Understanding accretion in X-ray Binaries: WINDS

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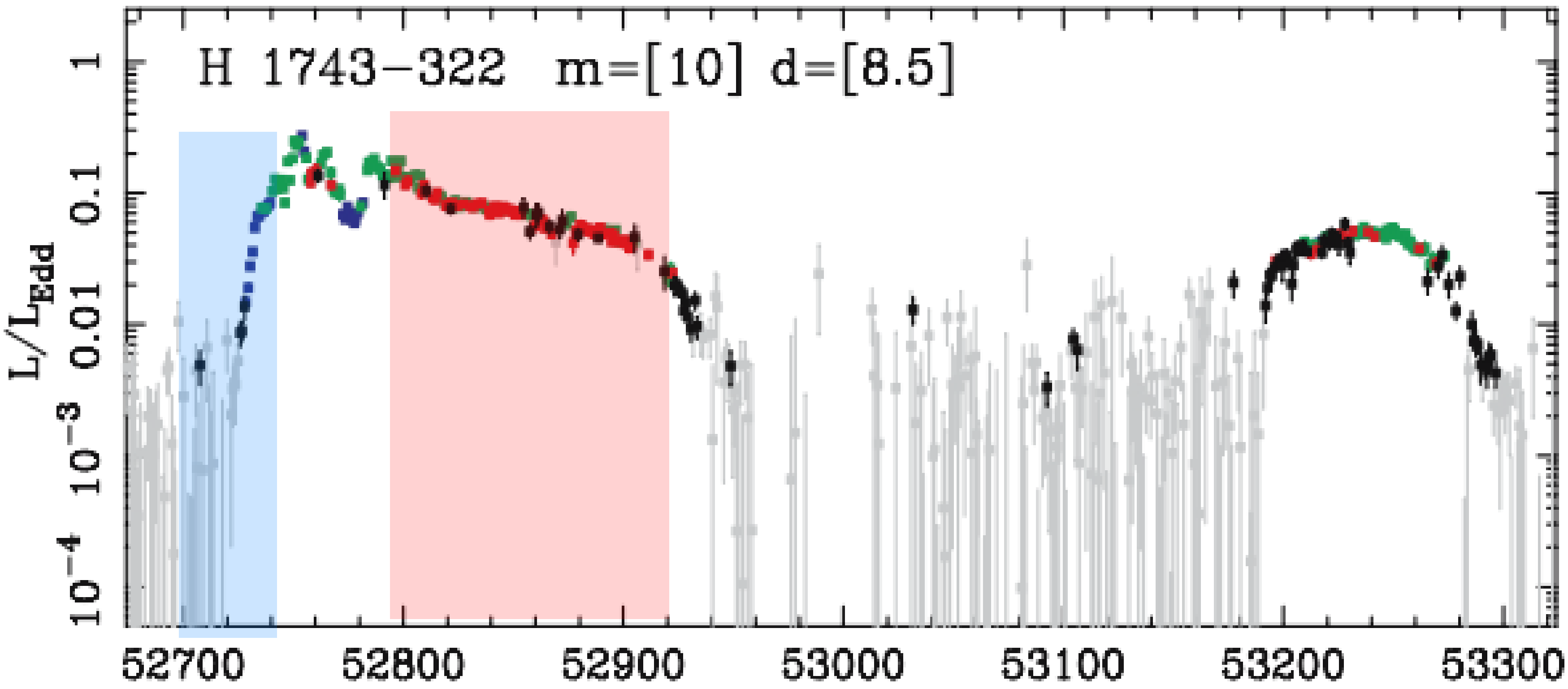
Stellar mass Black Hole Binaries

Accretion disc instability at H ionisation

Fast rise: few days- week

Slow decline: months. Need effective α>0.1-0.2

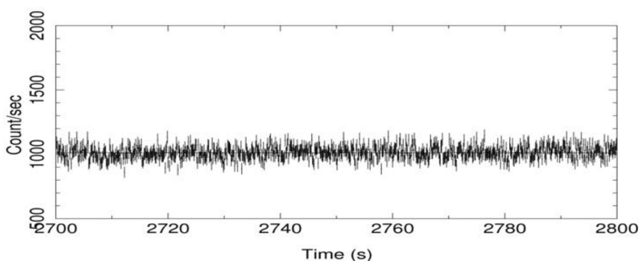


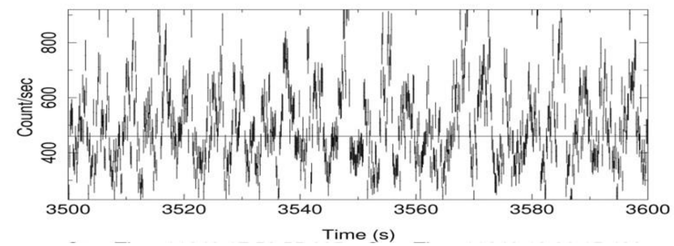
Fender, Belloni, Gallo 2004

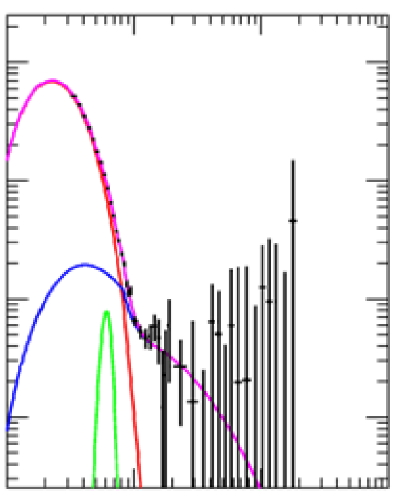
Soft, thermal
No fast var

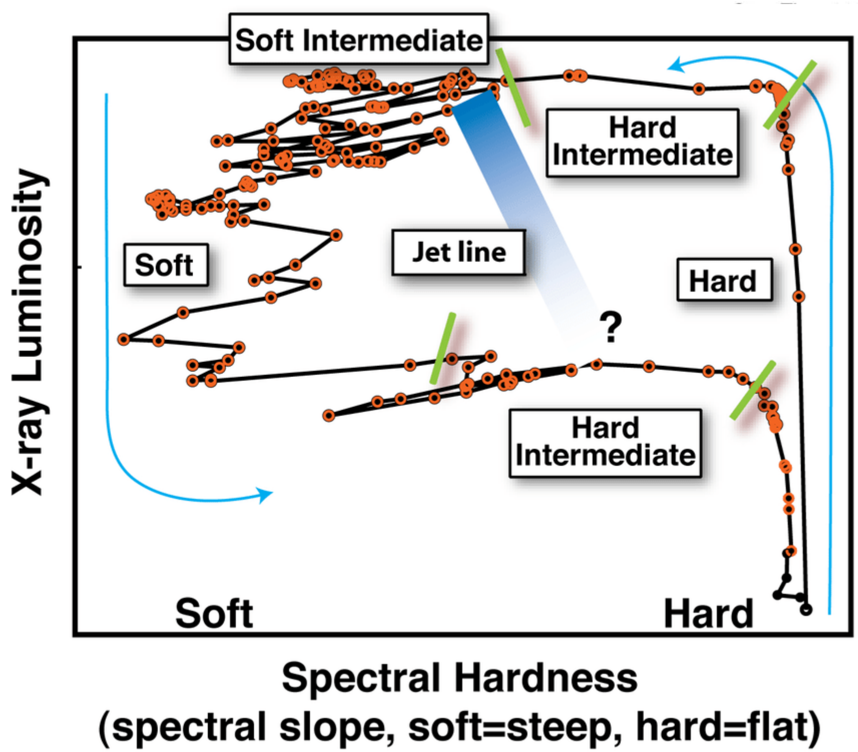
Disc + steep corona

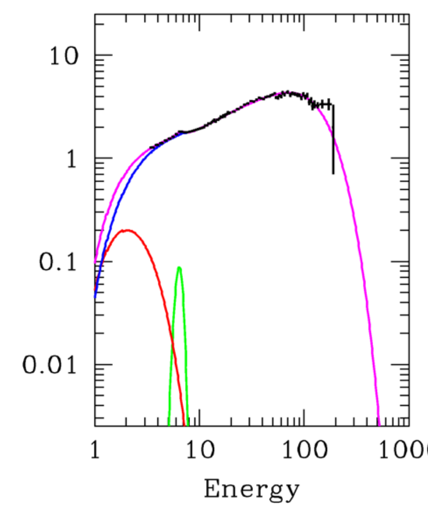
hard, Compton
Fast var



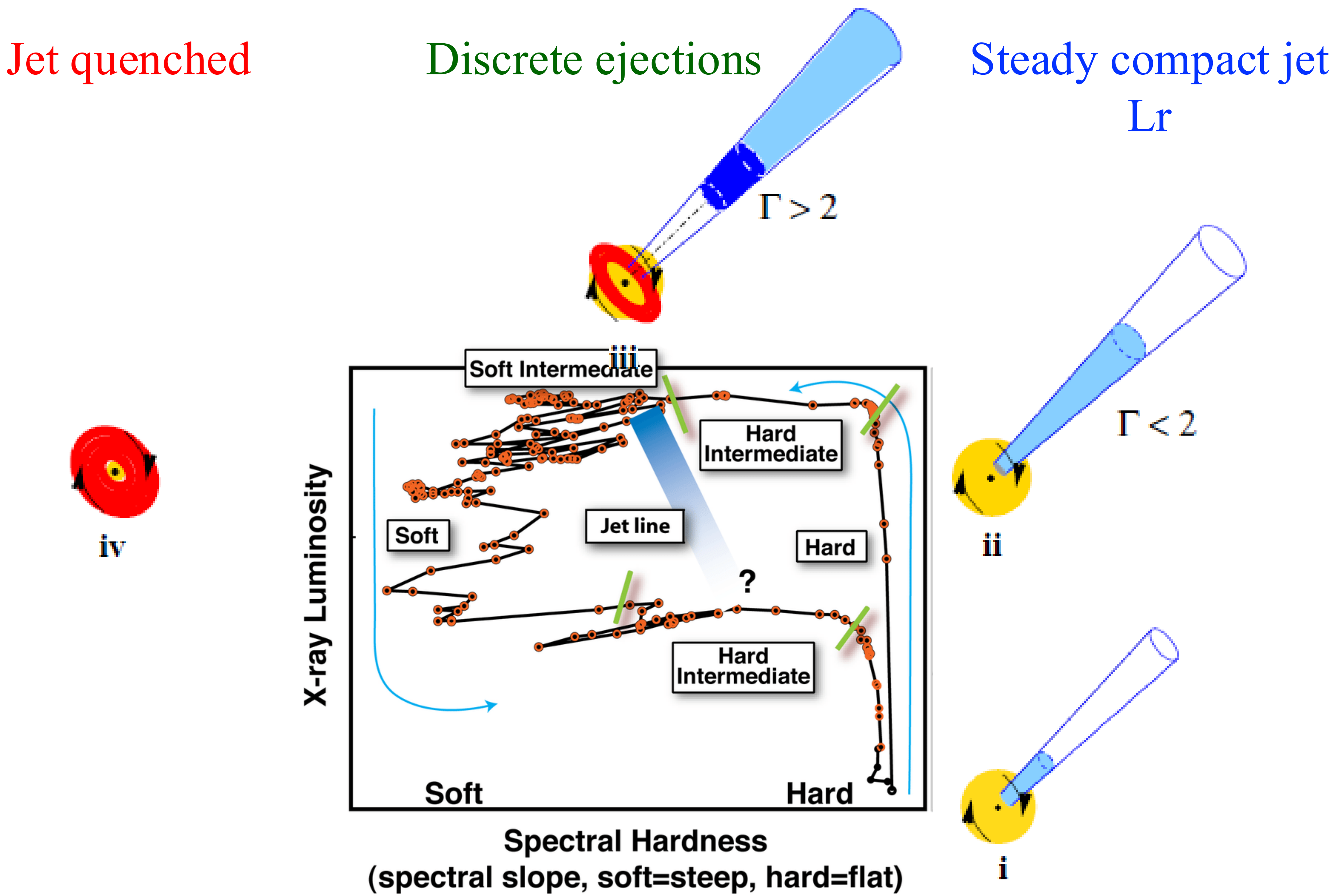




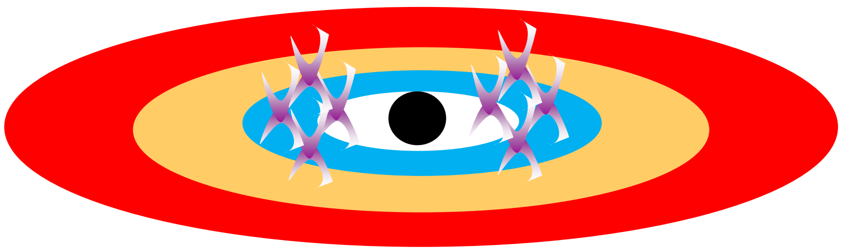


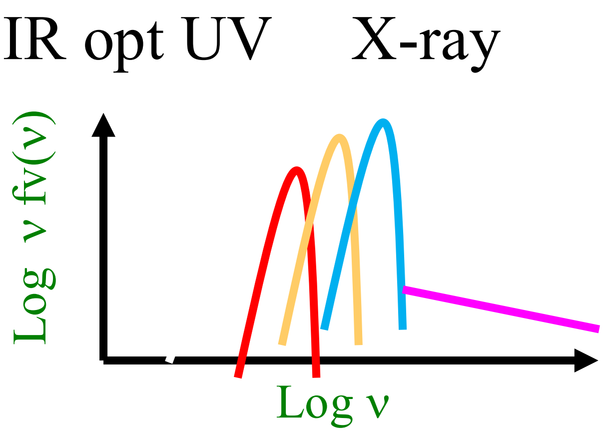


Fender, Belloni, Gallo 2004

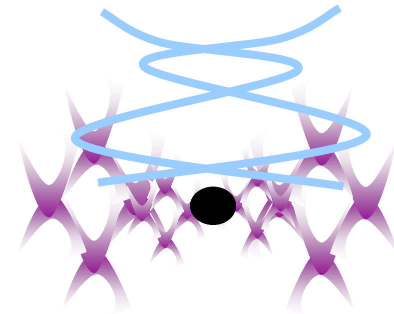


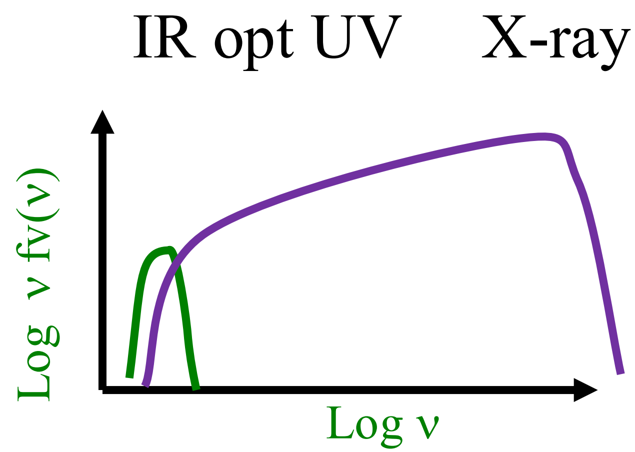
Analytic(hydro) theory of accretion





Discs: geometrically thin, cool,
optically thick SS73
Q=α(Prad+Pgas): L/LEdd<0.05
Main body of flow opaque





