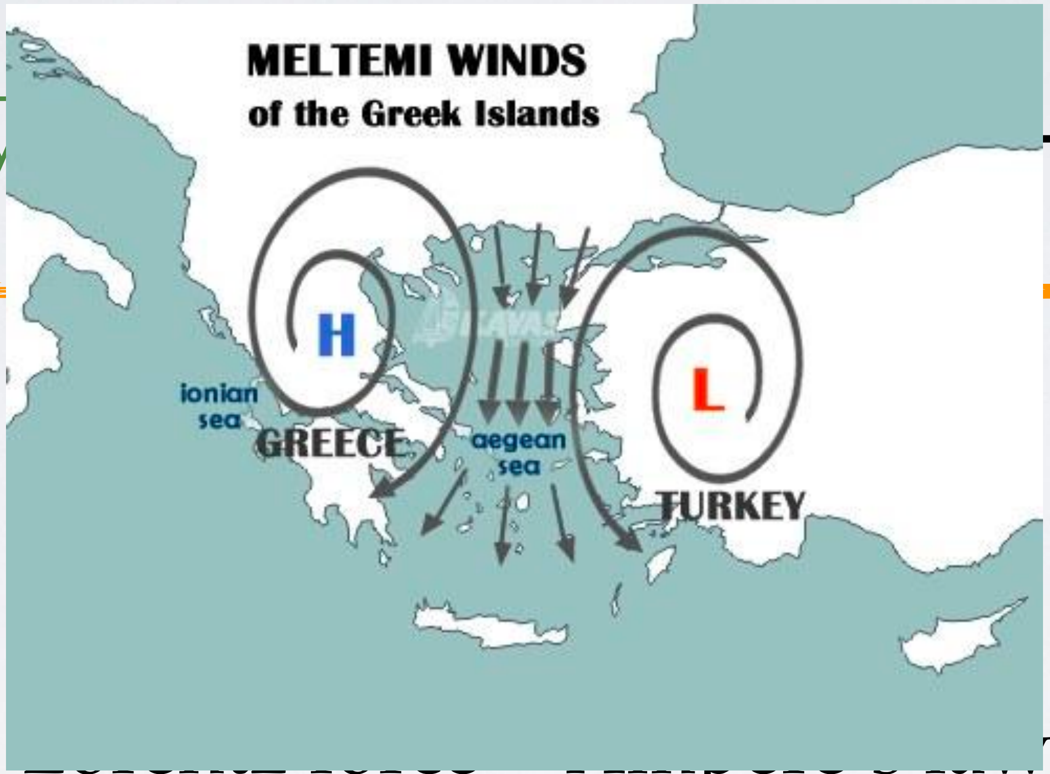
$$- \; \vec{F}_{\rm rad} - \rho\vec{g}$$

Hydrodynamics: why? ("Defying Gravity")

Lagrangian rate of change of momentum

Gravity of compact object

$$\rho\frac{d\vec{v}}{dt} = -\nabla \quad \cdots \quad - \vec{F}_{\mathrm{rad}} - \rho\vec{g}$$



Pressure gradient

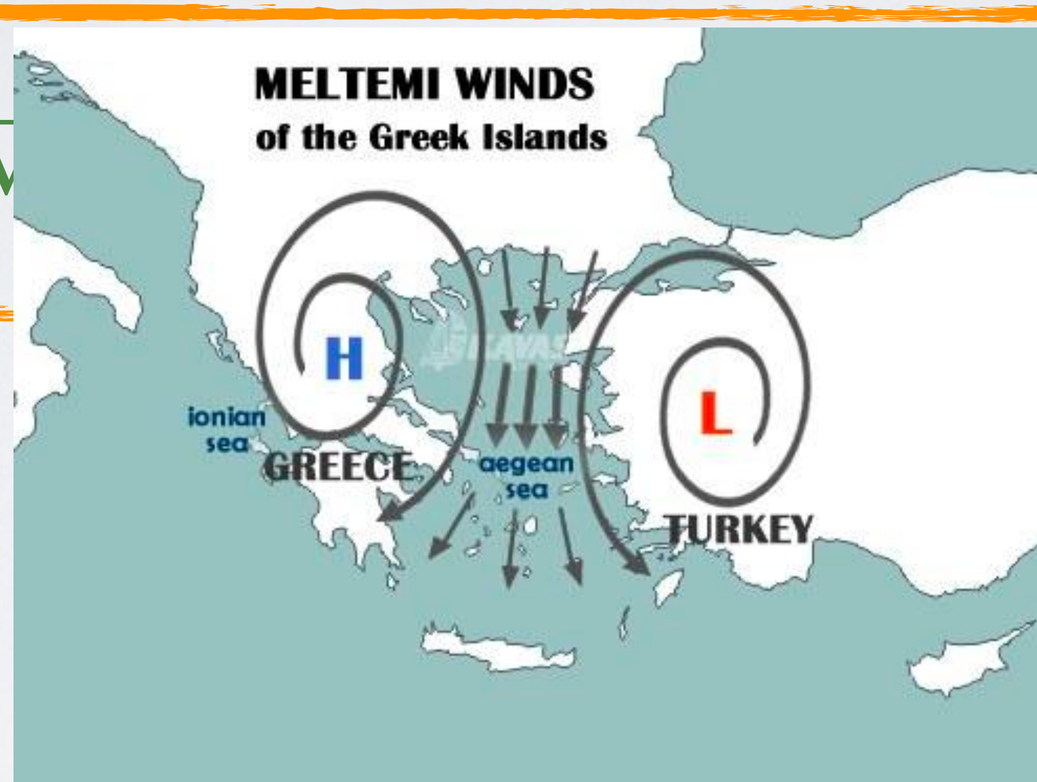
Radiation force

Hydrodynamics: why? (“Defying Gravity”)

Lagrangian rate of change of momentum

Gravity of compact object

$$\rho \frac{d\vec{v}}{dt} = -\nabla \quad \cdots \quad - \vec{F}_{\mathrm{rad}} - \rho \vec{g}$$



Pressure gradient

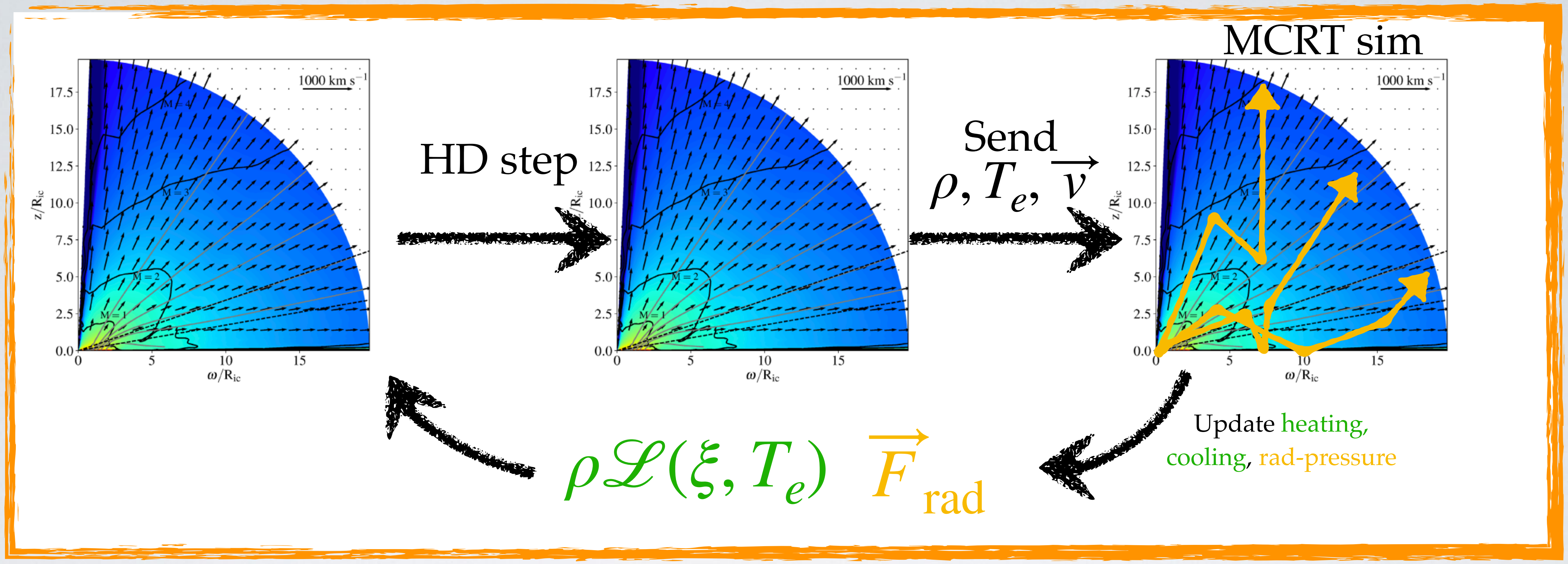
Radiation force

Thermal Driving

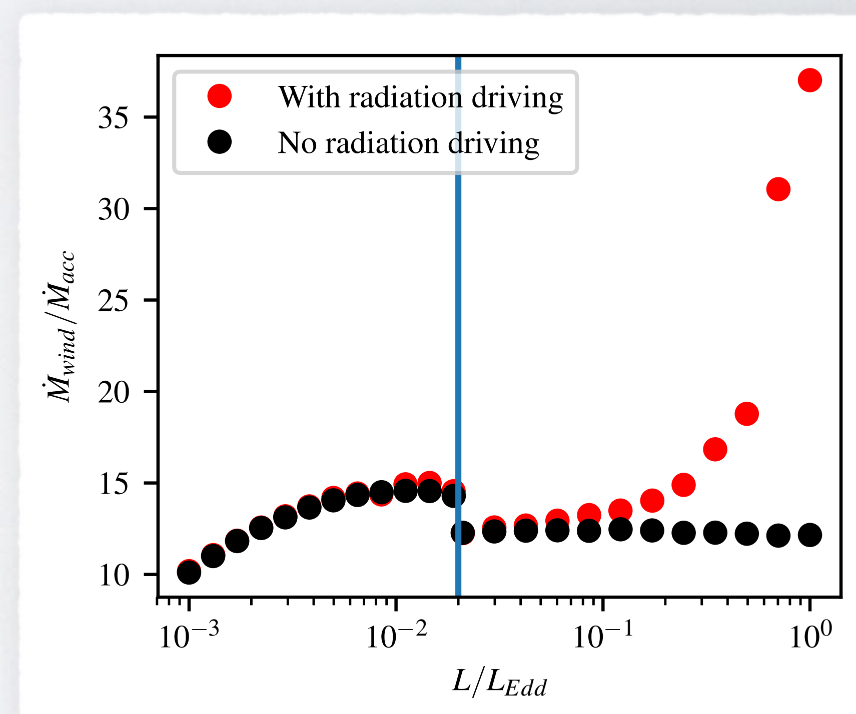
Magnetic Driving

Radiative Driving

Hydrodynamics: how?



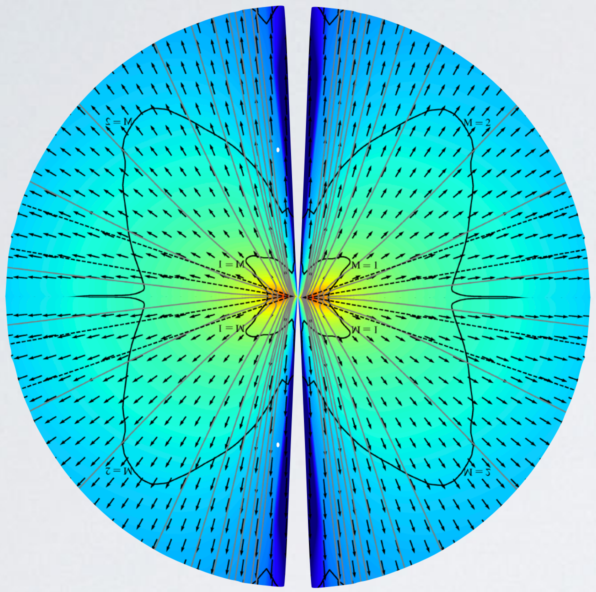
- Fully coupled Monte Carlo Radiative Transfer - Hydrodynamics
- Solve hydro (no B field) equations in PLUTO (finite volume Godunov MHD code, Mignone+ 2007).
- Operator splitting with full Monte Carlo radiative transfer: complete frequency dependence, multi-scattering, heating+cooling, line-driving
- Doing full MCRT changes stability curve due to frequency-dependent attenuation -> SED changes in space -> impacts heating and cooling



See also Tomaru

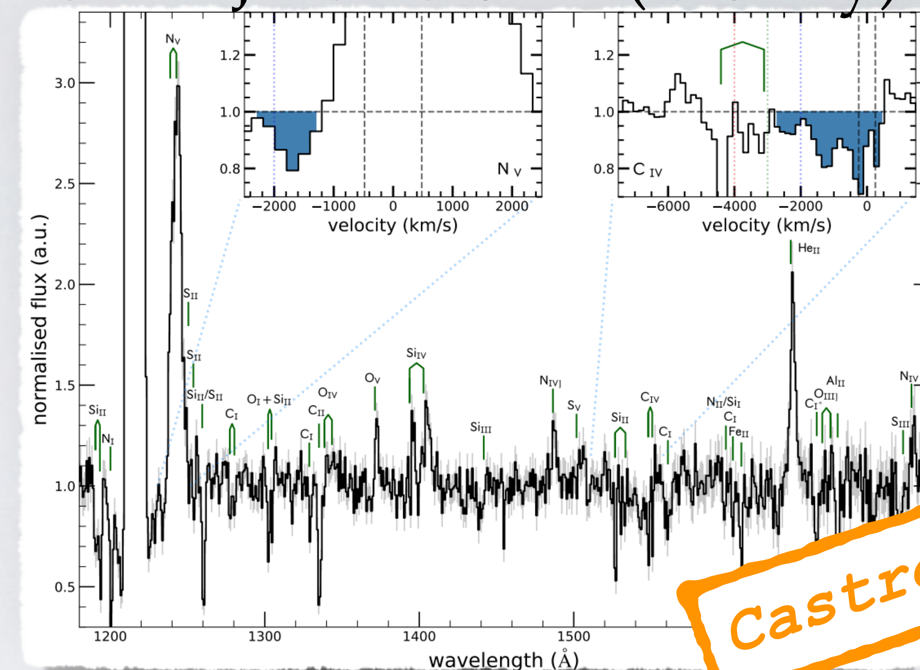
Four case studies

RT-Hydro



Higginbottom,…,JM+ 2018,2020

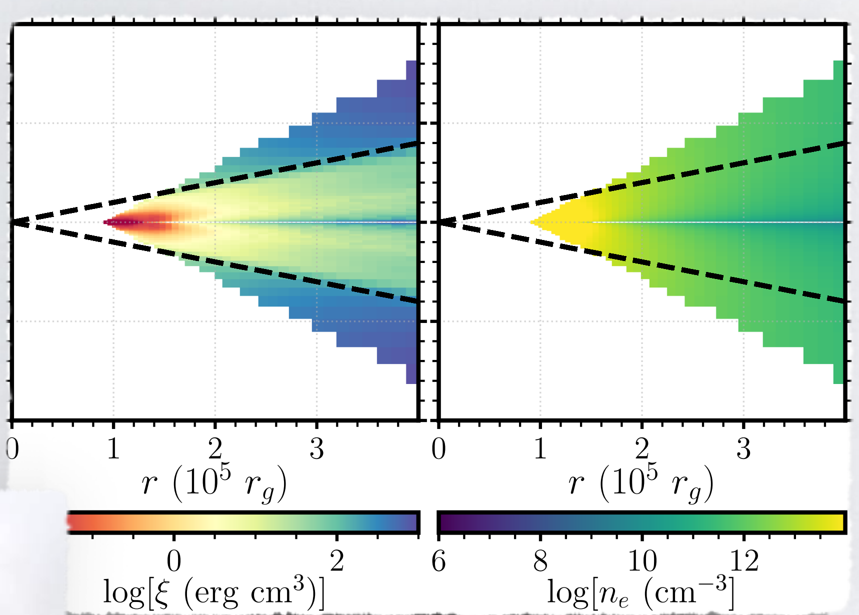
Swift J1858.6-0814 (Cloudy)



Castro Segura

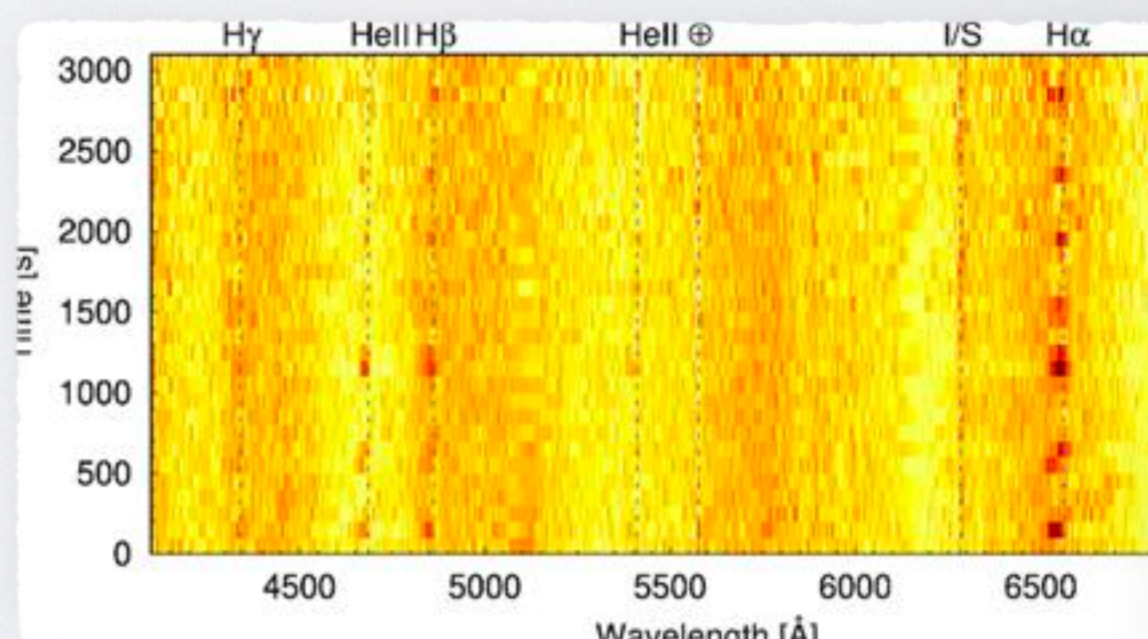
Castro Segura+ 2022, in prep.

MAXI J1820+020 (RT)



Koljonen, Long, JM+2020

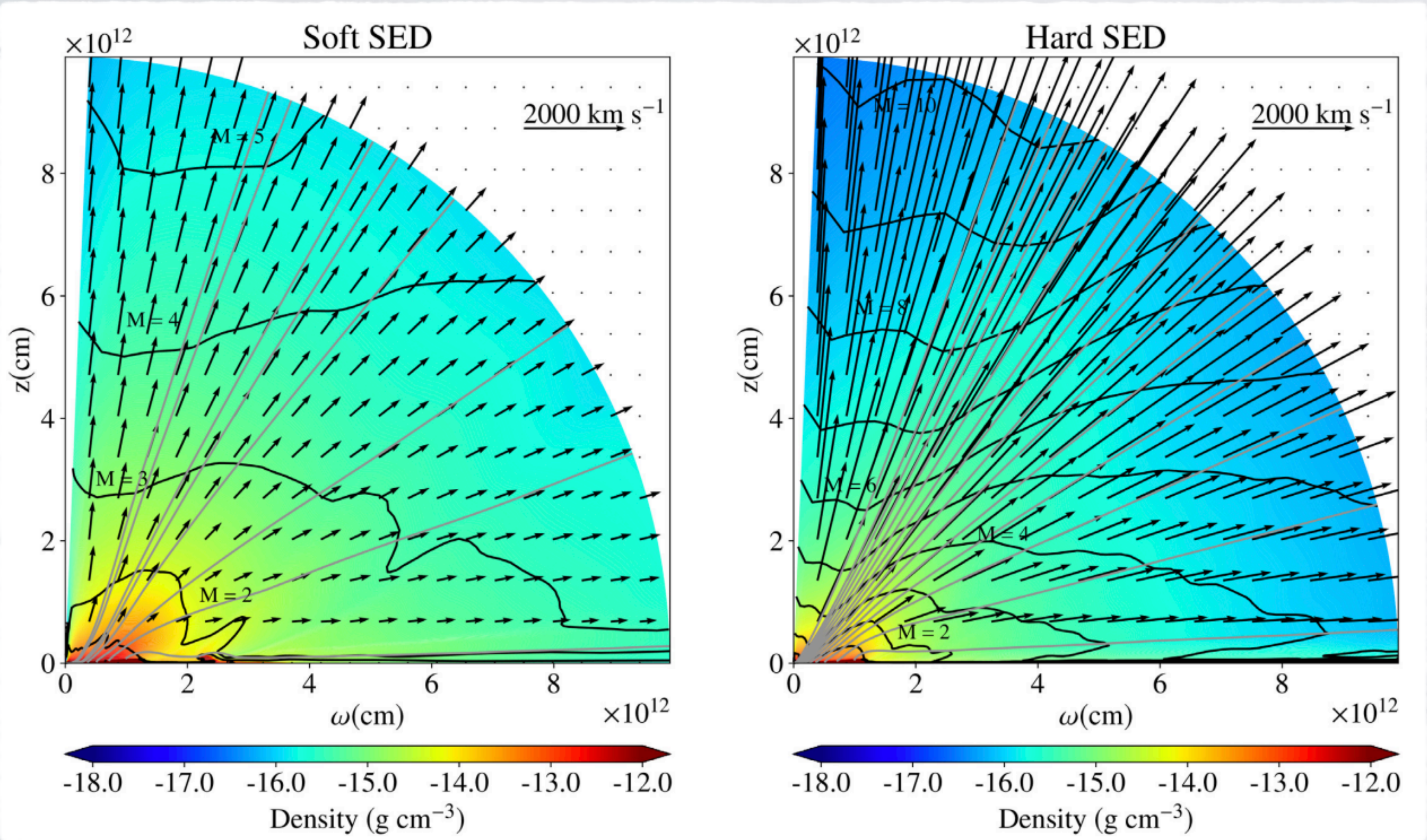
Swift J1357.2-0933 (RT)