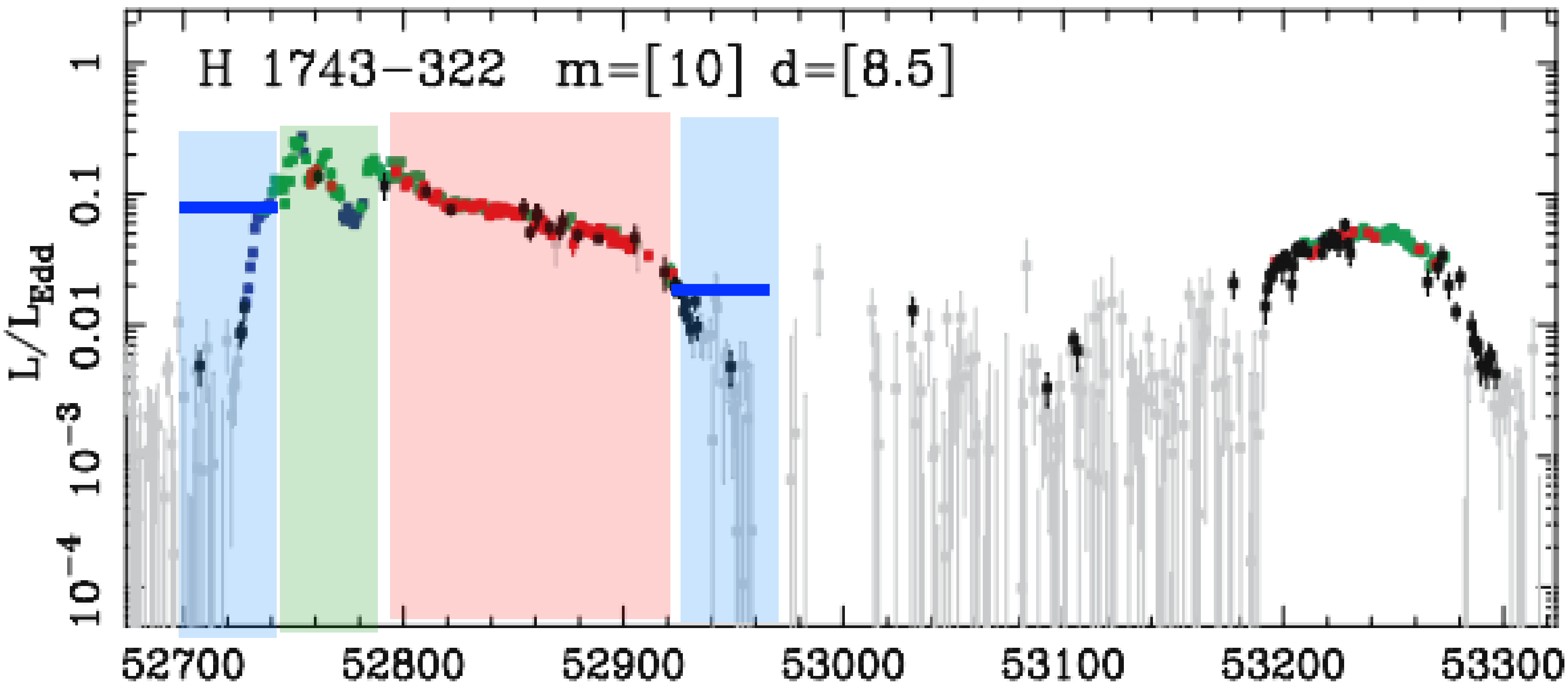
ADAF/RIAF geometrically thick,
hot, optically thin Narayan+Yi 95
Ti≠Te: L/LEdd <0.02
Main body of flow seen!
Supports B field for jet

Stellar mass Black Hole Binaries

Accretion disc instability at H ionization

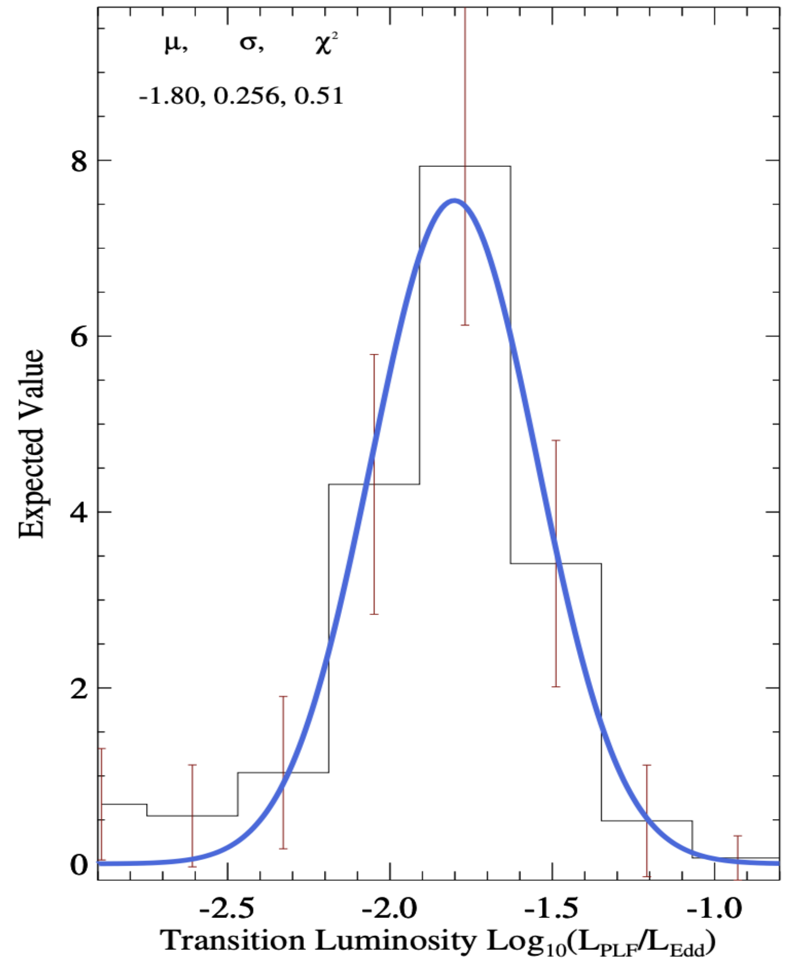
Fast rise: few days-week (out of steady state??)

Slow decline: months (steady state) X-ray irradiation keeps SS disc hot. Quiescence: disc drains on tvisc.



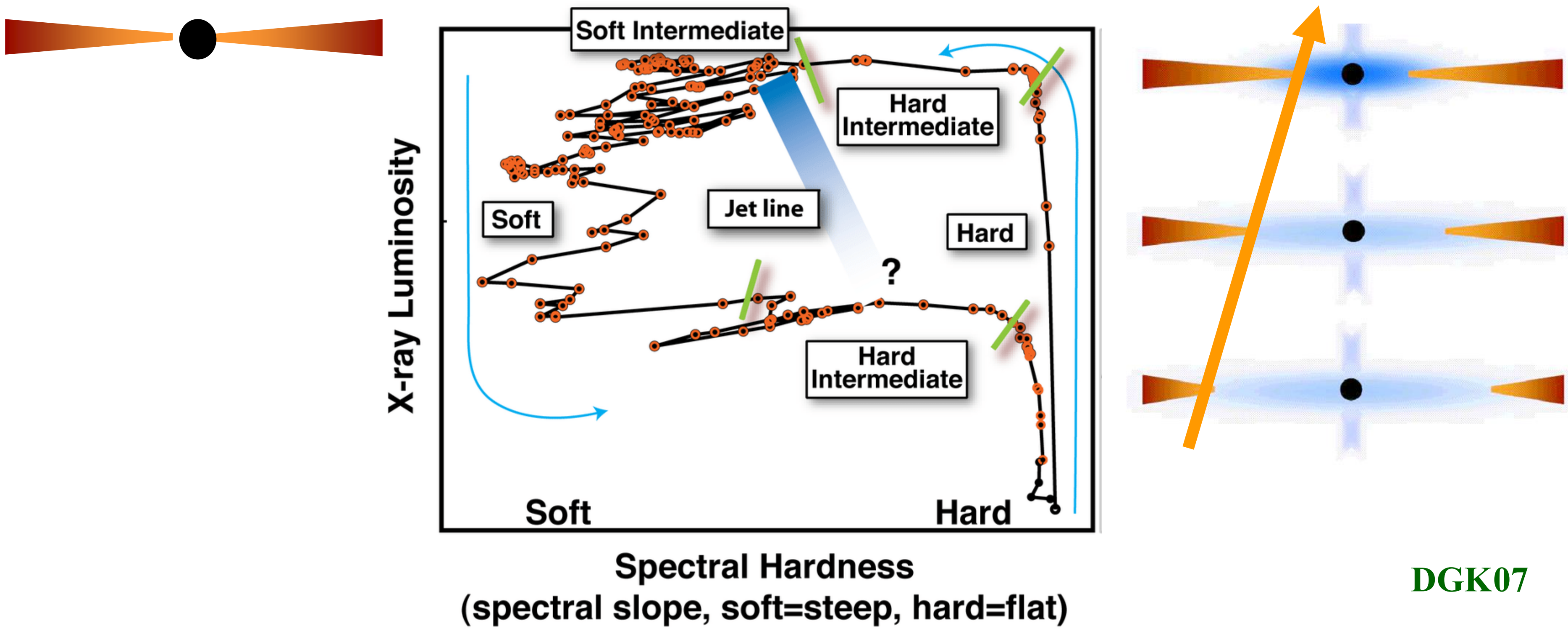
Spectral evolution in BHB outburst

- Hard-soft transition on fast rise – out of steady state?
- Soft-hard transition is on slow decline
- Picks out well defined ADAF max$1.3\alpha^2$ LEdd
- See on slow decline
- Maccarone 2003
- But not on fast rise! Hysteresis



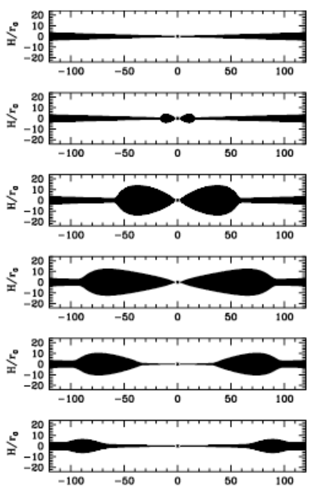
Vahdat Motlagh+ 2019

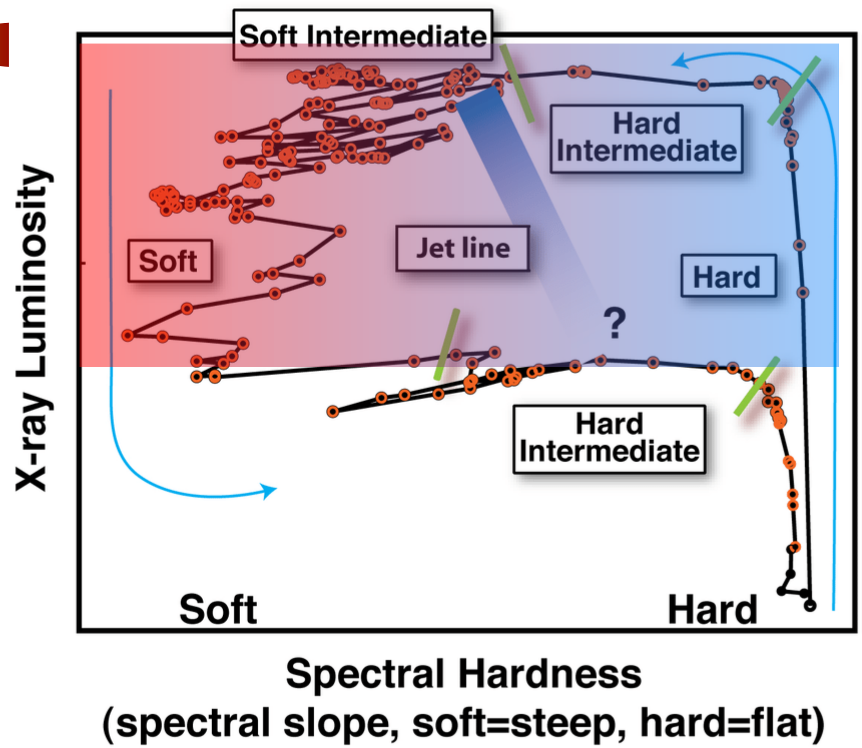
Accretion flow/jet evolution on HID

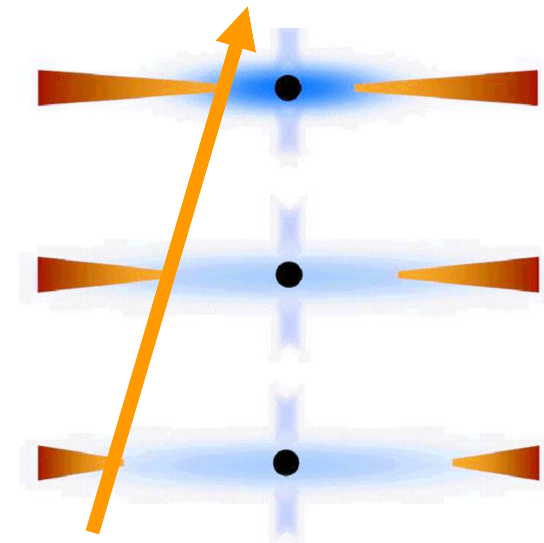


DGK07

NO MODEL FOR ALL BRIGHT



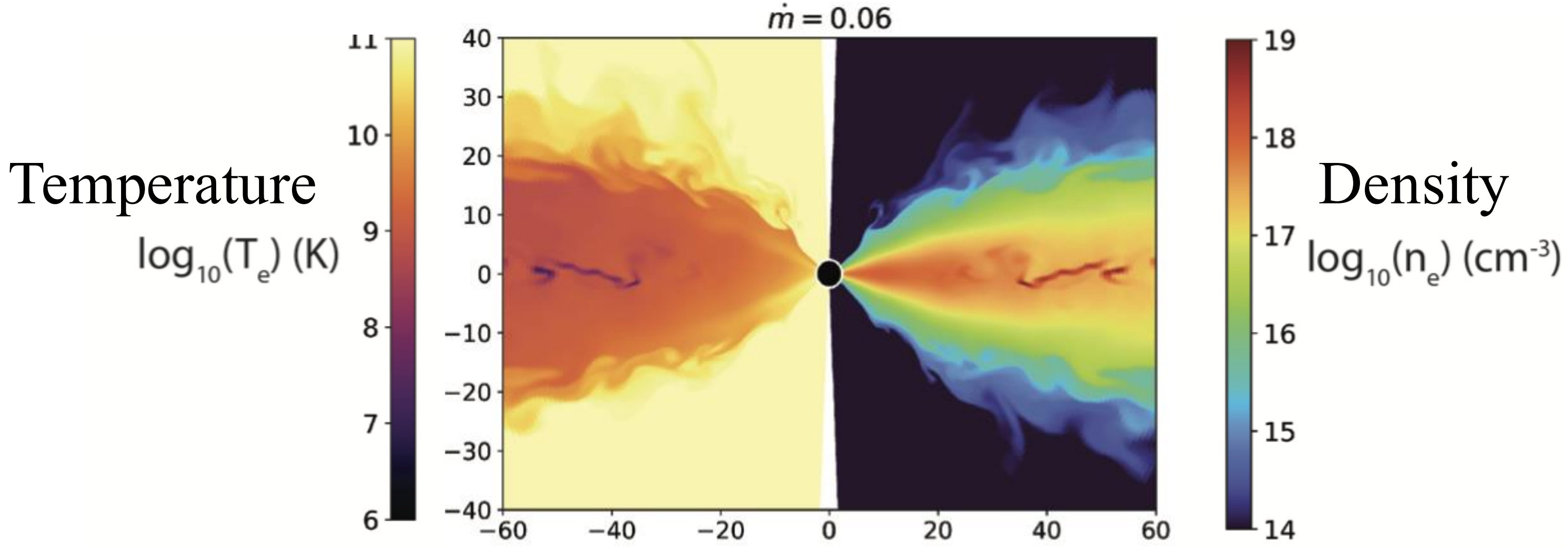




DGK07

- Heating α Ptot is Prad unstable. Not Ptot - MRI P_B ? Blaes+2025
- ADAF L(max)=1.3α^2 Ledd –bigger α on fast rise due to hydrodynamic turbulence coupling to MRI ??