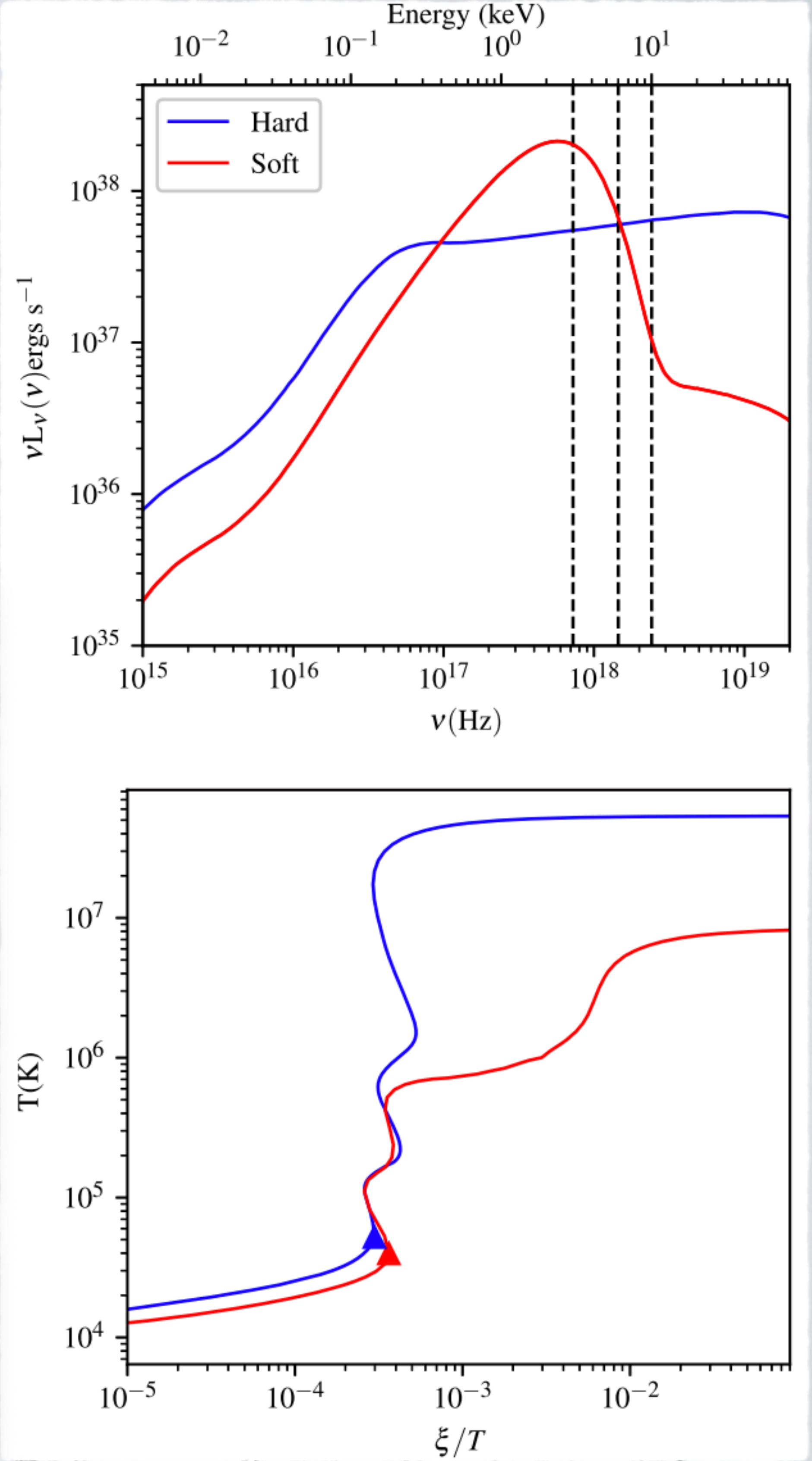


Charles, JM+ 2019

RT-hydro I: winds in all states expected?

- MCRT-hydro sims with H+C + rad pressure designed to simulate XRBs either side of hard-soft transition
- We find powerful outflows in both cases with $\dot{M}_{\rm w} \approx 2\dot{M}_{\rm acc}$
- Hard state wind is faster and more powerful! But also more tenuous and ionised, so lines are harder to detect



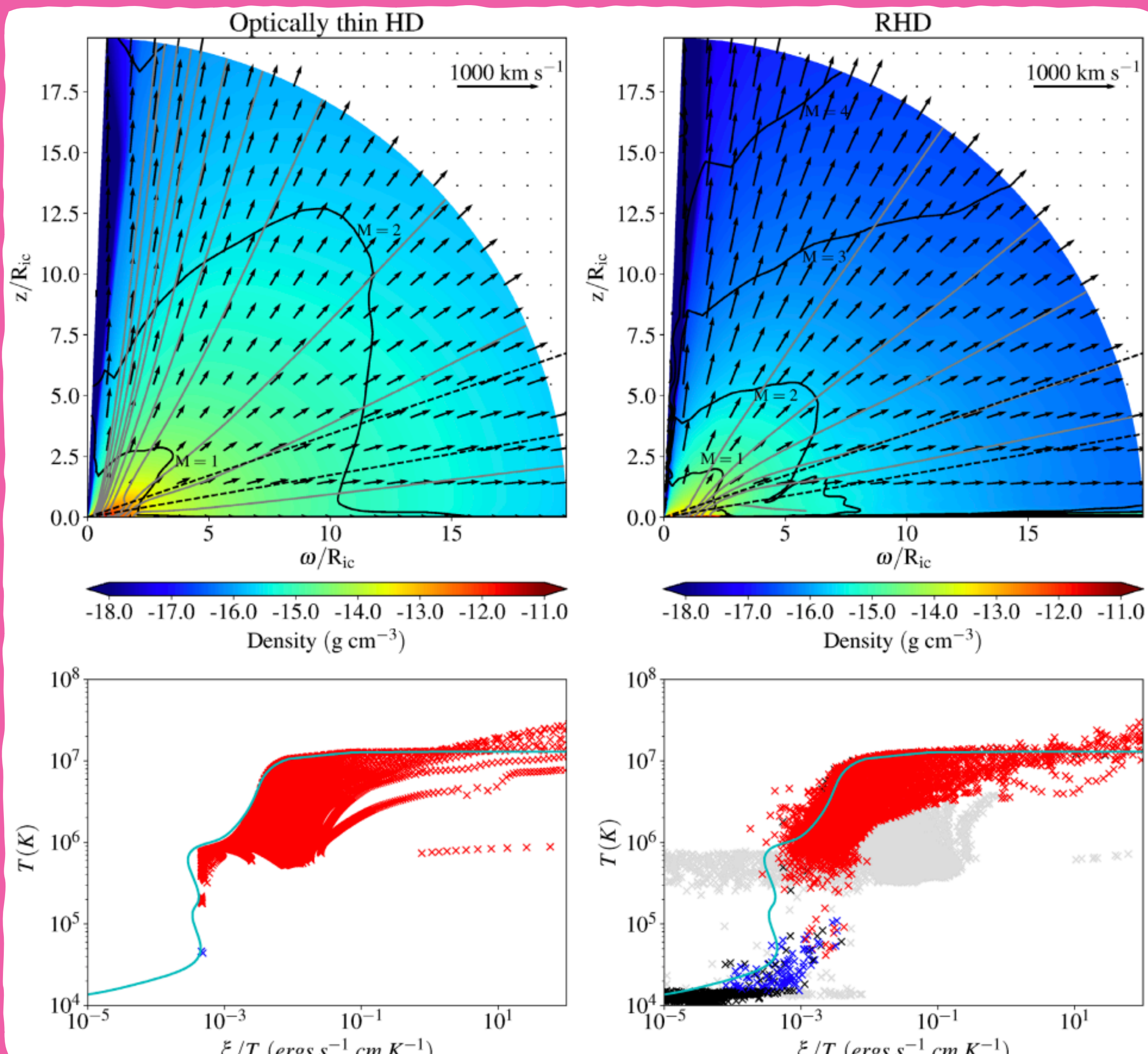


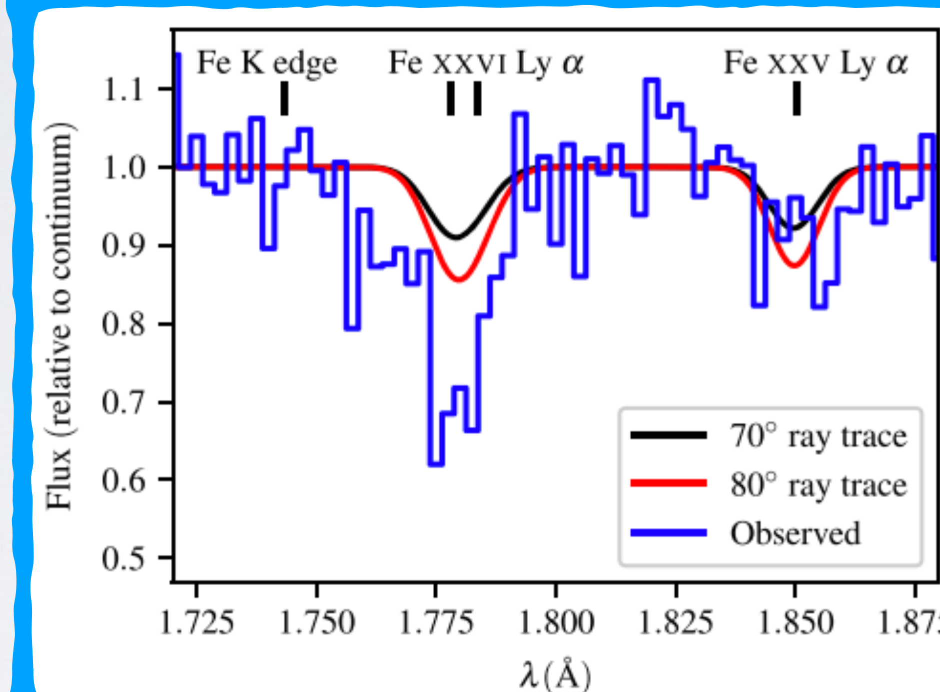
Higginbottom,…,JM+ 2020

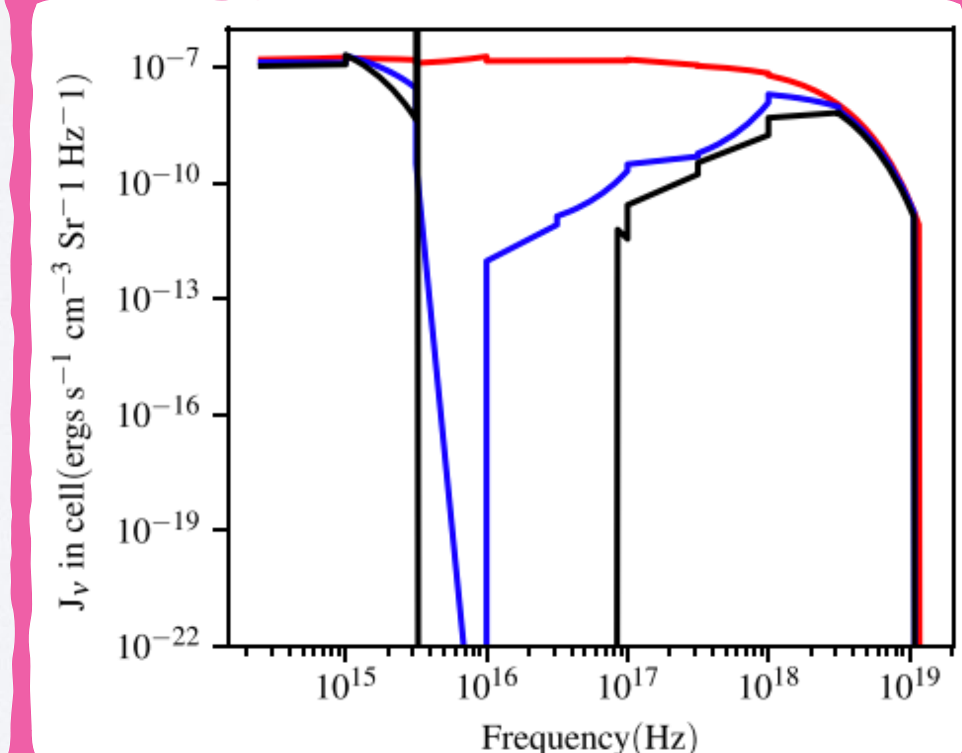
See also Done+ 2018, Petrucci+2021

RT-hydro II: GRO 1655-040

For parameters consistent with GRO1655-040, can produce absorption lines consistent with observations





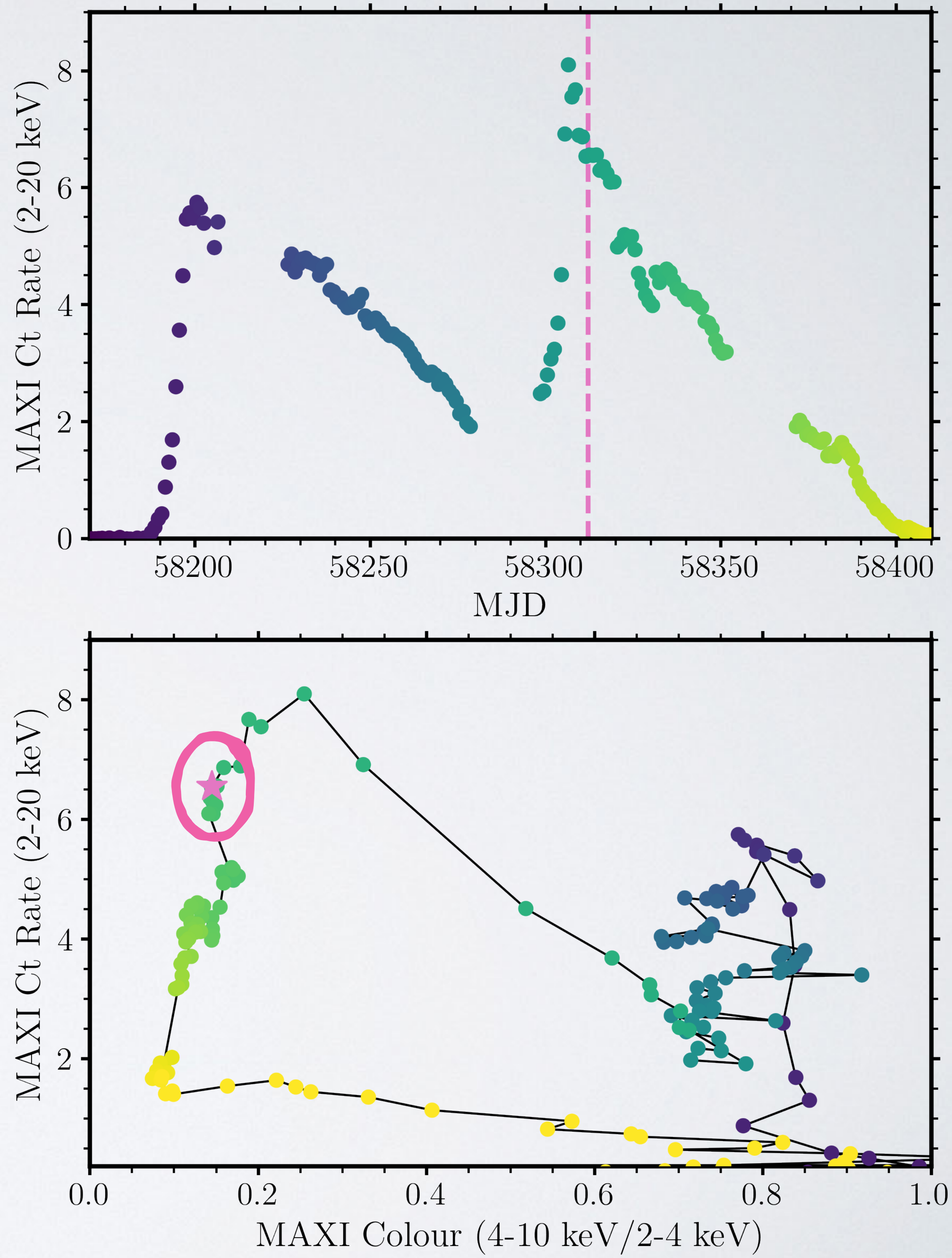


Full RT changes character of outflow (top), SED changes dramatically in wind launch layer (right)

Higginbottom,…,JM+ 2018,2019

MAXI J1820: Origin of soft state emission lines

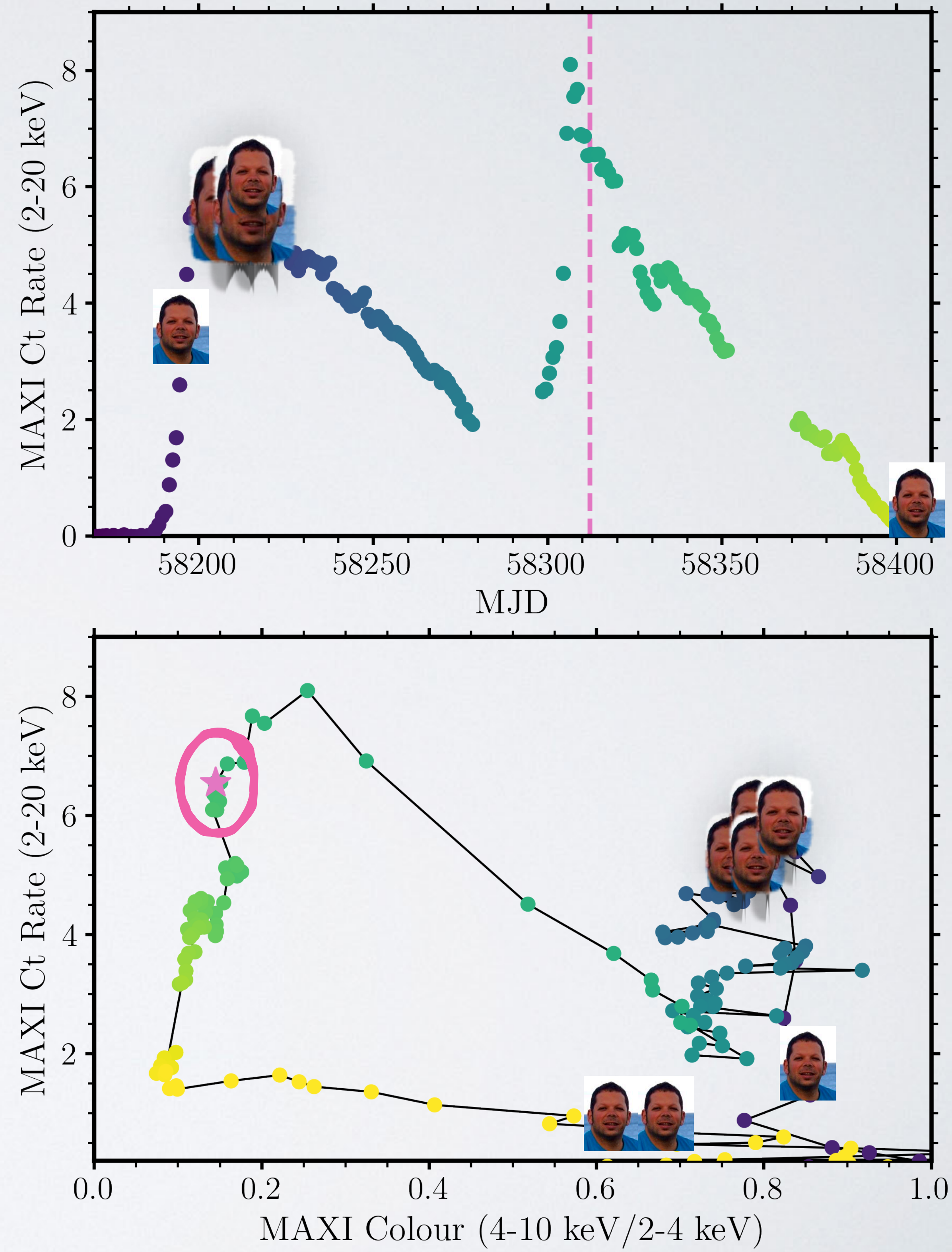
- 2018 outburst, soft-state XShooter VLT spectrum
- SED fit (incl. NuSTAR, Swift, NICER) with irradiated disc model
- Main features:
    - Rich emission line spectrum (Hydrogen series, He I and II, Ca II, Bowen)
    - Flat Balmer decrement (~1.3)
    - No obvious wind absorption features (consistent with Munoz-Darias 2019)
- MCRT biconical wind model provides excellent qualitative match to the spectrum