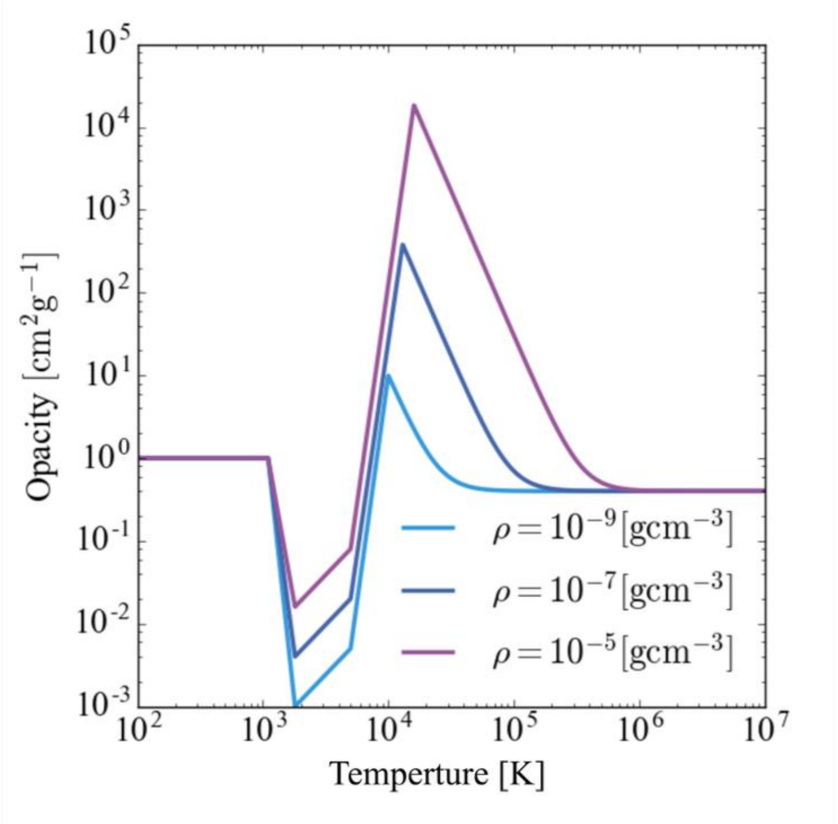
Thermal instability: disc-hot flow?

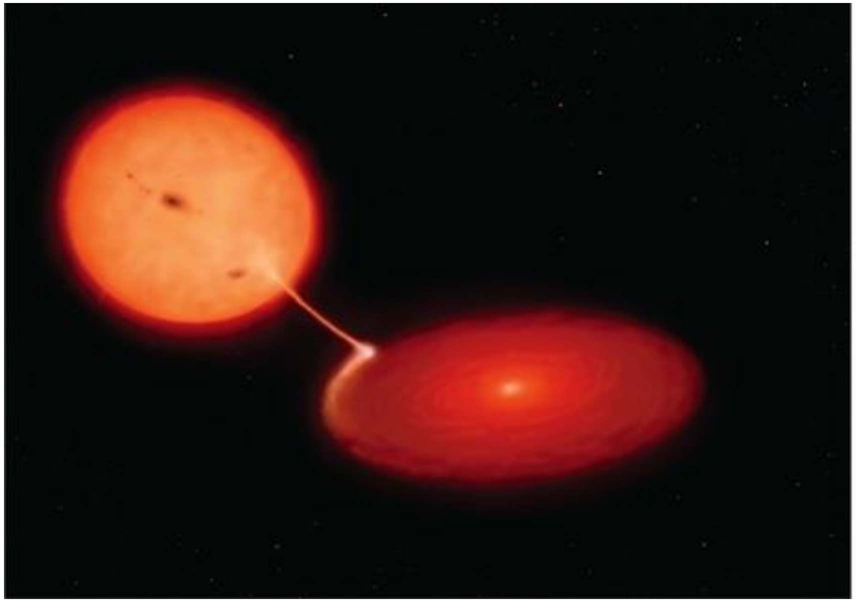


- Nemmen+ 2024. Hydrodynamics (no B field, α viscosity) Pluto
- Optically thin cool: 2Te,ions, brems, sync - tangled B, SSC
- Optically thick cool: atomic to blackbody (Hubeny+ 1990)

H ionisation disc instability

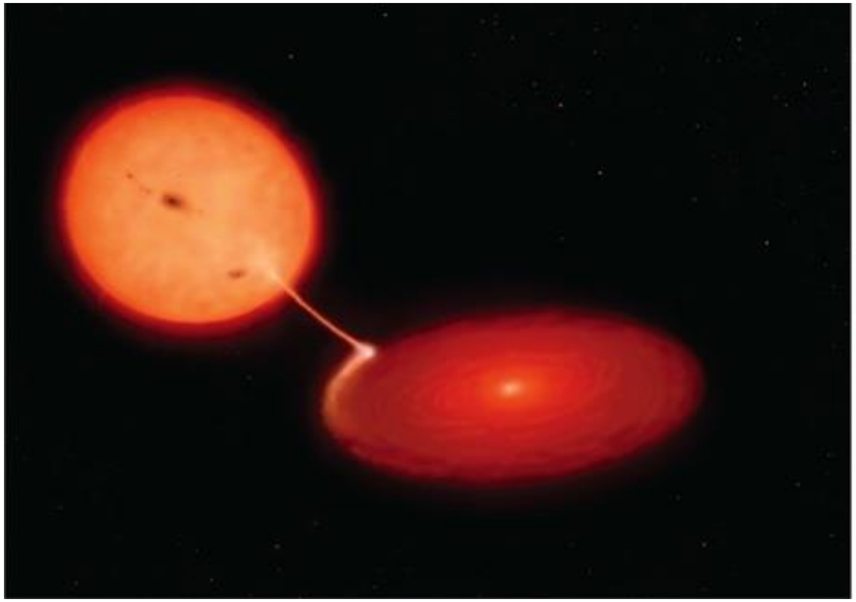
- ring at circularization radius
- H ionisation 6000K opacity jumps x10^6 for x3 in T

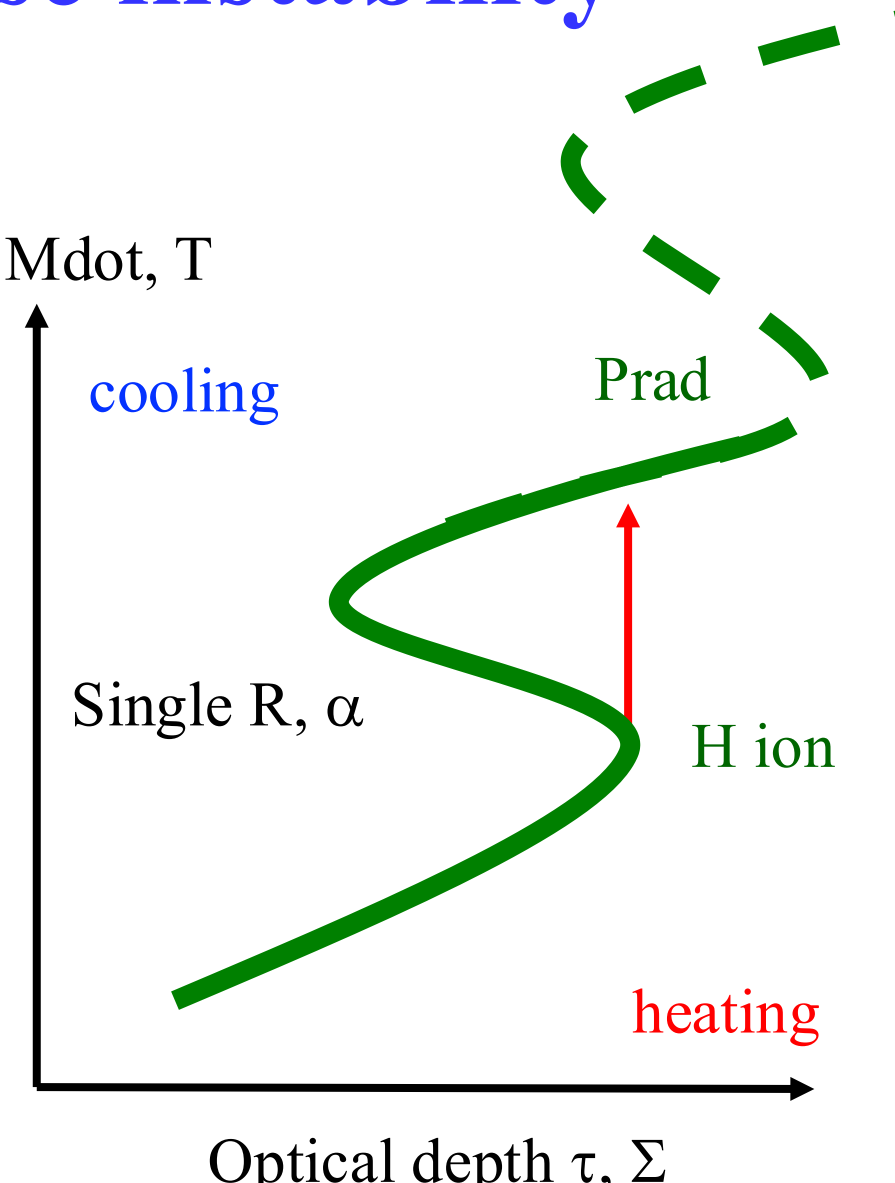




H ionisation disc instability

- ring at circularization radius
- Increases in surface density and temperature
- Crosses 6000K, opacity jumps, disk heats up, corresponds to bigger Mdot
- Heating=cooling S curve





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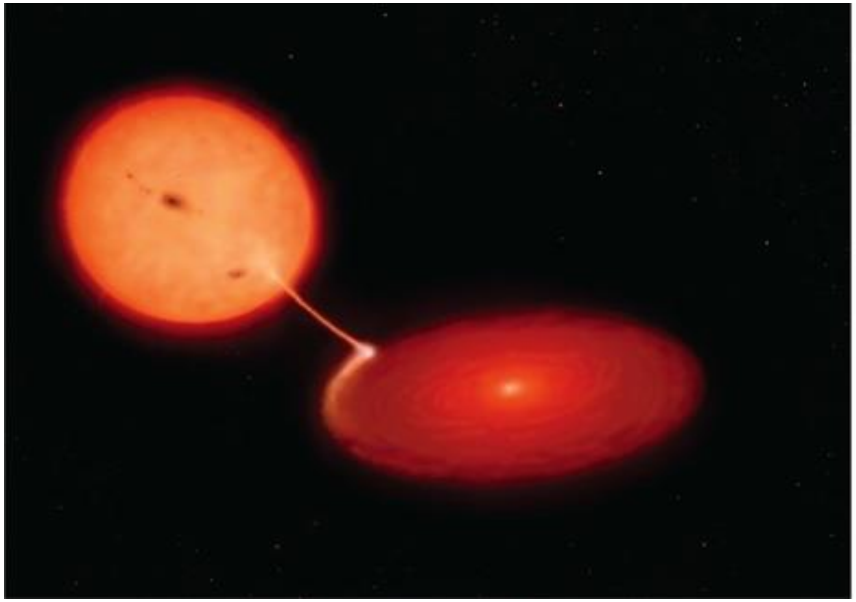
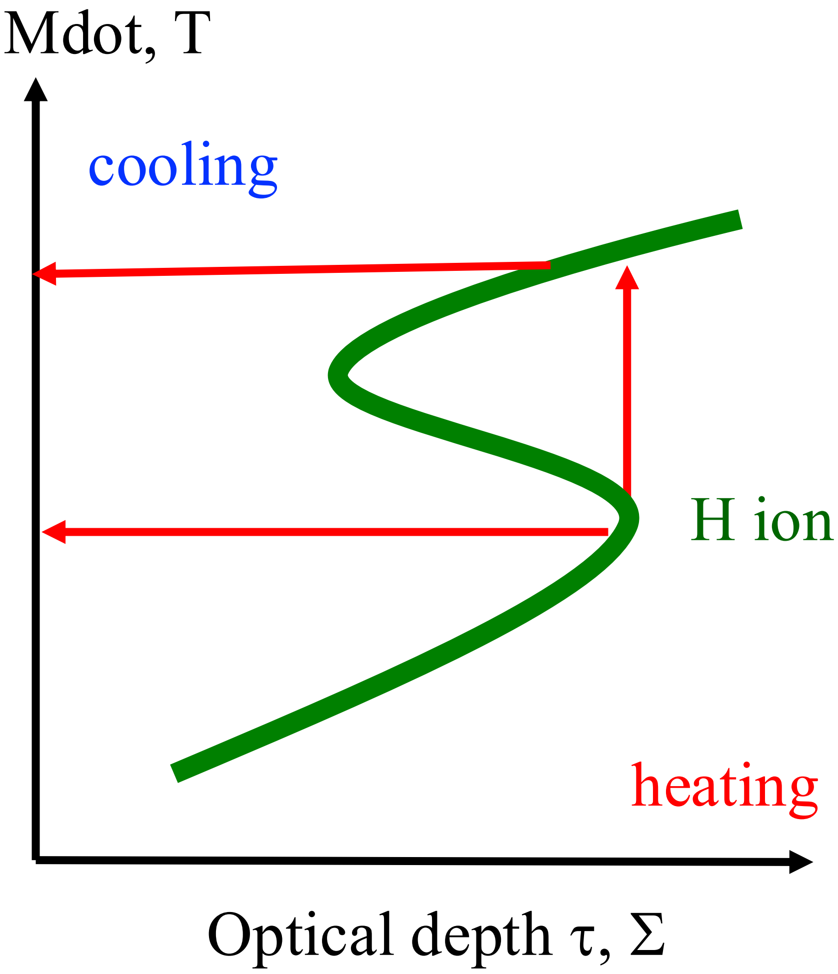
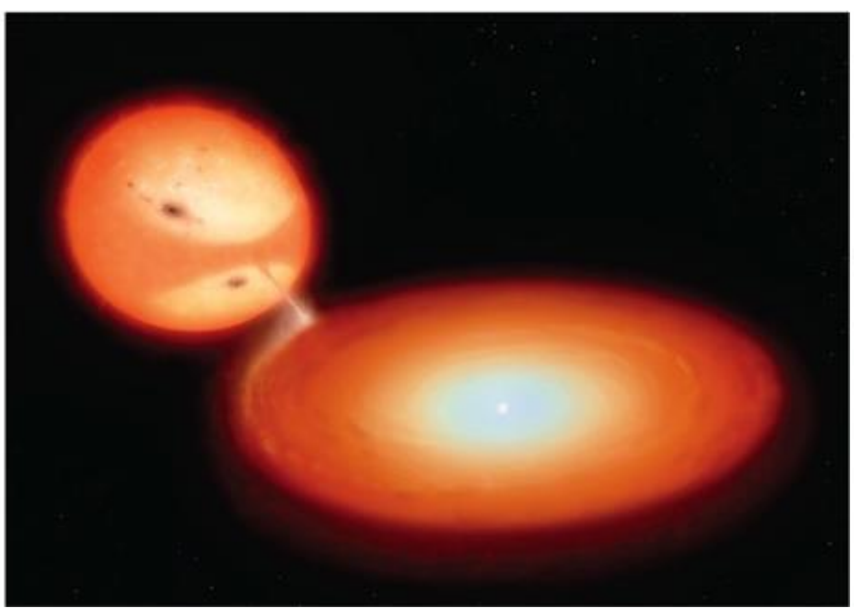
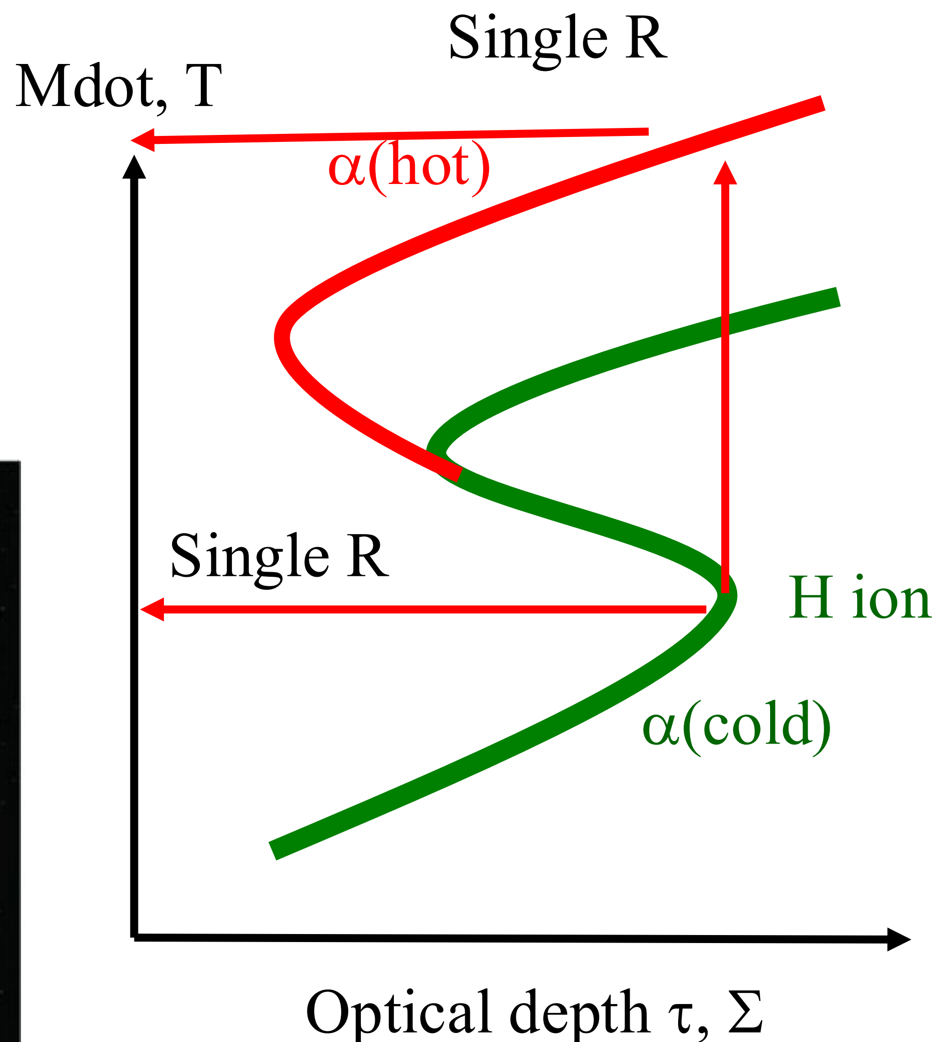