Koljonen, Long, JM+2020

MAXI J1820: Origin of soft state emission lines

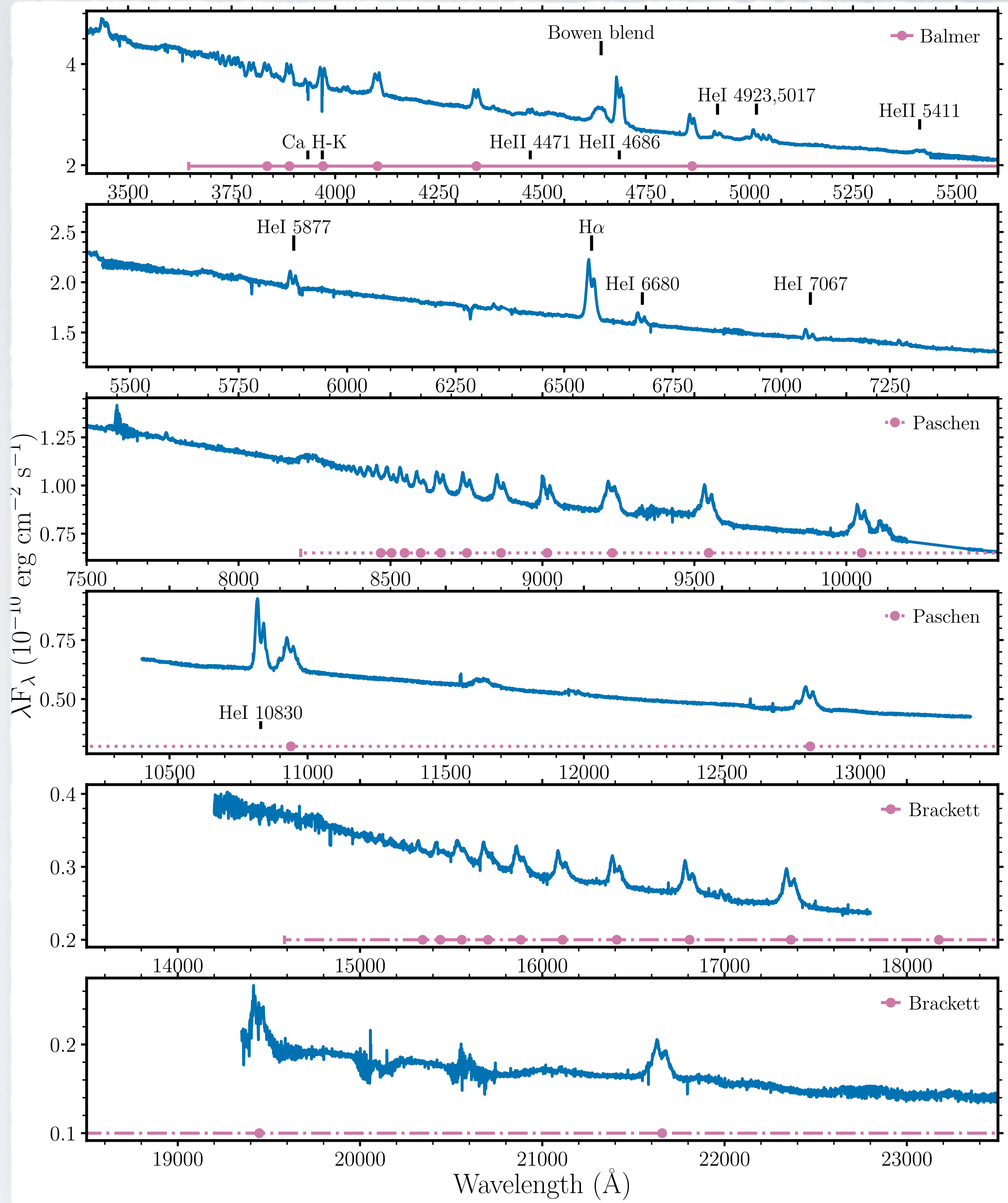
- 2018 outburst, soft-state XShooter VLT spectrum
- SED fit (incl. NuSTAR, Swift, NICER) with irradiated disc model
- Main features:
  - Rich emission line spectrum (Hydrogen series, He I and II, Ca II, Bowen)
  - Flat Balmer decrement (~1.3)
  - No obvious wind absorption features (consistent with Munoz-Darias 2019)
- MCRT biconical wind model provides excellent qualitative match to the spectrum



Koljonen, Long, JM+2020

MAXI J1820: Origin of soft state emission lines

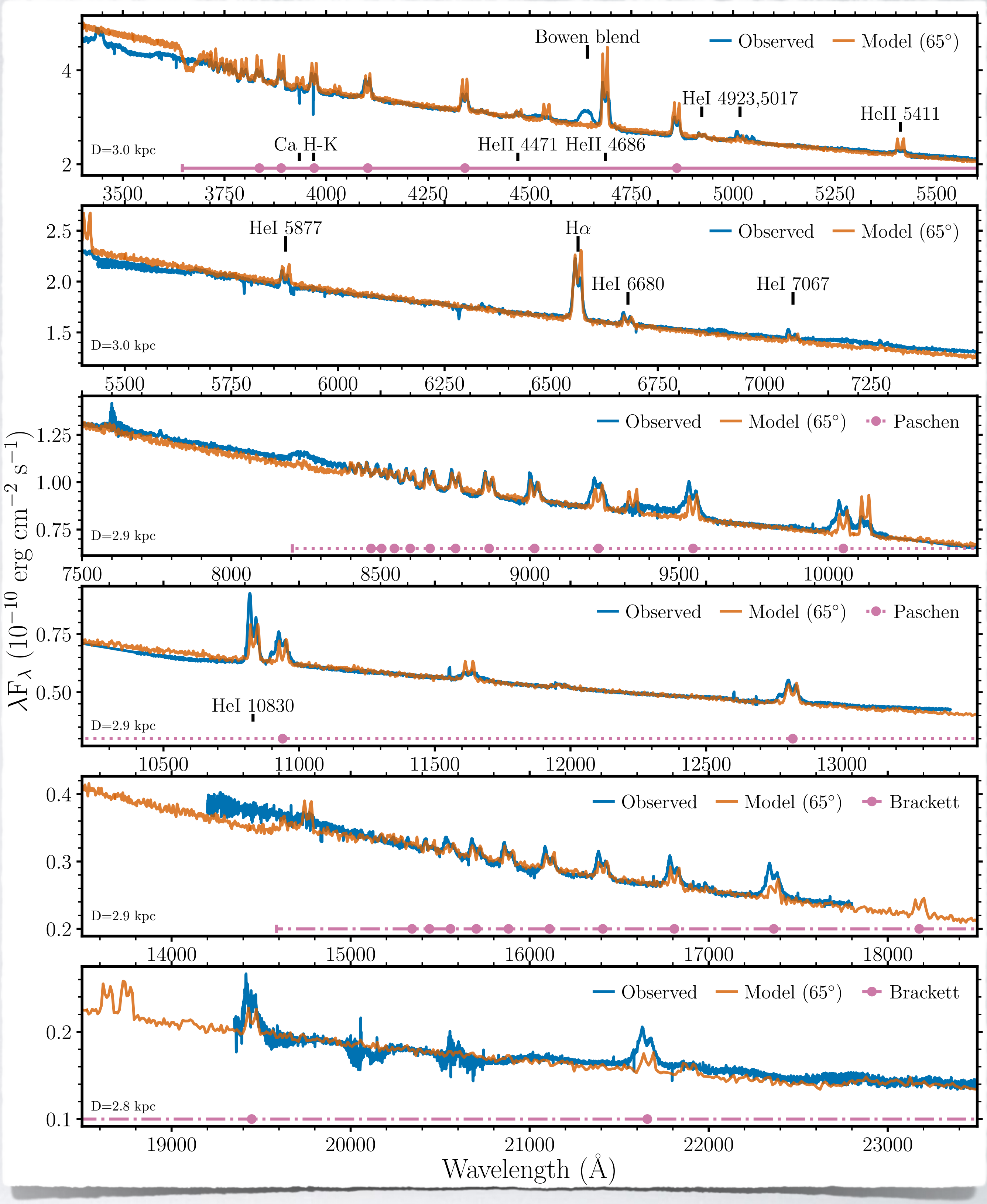
- 2018 outburst, soft-state XShooter VLT spectrum
- SED fit (incl. NuSTAR, Swift, NICER) with irradiated disc model
- Main features:
    - Rich emission line spectrum (Hydrogen series, He I and II, Ca II, Bowen)
    - Flat Balmer decrement (~1.3)
    - No obvious wind absorption features (consistent with Munoz-Darias 2019)
- MCRT biconical wind model provides excellent qualitative match to the spectrum



Koljonen, Long, JM+2020

MAXI J1820: Origin of soft state emission lines

- 2018 outburst, soft-state XShooter VLT spectrum
- SED fit (incl. NuSTAR, Swift, NICER) with irradiated disc model
- Main features:
  - Rich emission line spectrum (Hydrogen series, He I and II, Ca II, Bowen)
  - Flat Balmer decrement (~1.3)
  - No obvious wind absorption features (consistent with Munoz-Darias 2019)
- MCRT biconical wind model provides excellent qualitative match to the spectrum



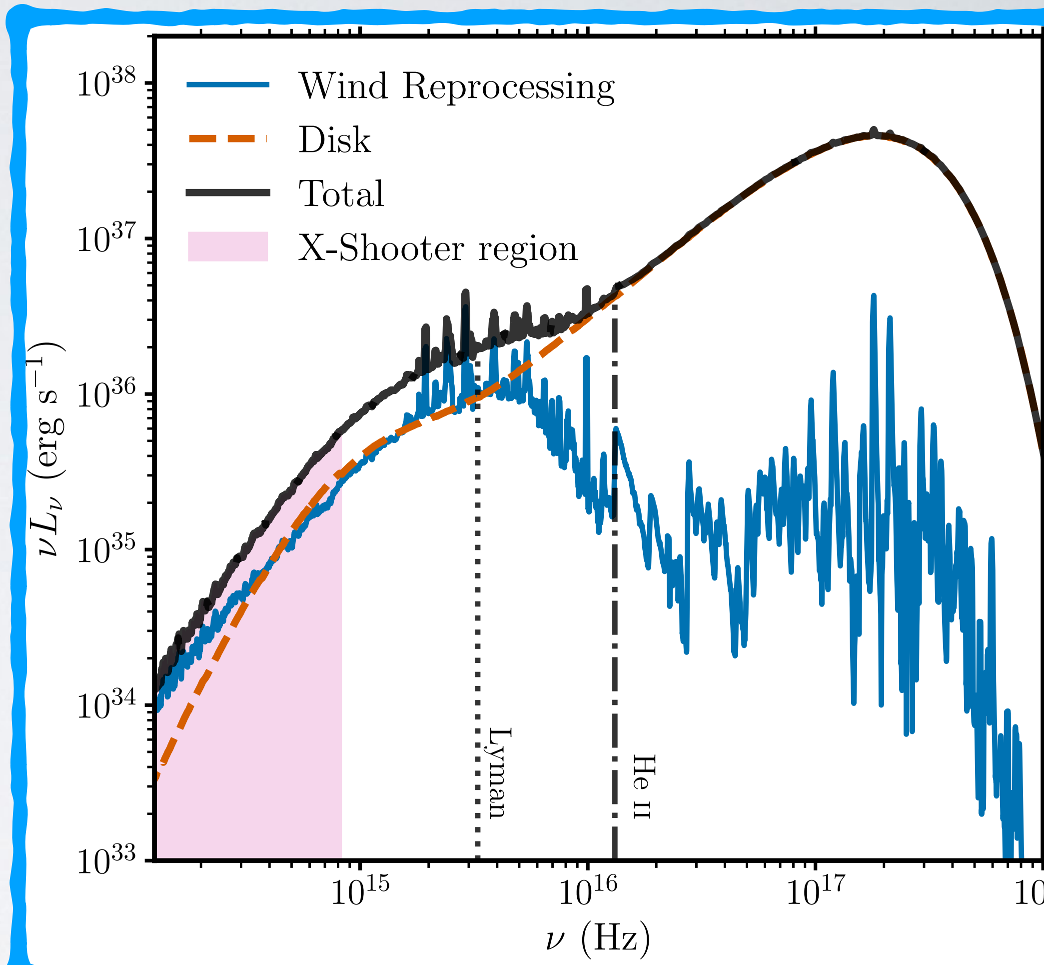
See also B.Tetarenko

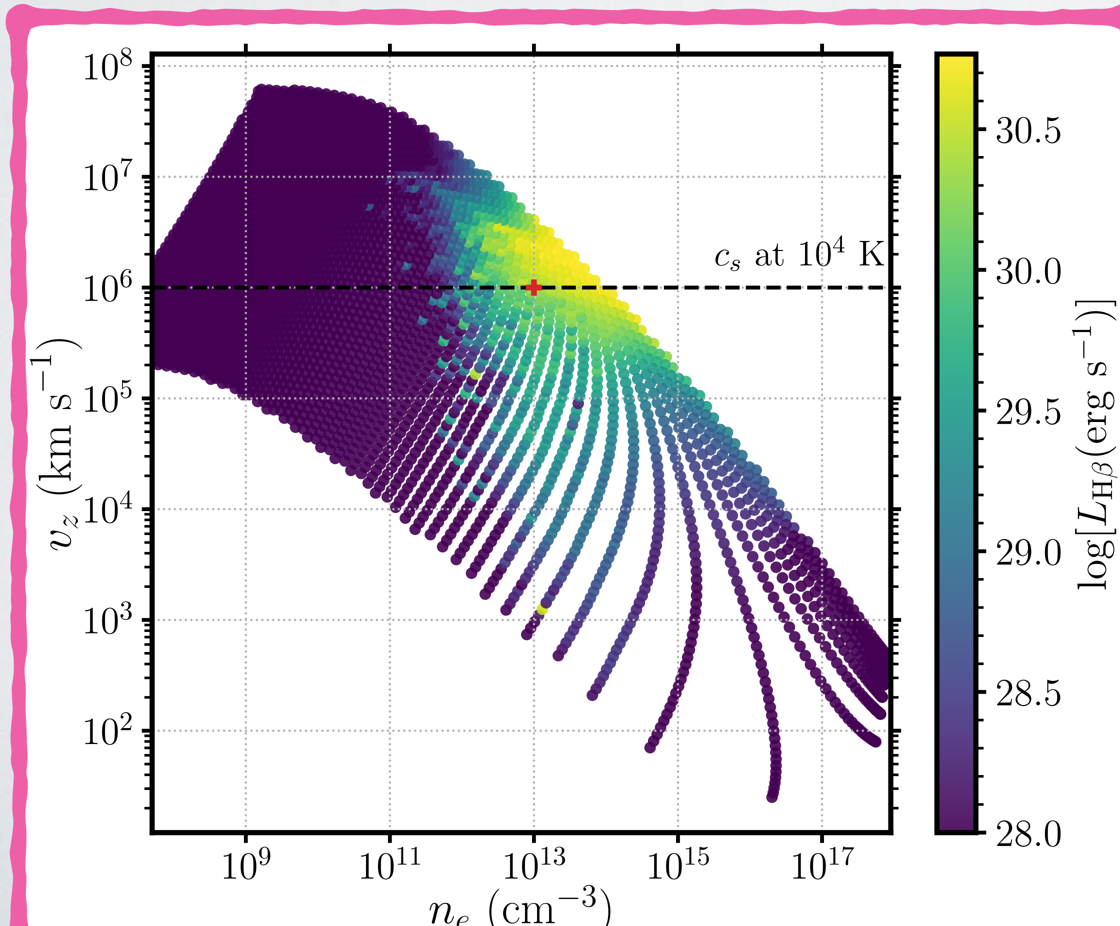
Koljonen, Long, JM+2020

Koljonen, Long, JM+2020

MAXI J1820: Reprocessing in a wind base?

Disc winds can be significant "continuum reprocessors" and change slope of continuum SED: consistent with our work on TDEs, AGN, CVs (Matthews+ 2015,2016; Parkinson+2022)



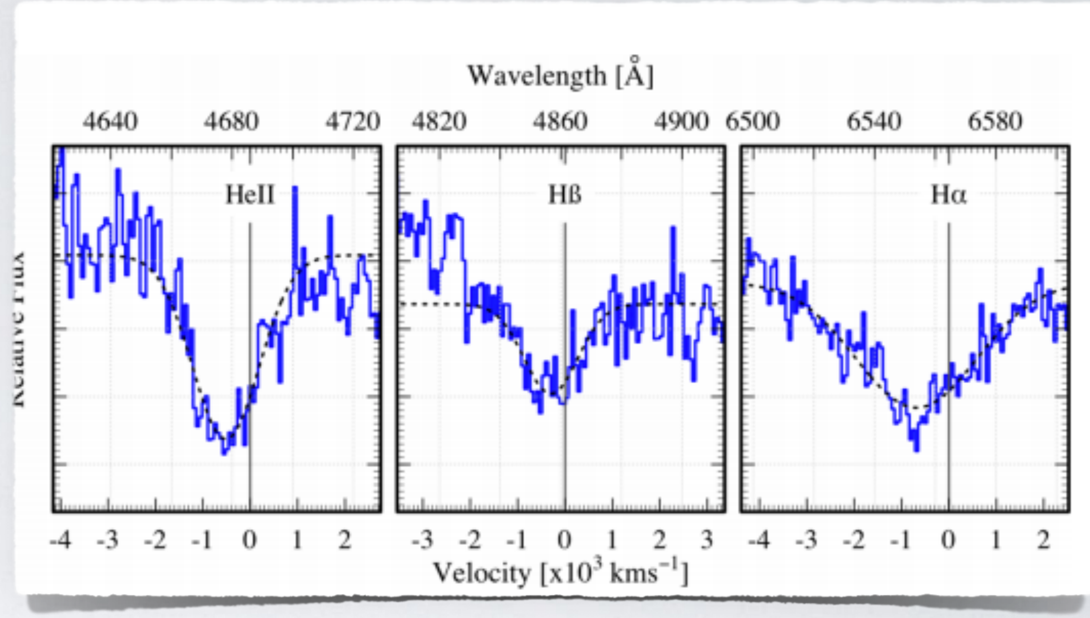


Emission lines consistent with coming from a disc wind base or "chromosphere", close to sonic point

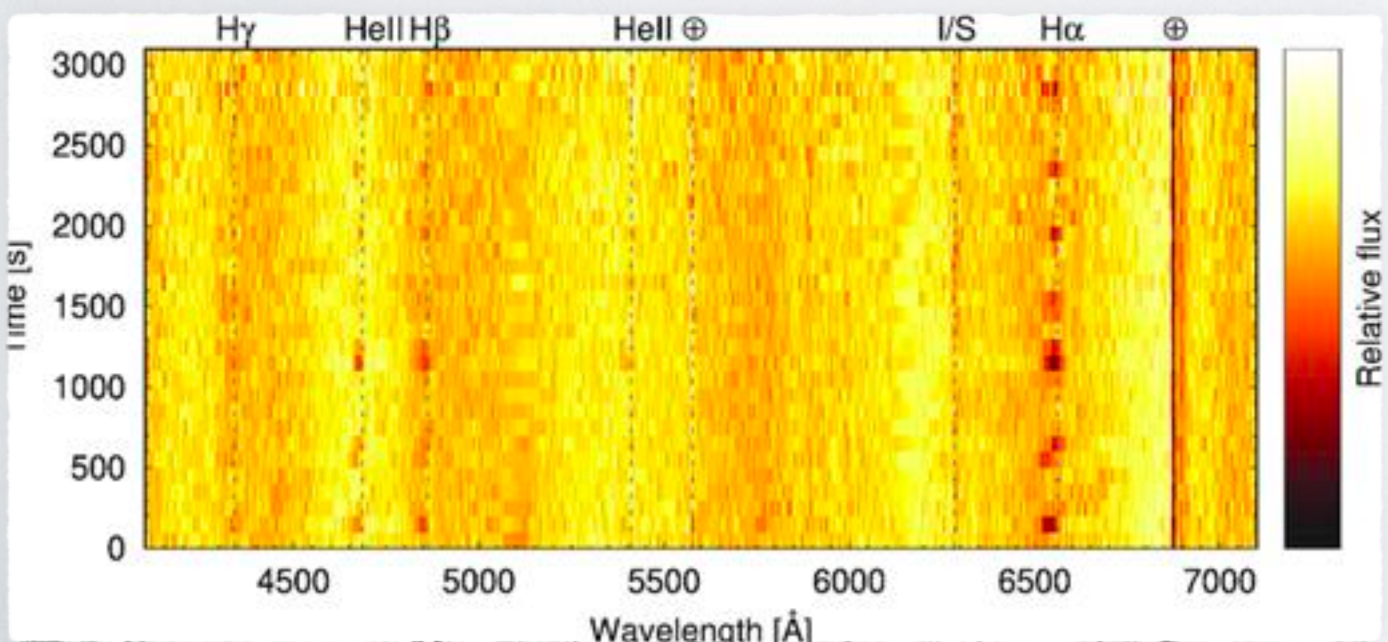
Charles, JM+2020

Swift J1357.2: Unprecedented He II absorption

- Swift J1357.2 is a faint X-ray transient with uncertain distance and primary
- Amazing quasi-periodic signatures in He II 4686 (first time ever in XRB?)
- We applied MCRT in a simple 1D model to see what conditions create He II line absorption