H ionisation disc instability

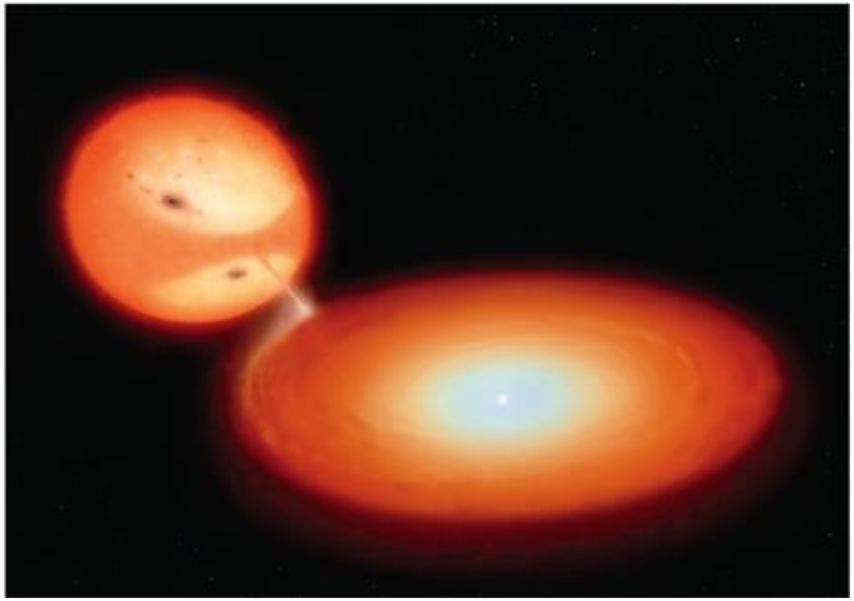
- triggers alpha change
- Increases jump in mdot
- So the next ring inwards hits instability also
- Grows into global instability
- Osaki, Smak….

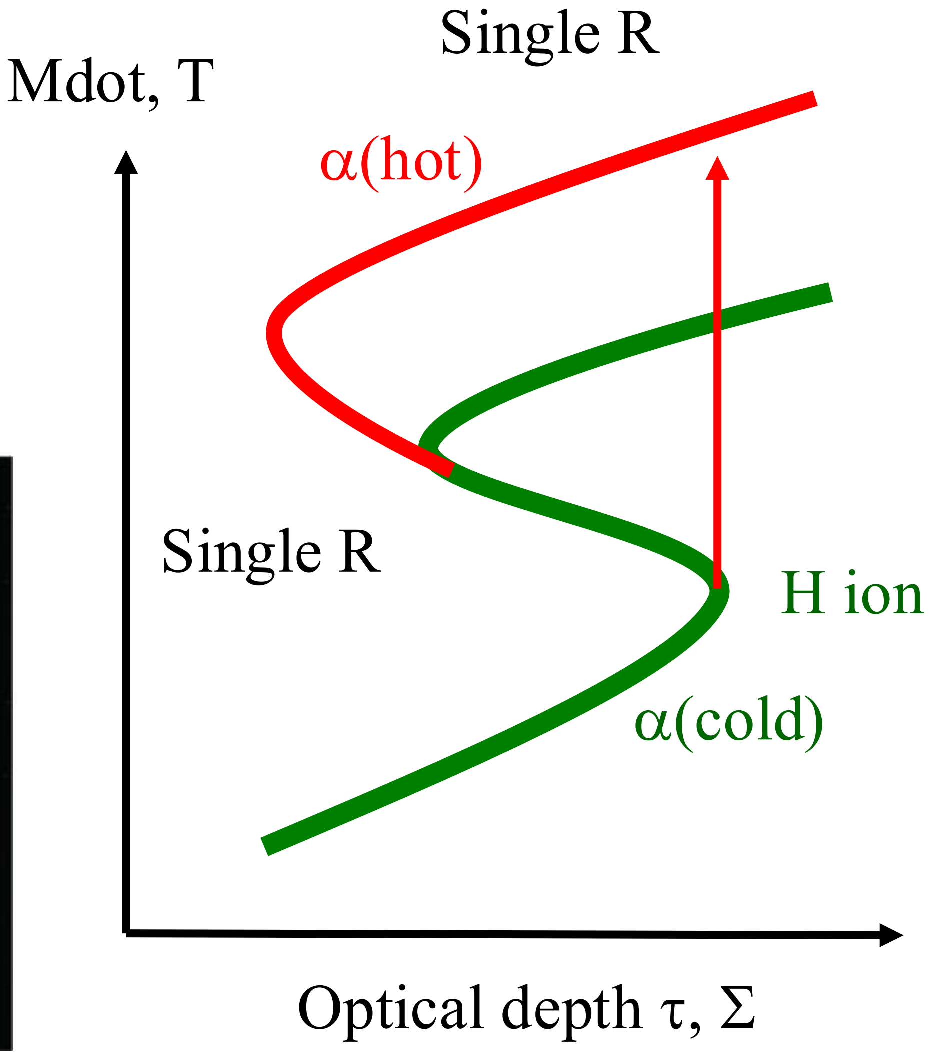




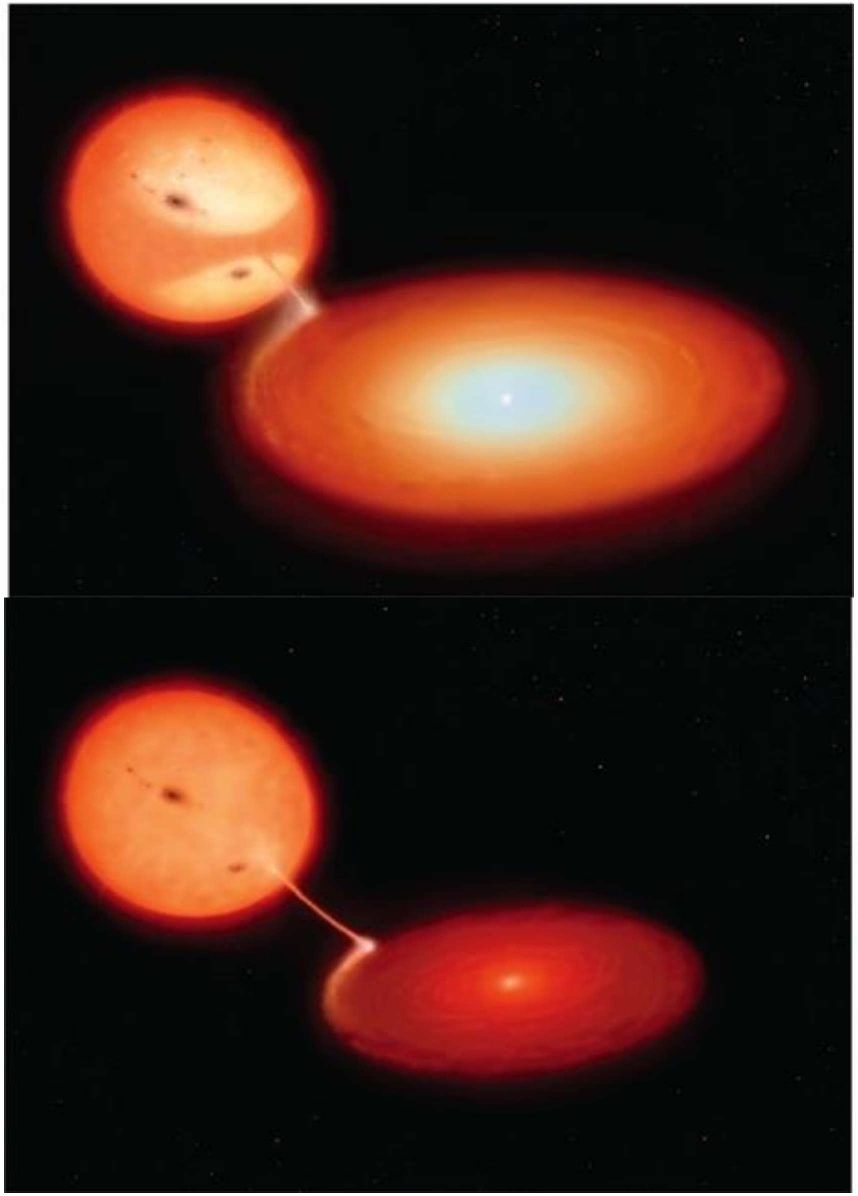
H ionisation disc instability

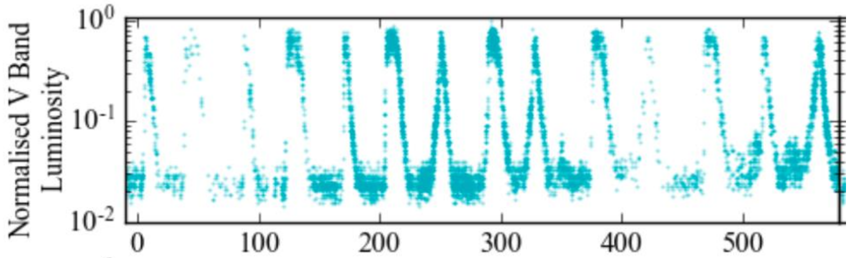
- What sets α(hot)?
- MRI ~0.01 rather than >0.1
- What sets α(cold) ?
- MRI goes to 0!! Scepi et al





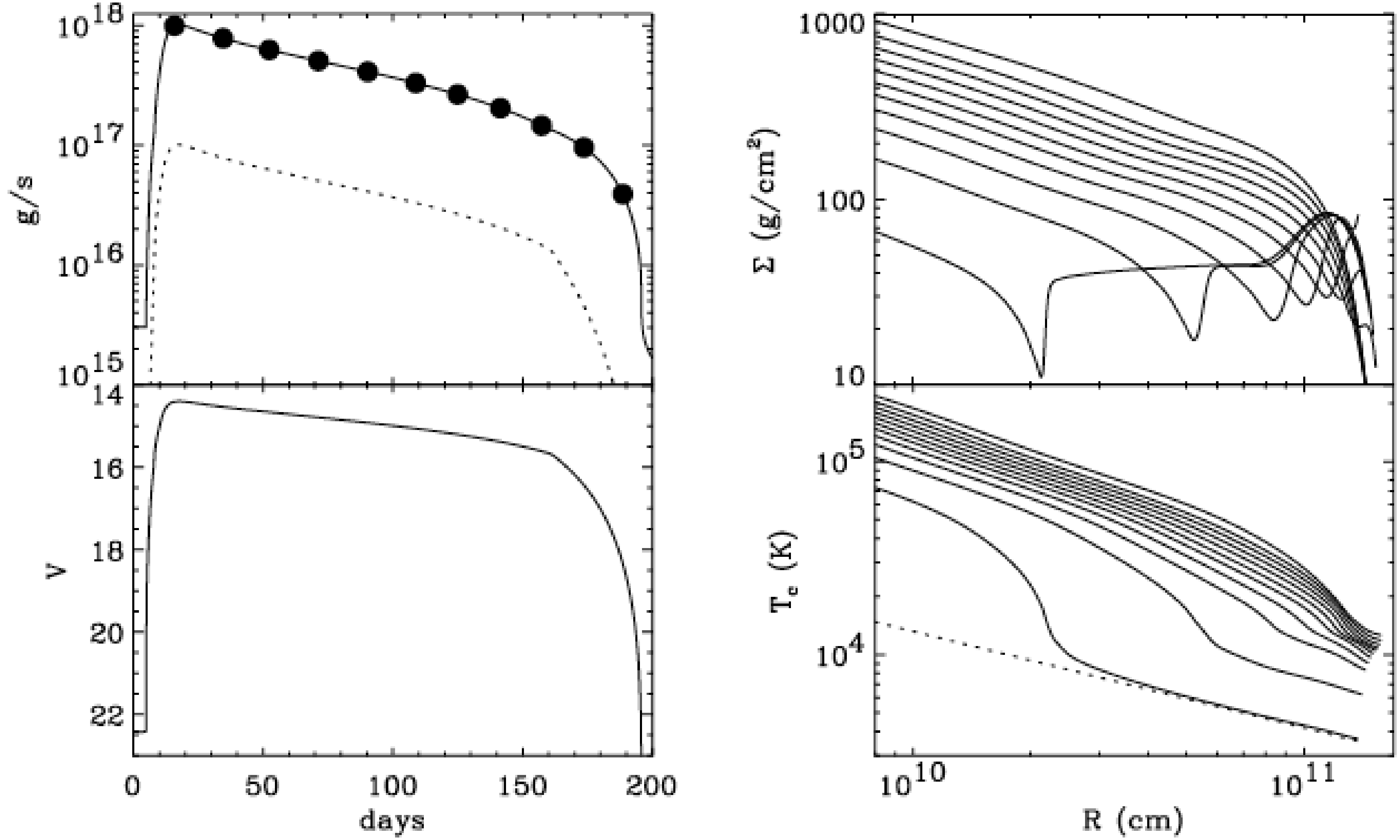
Disk Instability





- White dwarf disc instability
- SS Cyg
- Heating wave/cooling wave
- Outburst 1 week/few month
- VERY different in BHB
- Outbursts last months but only every few/many years
- X-ray irradiation controls decline King & Ritter 1998

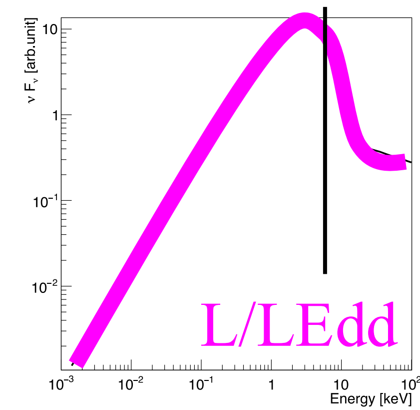
BHB – constant C irradiation fraction: FRED lightcurves



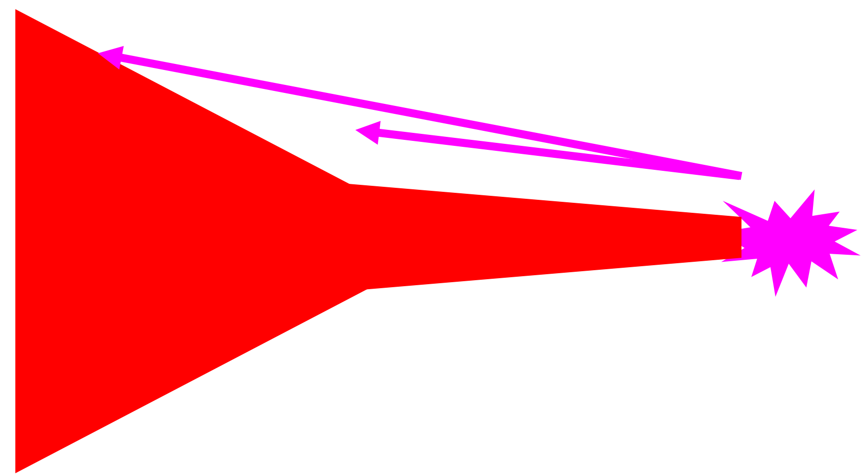
Dubus et al 2001

How does irradiation work?

TIC



- Direct irradiation of X-ray source (inner disc+corona) heats disc surface
- top of disc n low so only processes are comp.
- heating = cooling: Tic
- set by spectral shape
- same temp at all radii
- Thermal instability of X-ray illuminated gas in pressure equ Krolik+81



Begelman McKee Shields 1983

How does irradiation work?

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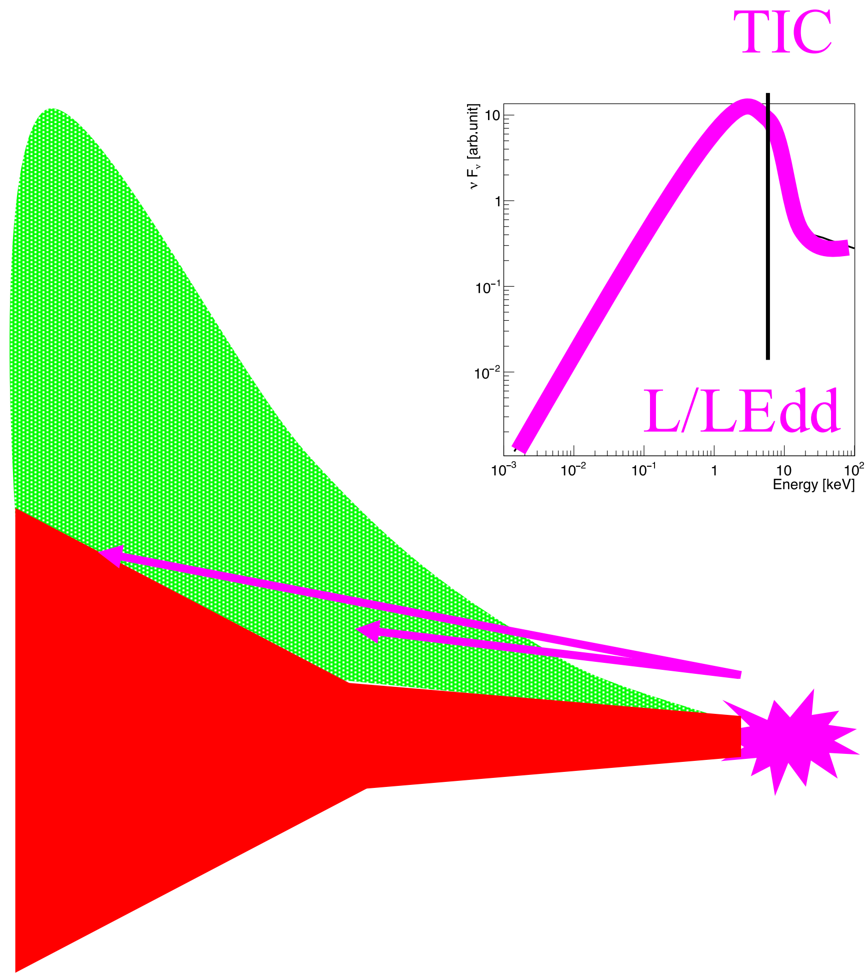
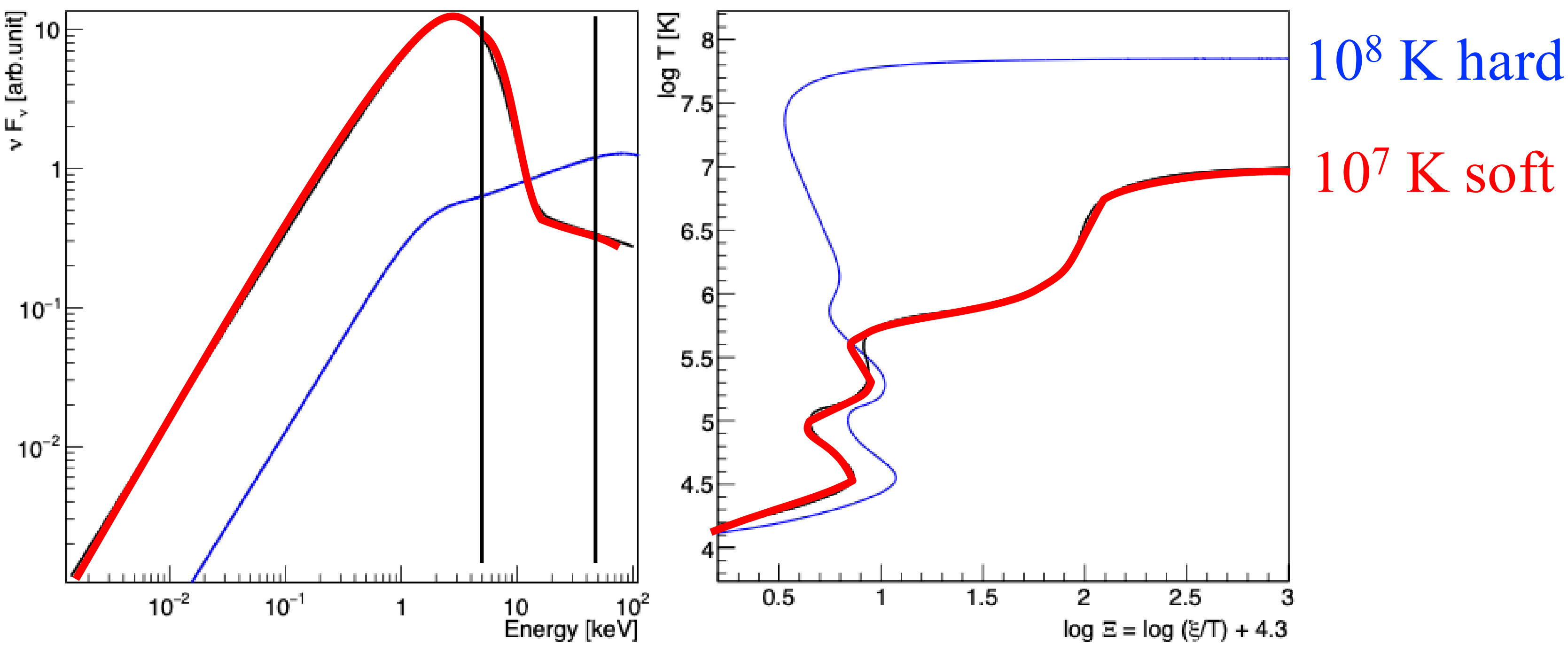


Begelman McKee Shields 1983

density of atmosphere fixed by L, Tic

TIC TIC Tomaru, CD+ 2019



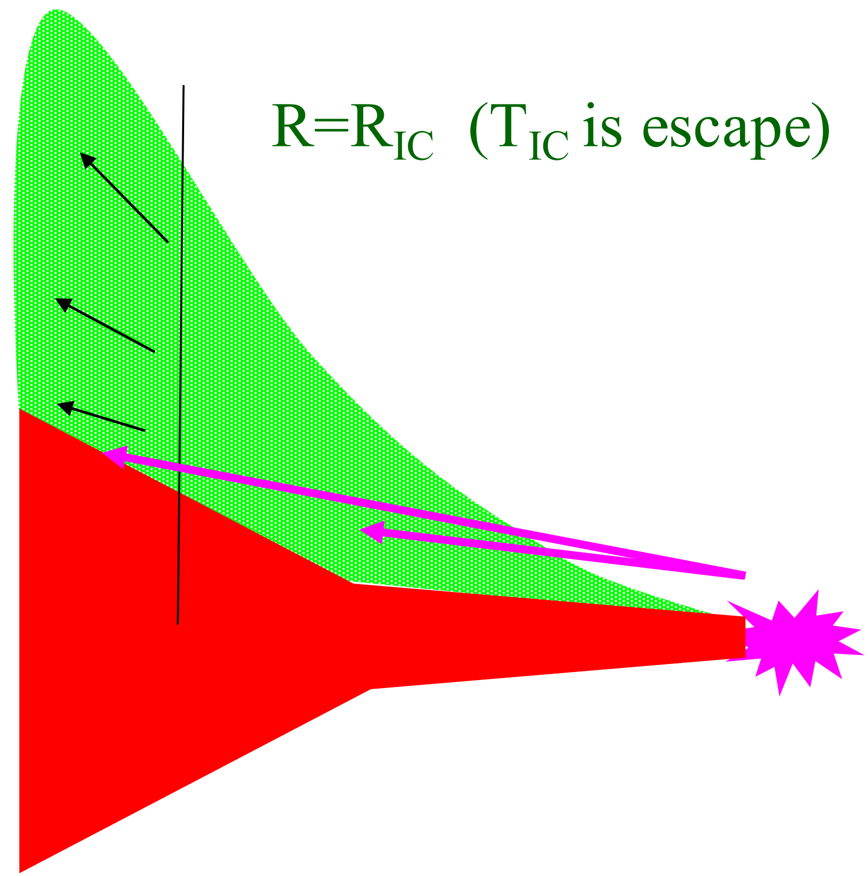
$$\text{Log } \Xi\text{crit} = \text{Prad/Pgas} \sim 10 = \frac{L}{4\pi R^2 c \; n \; kTic} \qquad \text{so } n(r) = \frac{L}{120 \; R^2 c \; kTic}$$

Krolik+ 1981, Begelman McKee Shields 1983

Thermal winds at large radii, heated atmosphere at smaller R

- Radius where thermal velocity is escape: RIC
- Wind for $R > R_{IC}$ driven by pressure gradient so $v_\infty = v_{esc}$
- SLOW $v_{esc}/c = (Rg/R)^{1/2}$
- NARROW as same Tic

- Irradiation makes thermal winds !! CALCULABLE
- Extra push from Prad

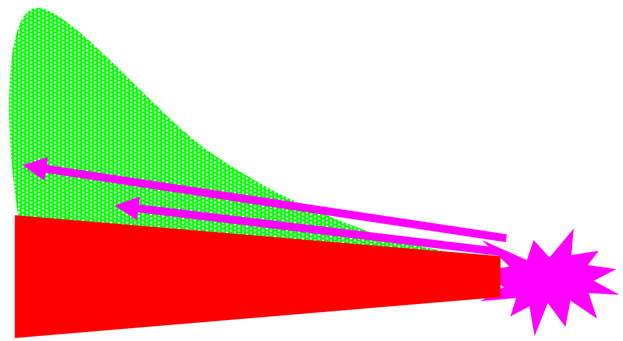


Begelman McKee Shields 1983
Done Takahashi & Tomaru 2018

Thermal winds at large radii, heated atmosphere at smaller R

- Can't have thermal wind if launched at $R \ll 0.1\ R_{IC}$ by $L \ll L_{edd}$
- Smaller discs generally NOT H-ionisation unstable so no outbursts
- And no thermal winds, just atmosphere
- neutron stars…

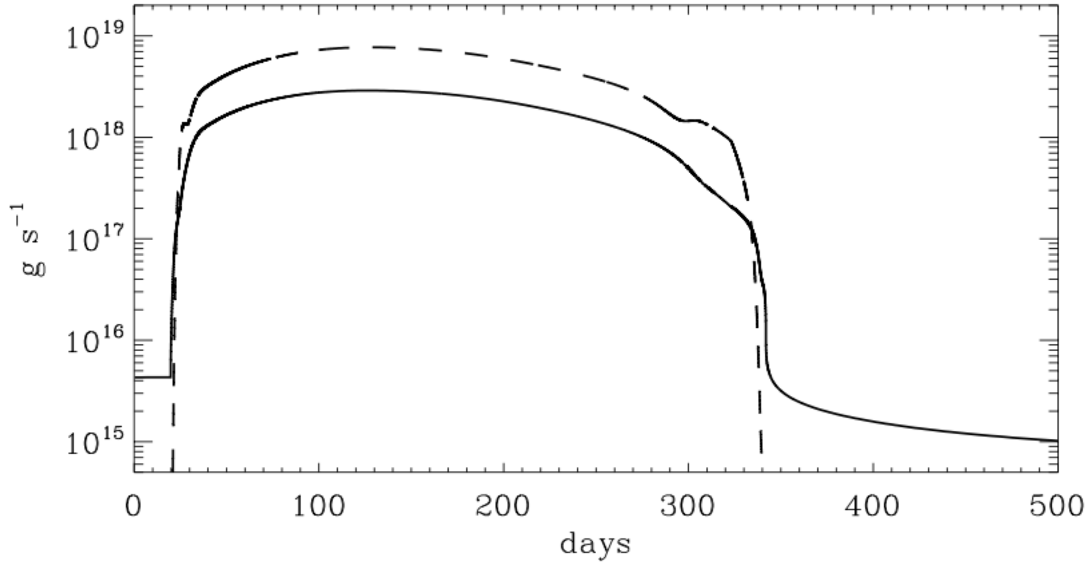
$R = R_{IC}$ (T_{IC} is escape)