See also Caruso

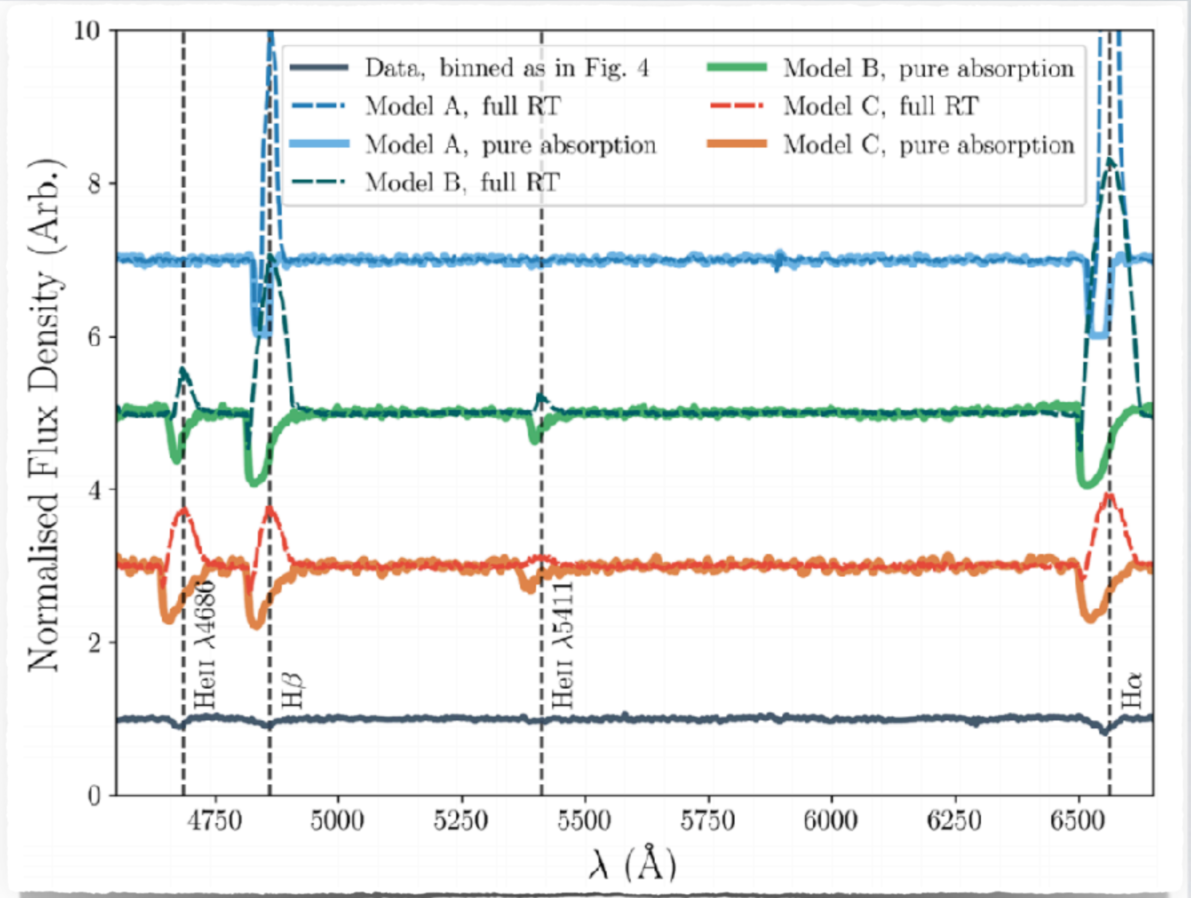


John Paice

Charles, JM+2020

Swift J1357.2: Unprecedented He II absorption

- Swift J1357.2 is a faint X-ray transient with uncertain distance and primary
- Amazing quasi-periodic signatures in He II 4686 (first time ever in XRB?)
- We applied MCRT in a simple 1D model to see what conditions create He II line absorption



See also Caruso

Dense hot outflowing wind: $T_e \gtrsim 30{,}000$ K, $N_H \gtrsim 10^{24}$ cm^{-3}

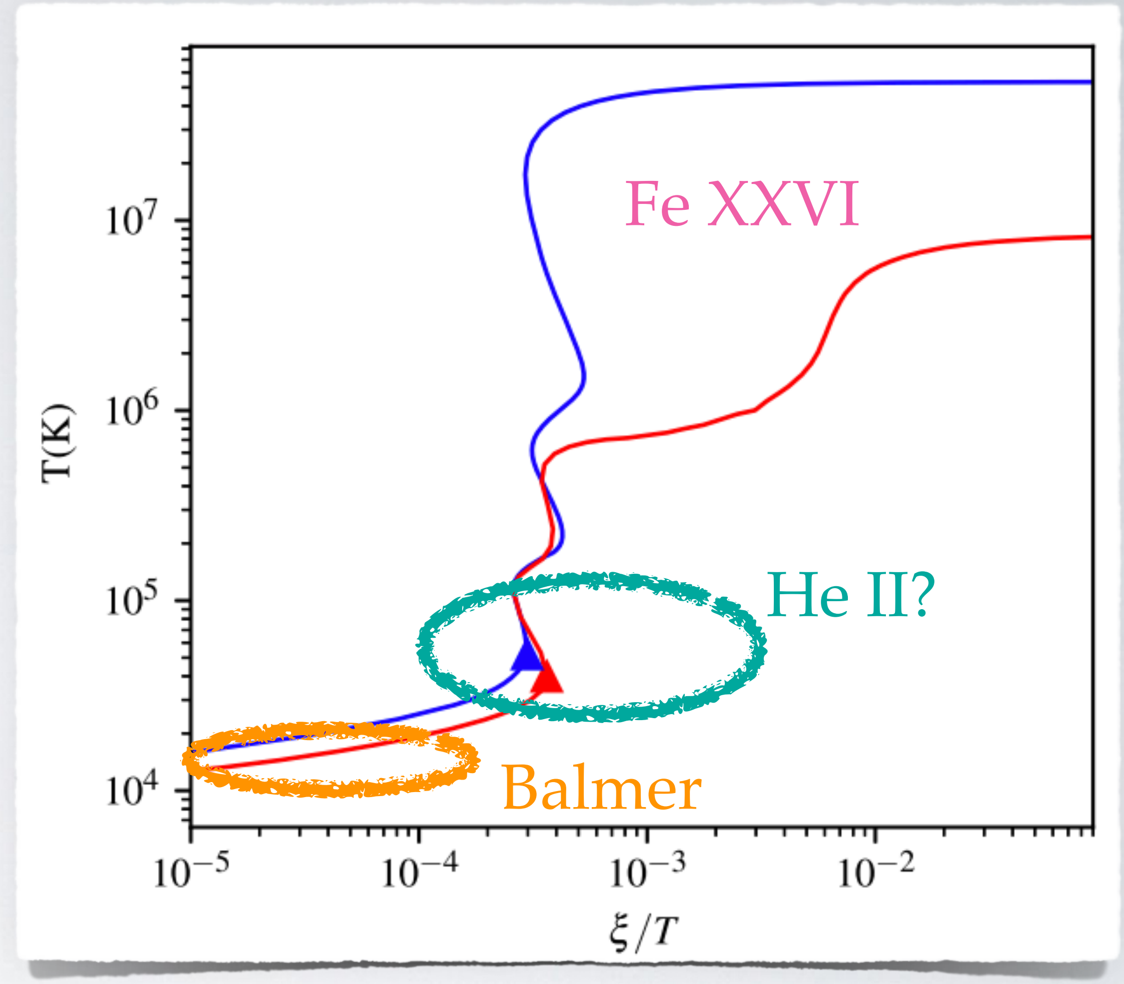
High (intrinsic) X-ray luminosity needed: $L_X \gtrsim 4 \times 10^{36}$ erg s^{-1}

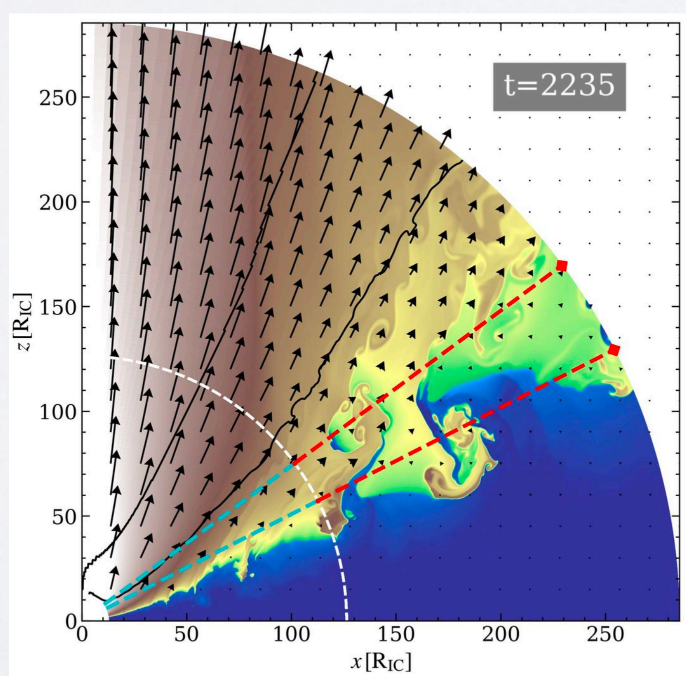
A truly remarkable BH ADC system with quasi-periodic He II 4686 + Balmer absorption on a variable dip period