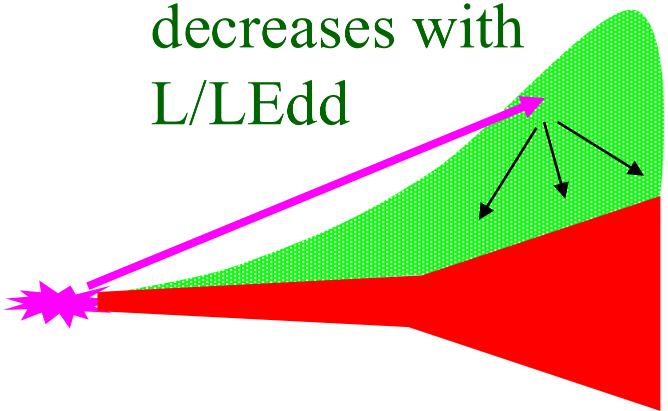


Begelman McKee Shields 1983

Thermal wind: scattered fraction changes with L/Ledd and T_{IC}

- Need to know 2D structure… radial?
- Get long plateau
- Wind decreases with decrease in L/Ledd
- Scattered fraction decreases with L/LEdd





Done+ 2018
Dubus, CD ..2019

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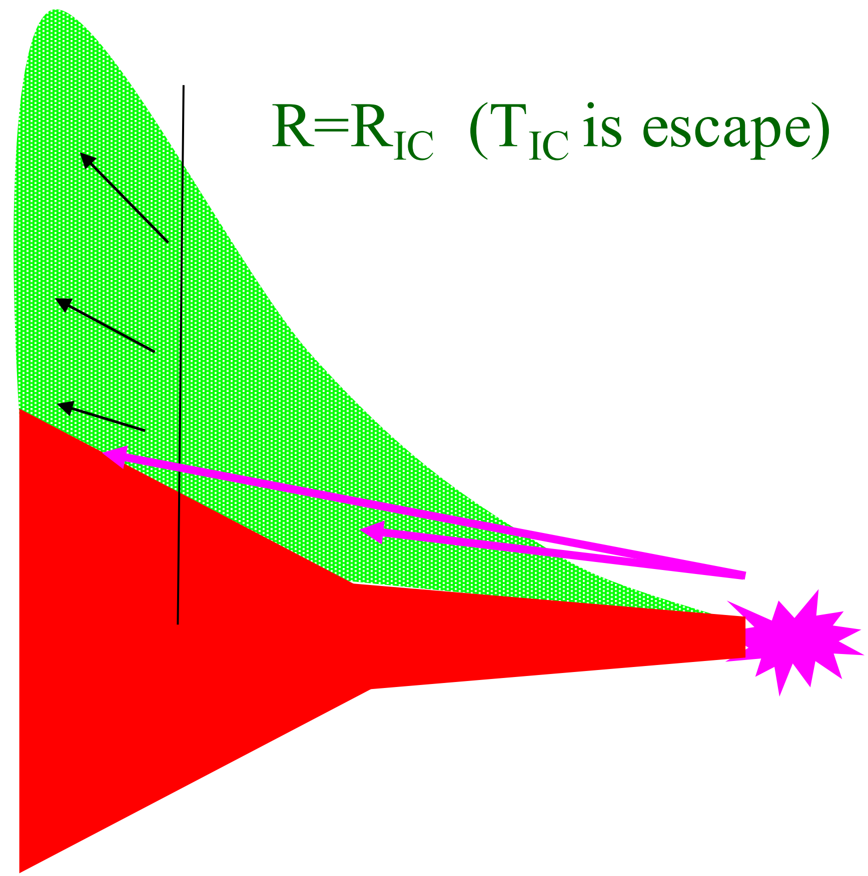
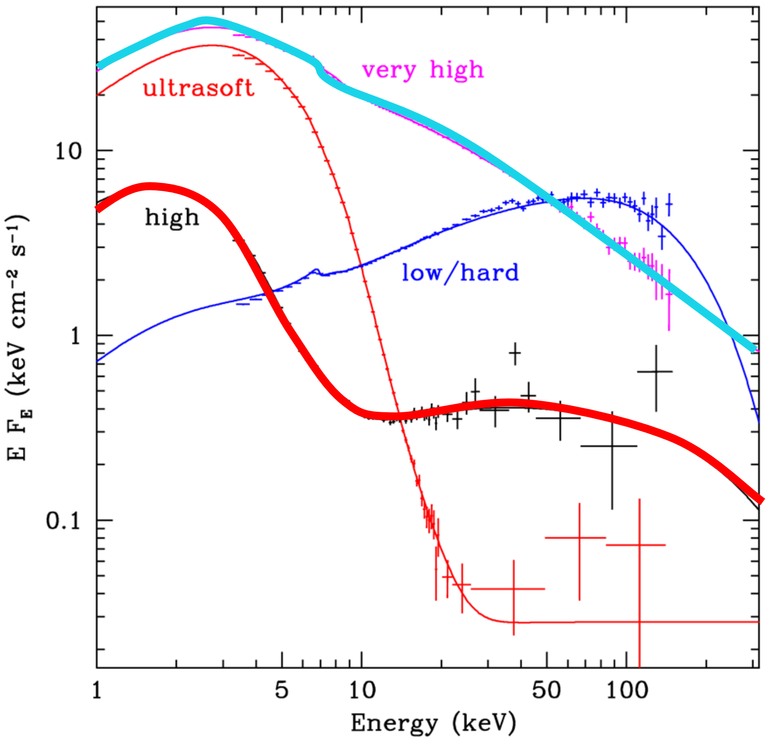
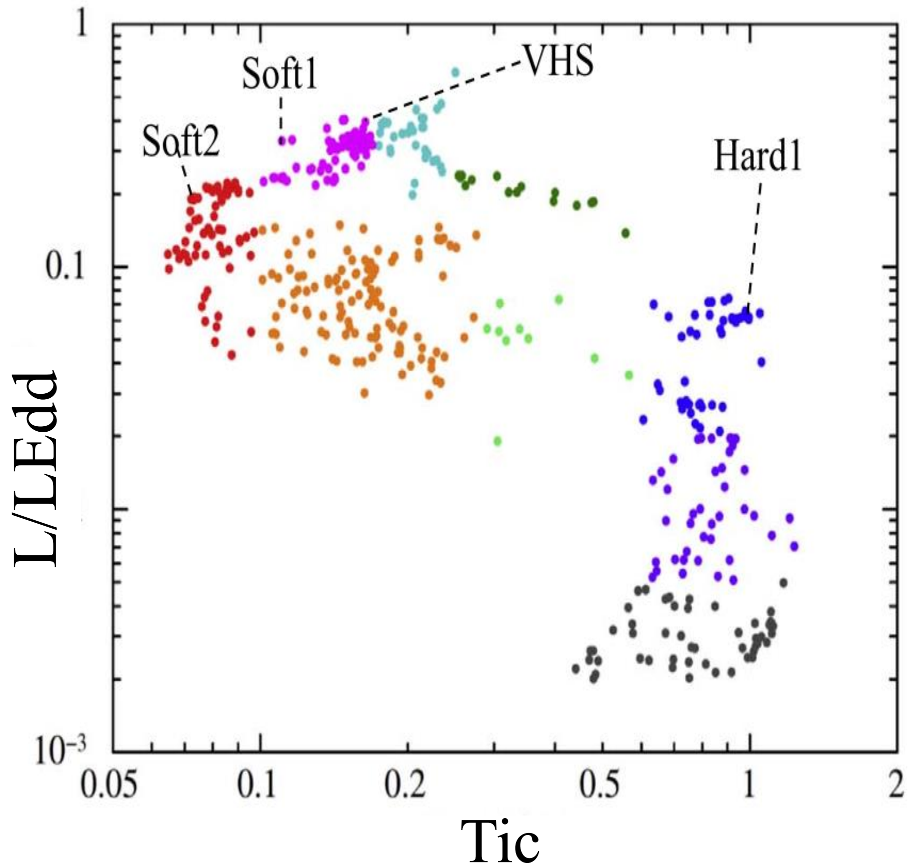


Begelman McKee Shields 1983
Done Takahashi & Tomaru 2018

Simple analytic model for wind(z)

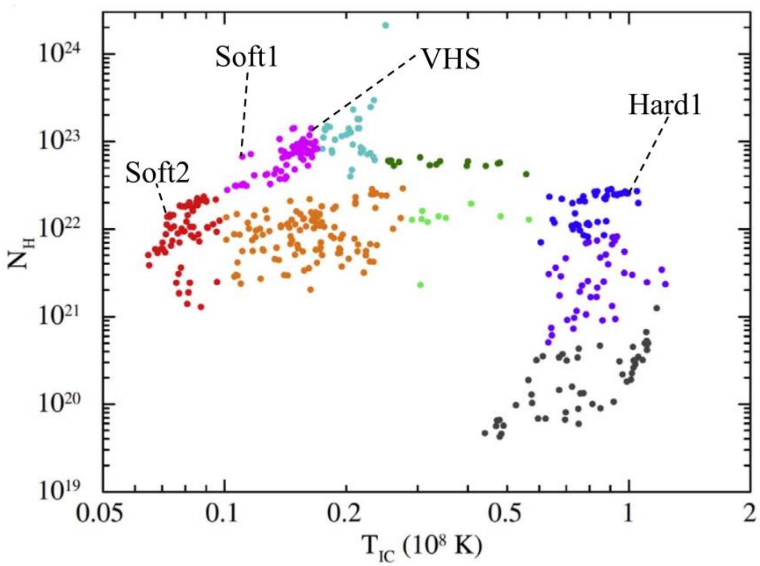


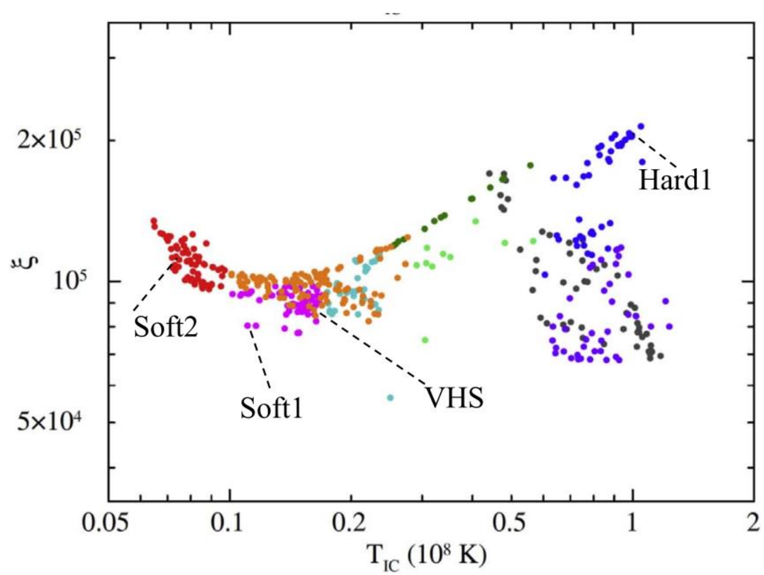


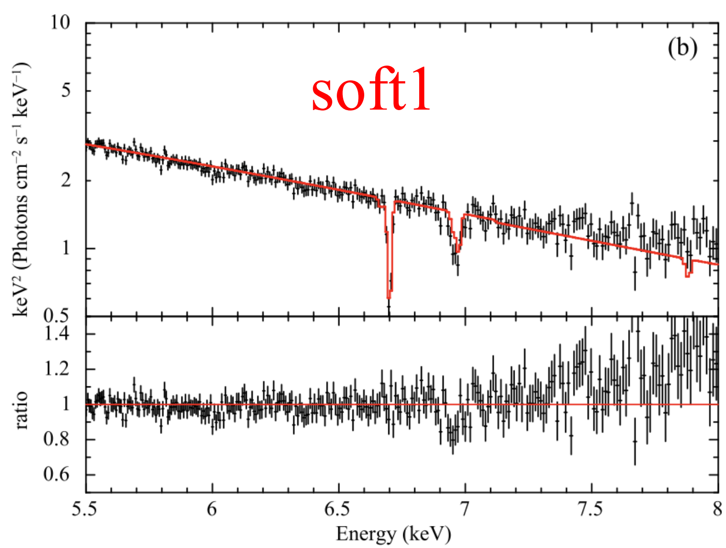
Shidatsu, CD+ 2019

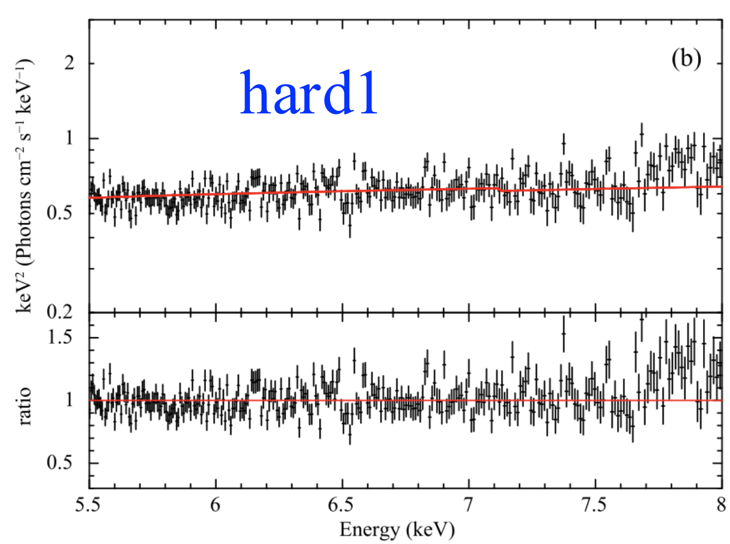
- Radial wind approximation
- $n \propto r^{-2}$ and log xi constant

Simple analytic model for wind(z)