Work ongoing on 2019 outburst with Jaco Brink, Phil Charles, David Buckley

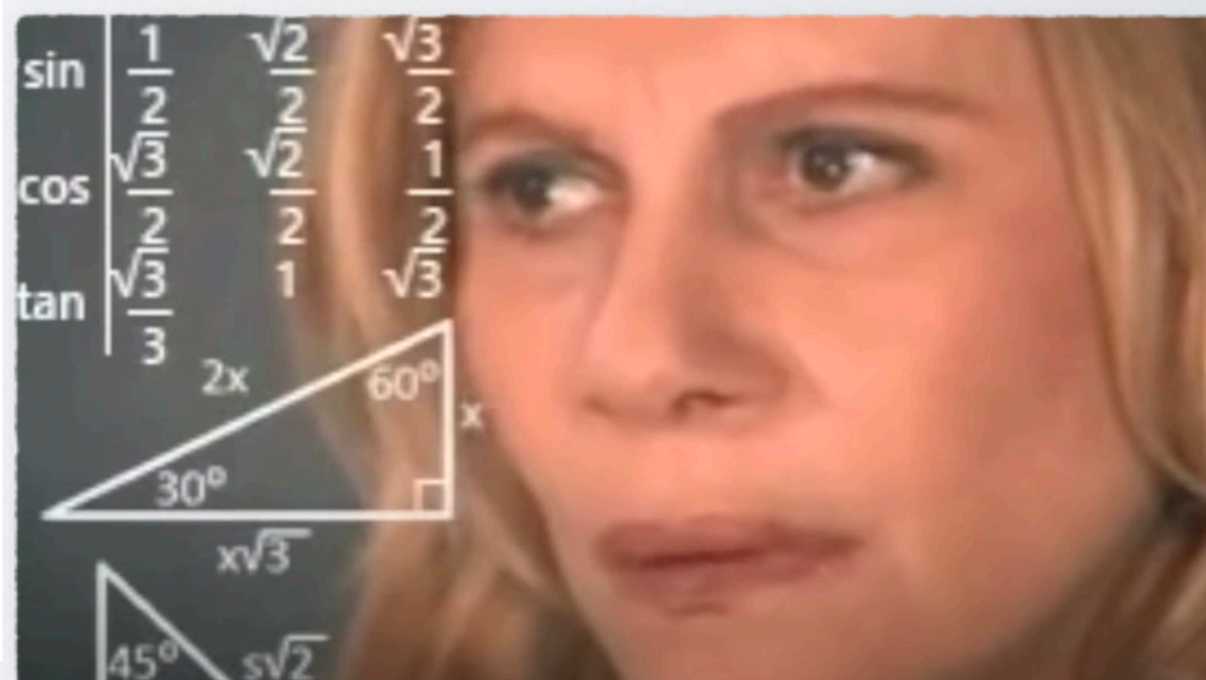
The challenge of cold outflows

- Fast material is hot, so how do you get "cold" 10^4-10^5 K winds?
- Clumping/condensation due to thermal instability doesn't work once thermal wind is developed (*"can't move left"*)
- MHD wind might work, but need high mass loss rates and/or clumping mechanisms
- Clumping near wind base a la Waters et al. 2019?
- More work needed!



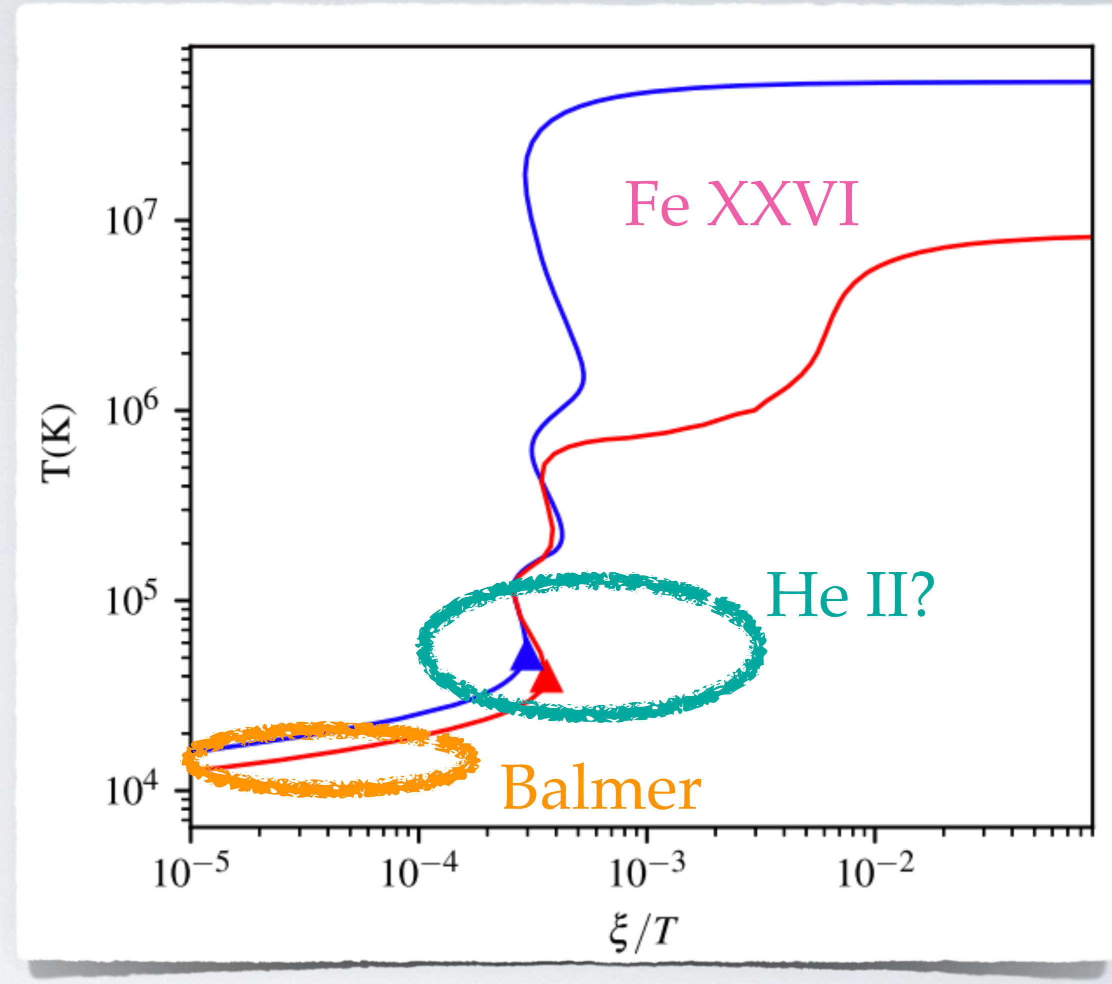


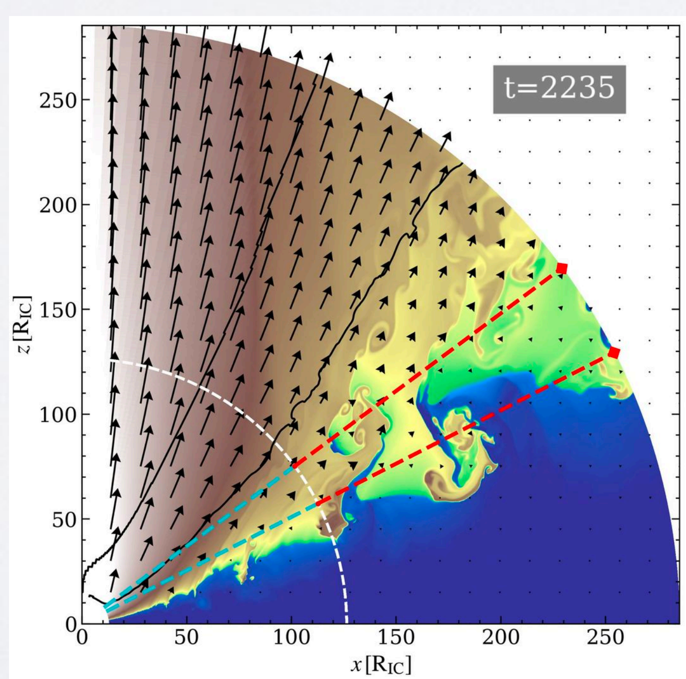
Waters+ 2019



The challenge of cold outflows

- Fast material is hot, so how do you get "cold" 10^4-10^5 K winds?
- Clumping/condensation due to thermal instability doesn't work once thermal wind is developed (*"can't move left"*)
- MHD wind might work, but need high mass loss rates and/or clumping mechanisms
- Clumping near wind base a la Waters et al. 2019?
- More work needed!

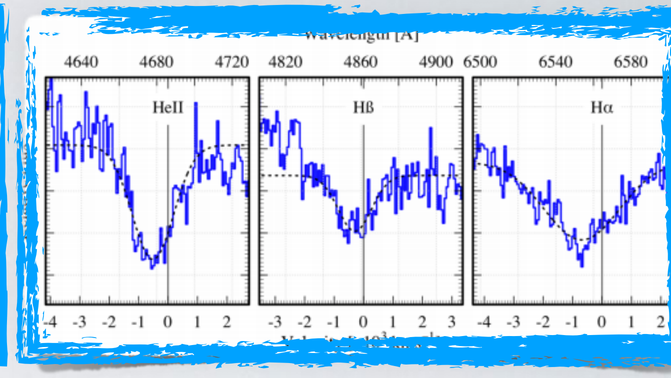




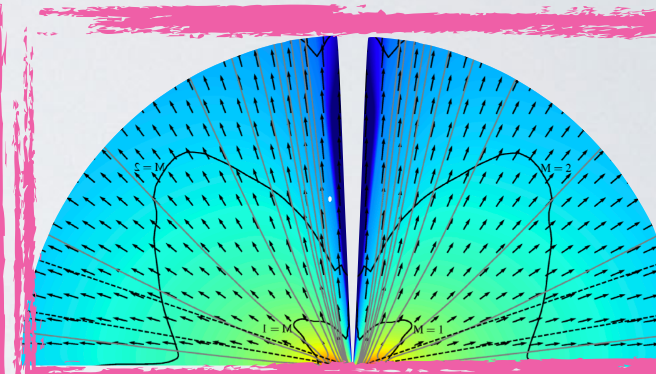
Waters+ 2019

Take-home Messages

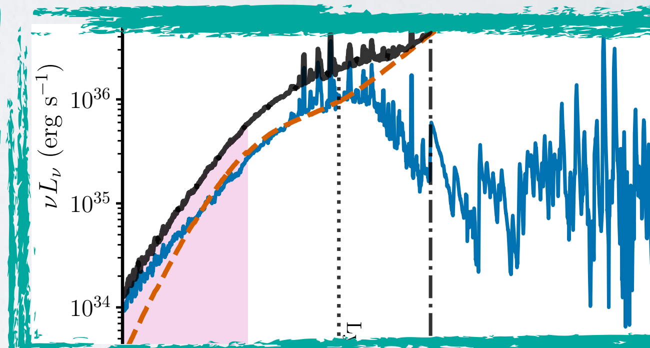
Rich, varied multiphase phenomenology
of optical-UV disc winds



Radiative transfer and hydrodynamics matters



It's not just lines: Winds and atmospheres are important continuum reprocessors



Physics of optical winds is unclear

Slides available at jhmatthews.github.io/microquasar