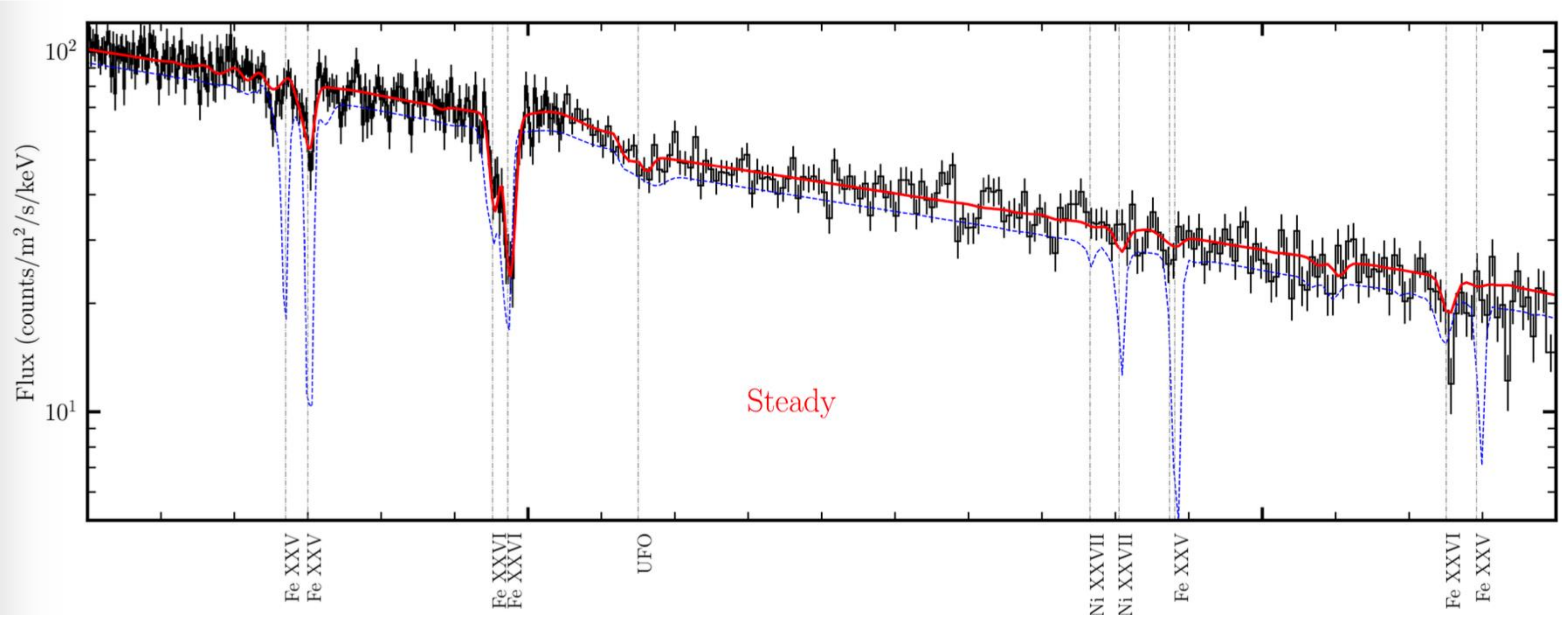






Shidatsu, CD+ 2019

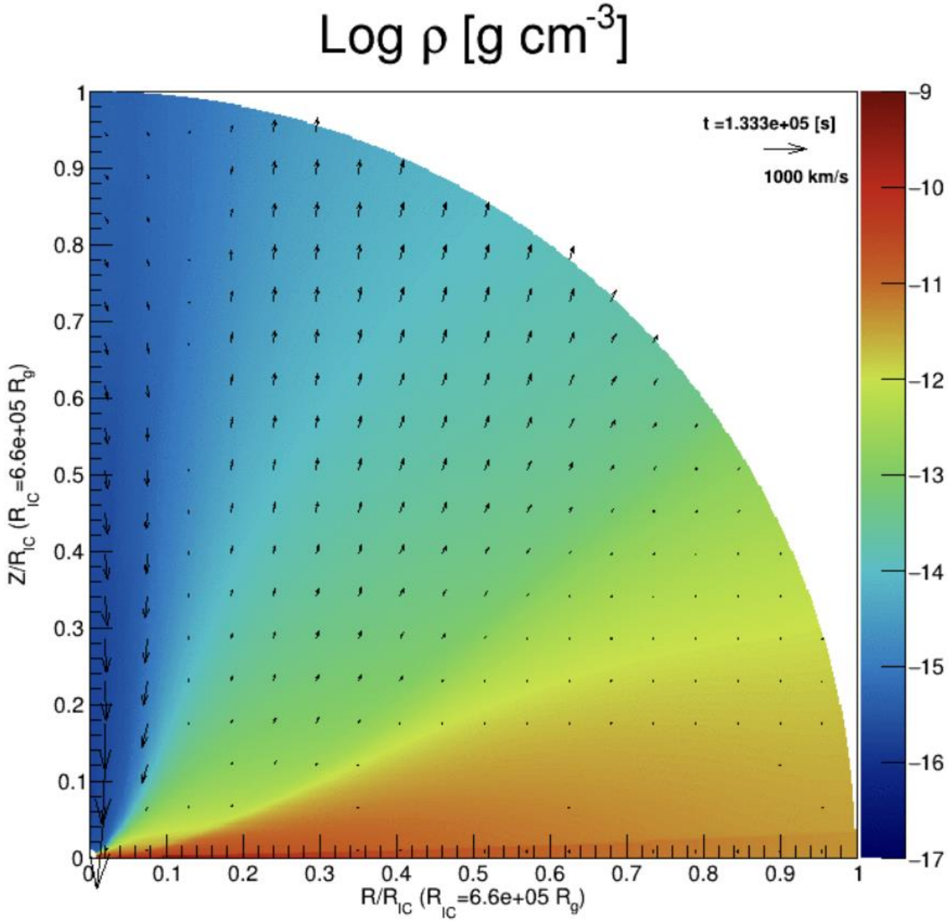
XRISM!!! Models too simple!!



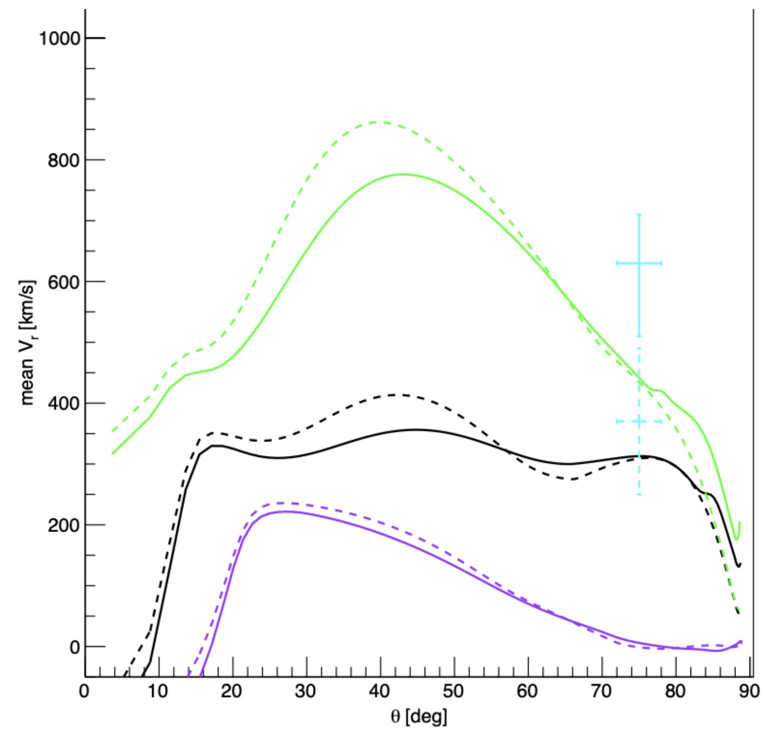
Miller, CD+ 2025

- XRISM PV 4U1630-40
- L/Ledd=0.05, TIC=2e7 K
- V~130 km/s σ=200 km/s Nh=10^{23} cm^{-2}, log xi = 5.7
- Multicomponent, time dependent…
- Analytic approx. has order of magnitude lower Nh,….

Need full hydro (or better streamlines)

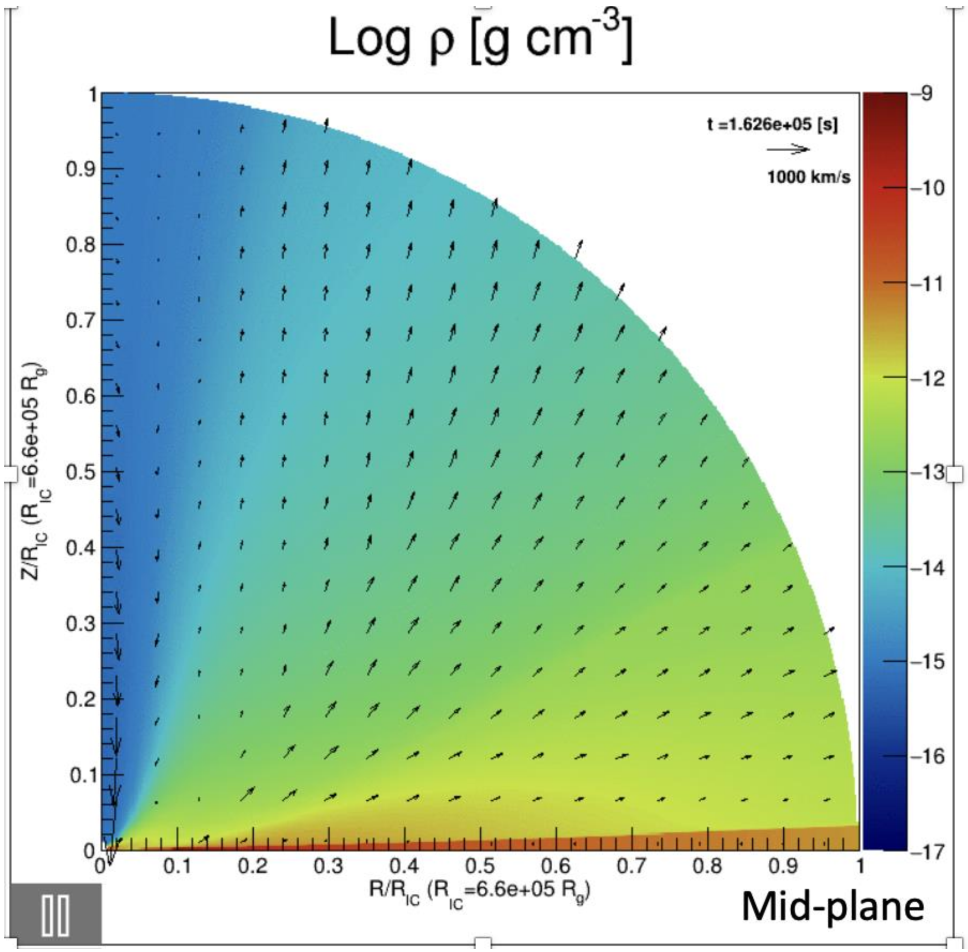


Tomaru, CD+ 2019

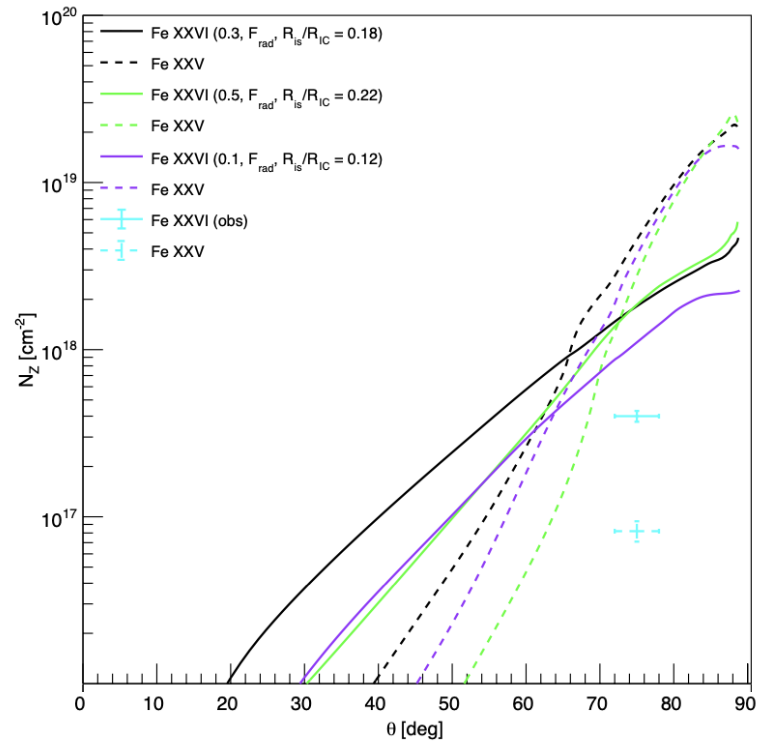


- L/Ledd =0.1 (slow so high Nh), 0.3 and 0.5
- Low L/Ledd has V~130 km/s σ=200 km/s Nh=10^{23} cm^{-2},

Need full hydro (or better streamlines)



Tomaru, CD+ 2019



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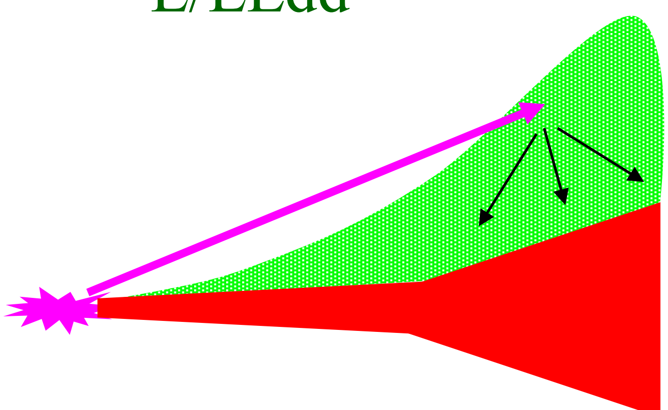
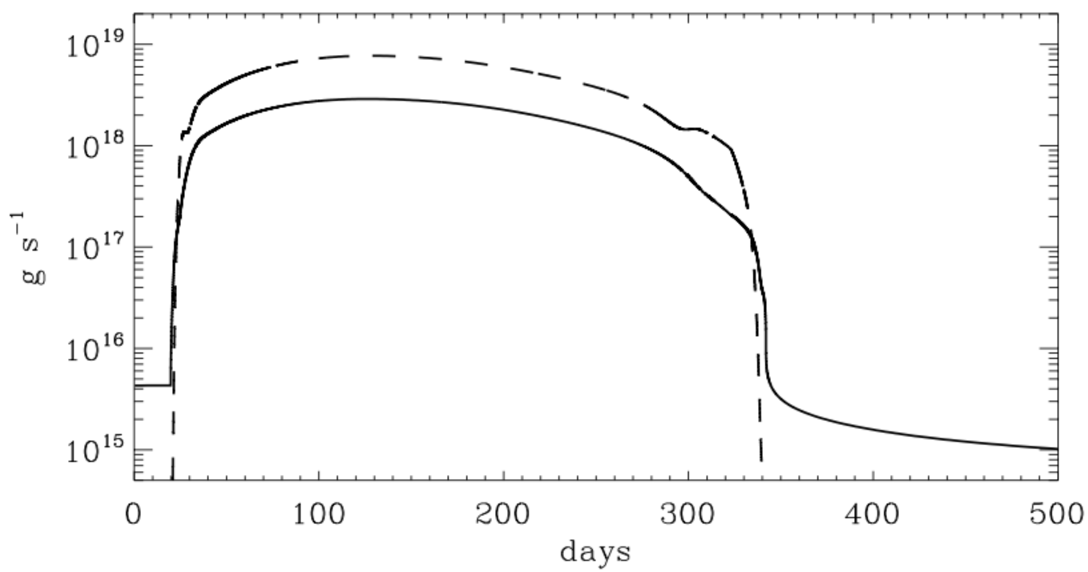
Thermal wind: scattered fraction changes with L/Ledd and T_{IC}

- Get long plateau
- Wind decreases with decrease in L/Ledd
- Scattered fraction decreases with L/LEdd



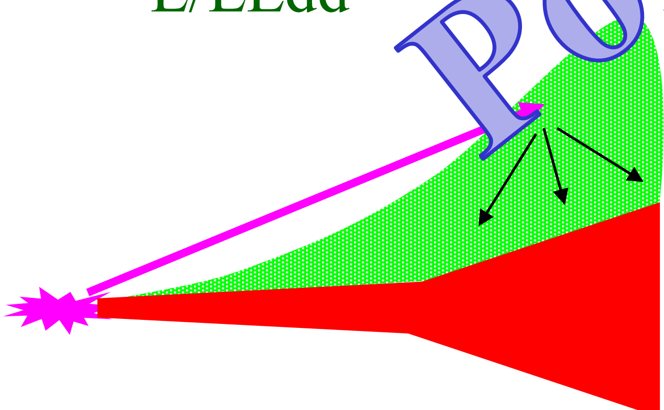


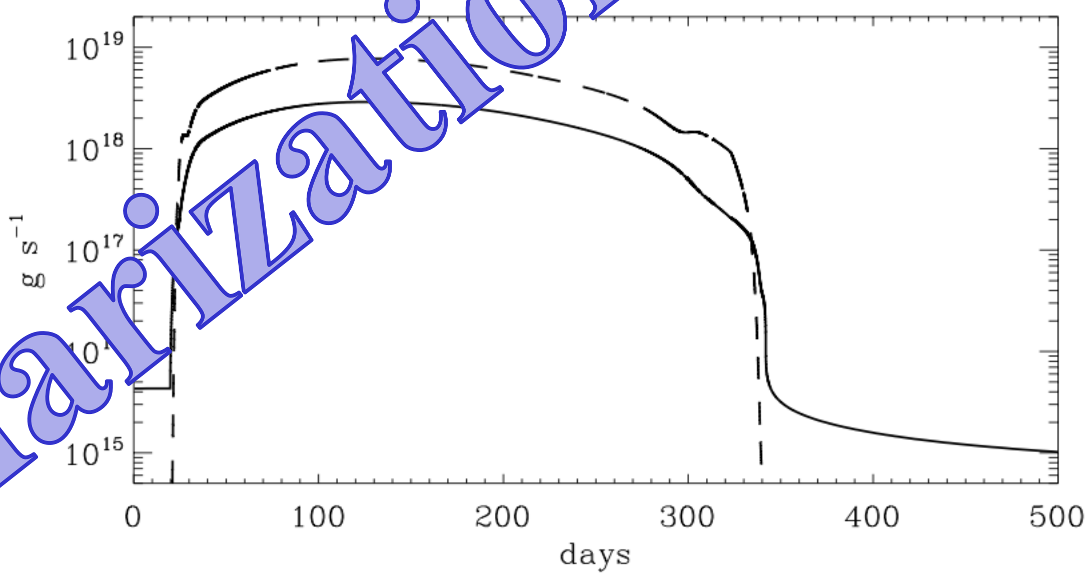
Dubus, CD ..2019

Thermal wind: scattered fraction changes with L/Ledd and T_{IC}

Polarization!!

- Get long plateau
- Wind decreases with decrease in L/Ledd
- Scattered fraction decreases with L/LEdd





Dubus, CD ..2019

Polarisation from e- scattering for intrinsic source spectra

High/soft state disc

Optically thick (tau>>1)

Last scattered photons vertical

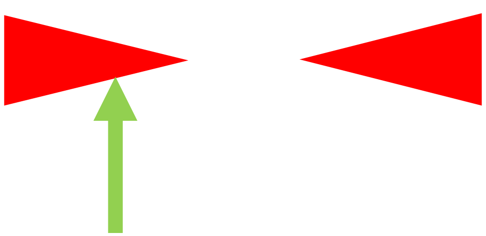
Polarisation horizontal (aligns with disc)

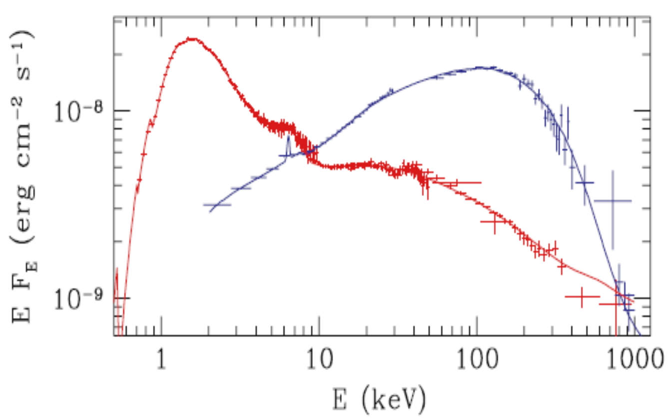
Low/hard state hot flow

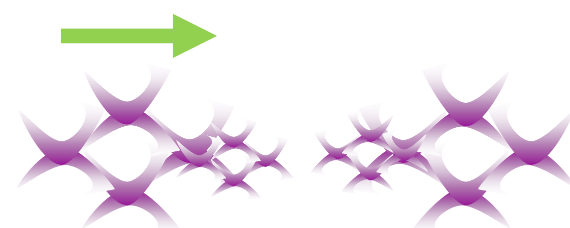
Optically thin (tau~1-2)

Last scattered photons horizontal

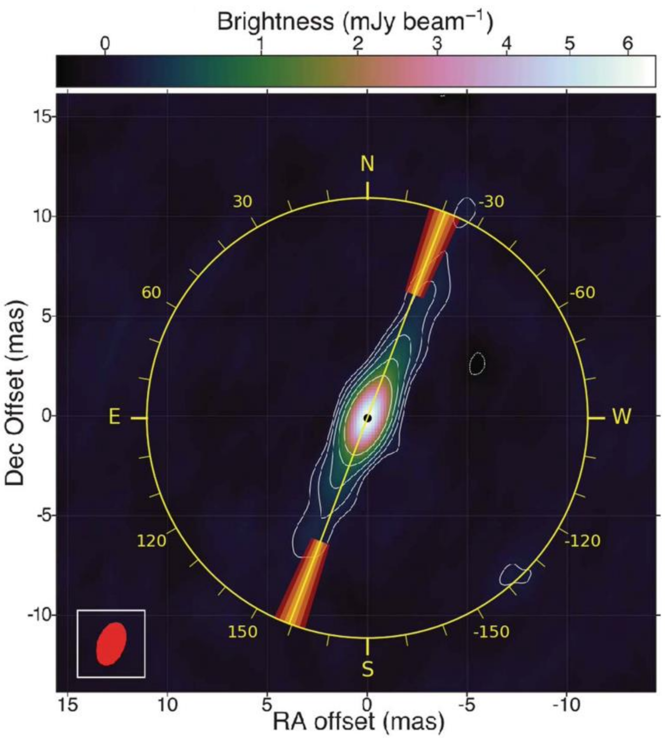
Polarisation vertical (aligns with jet)

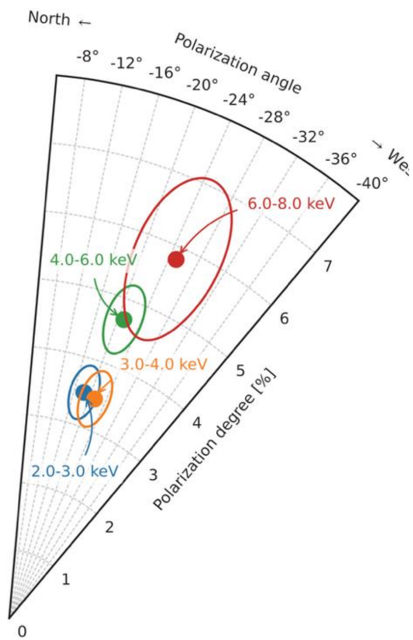


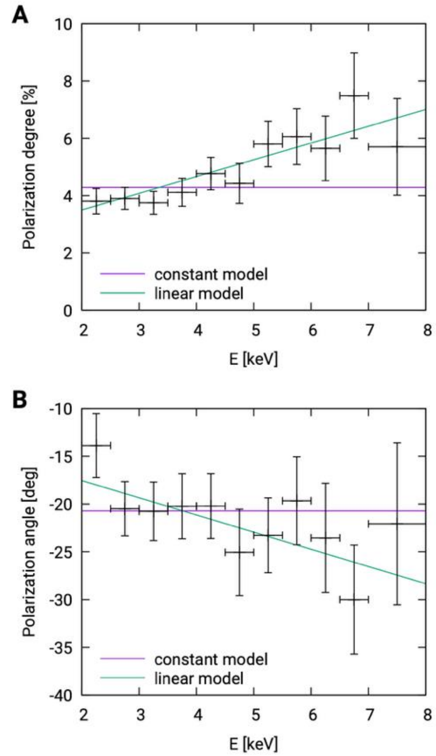




Polarisation low/hard state Cyg X-1

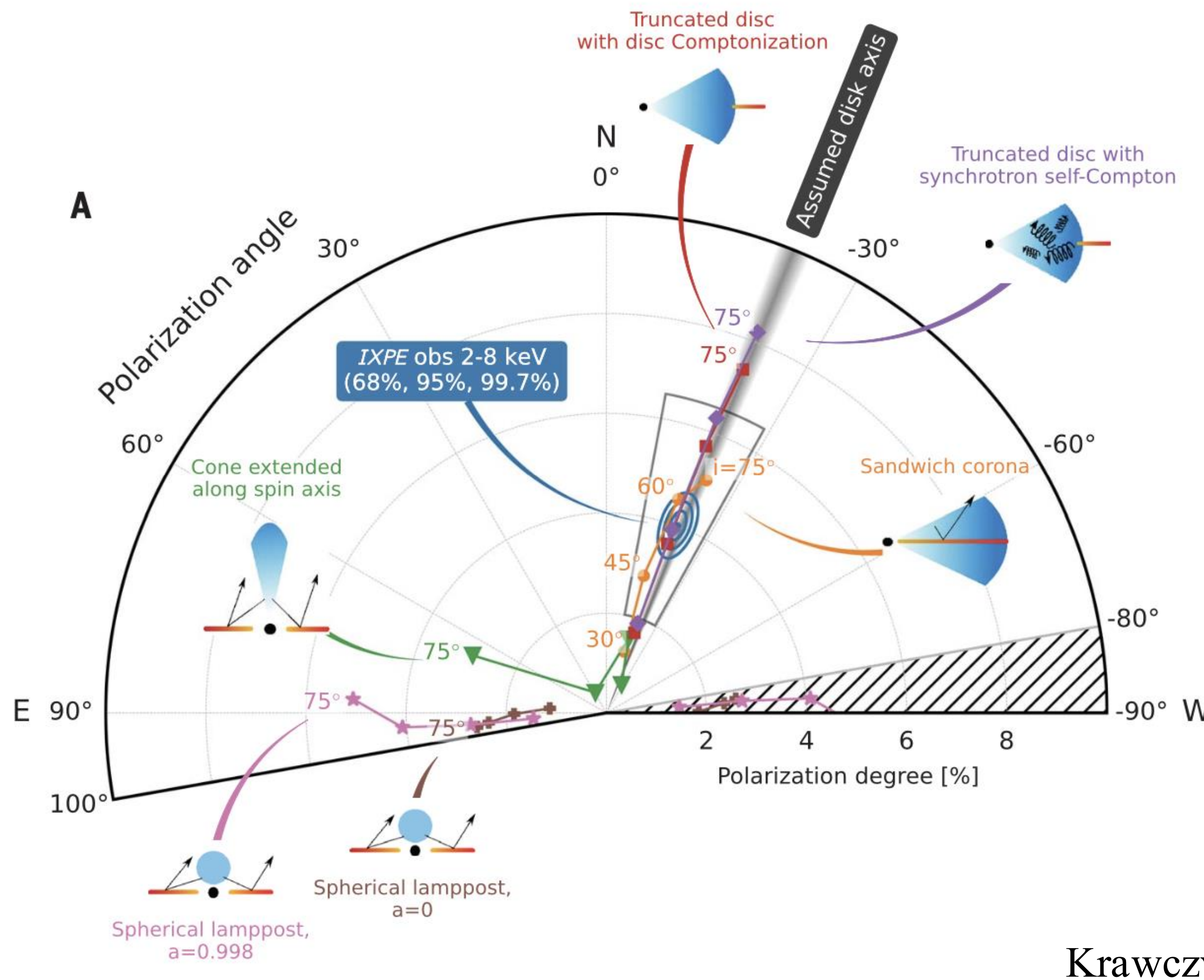






Krawczynski et al 2022

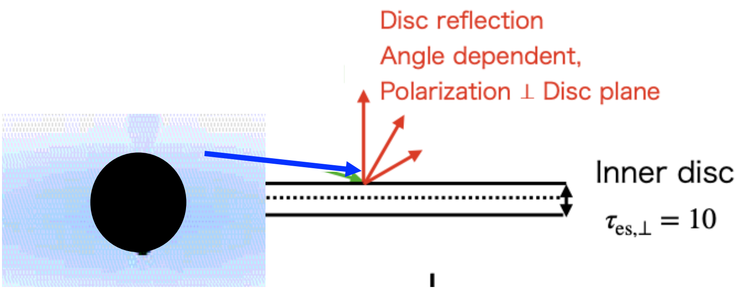
Polarisation low/hard state Cyg X-1



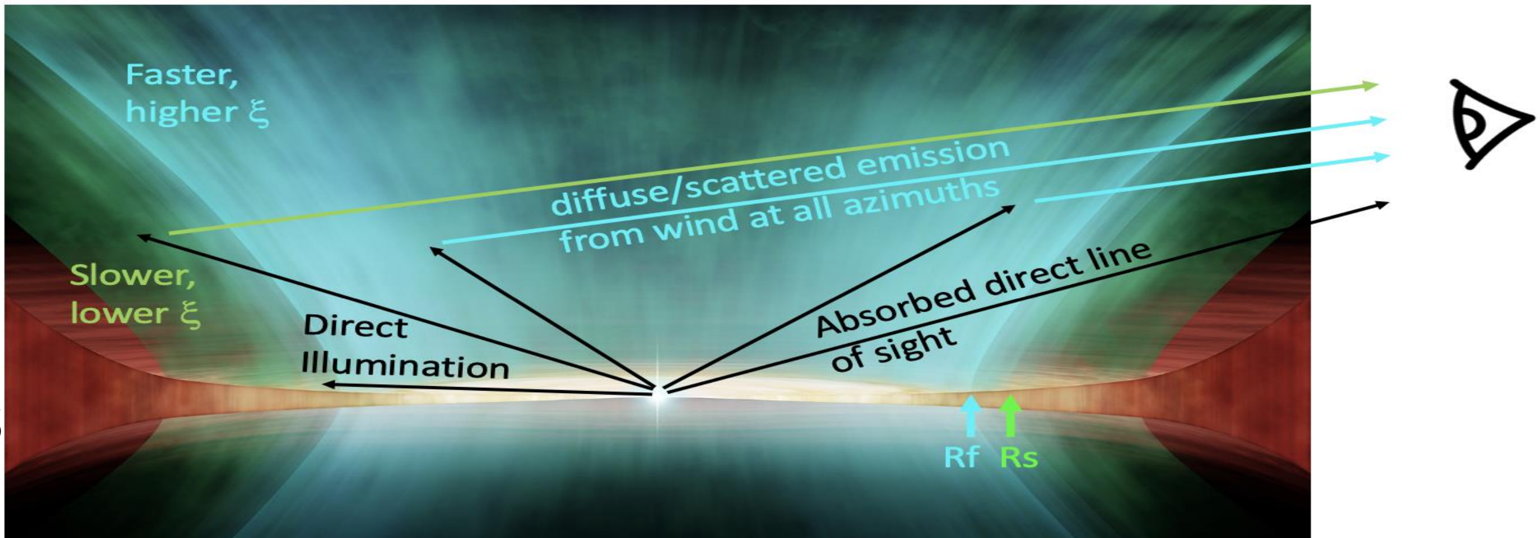
Krawczynski et al 2022

Additional Polarisation from wind scattering and reflection

Inner source intrinsic polarization perp to disc, inner disc reflection perp to disc



Plus scattering on wind perp to disc



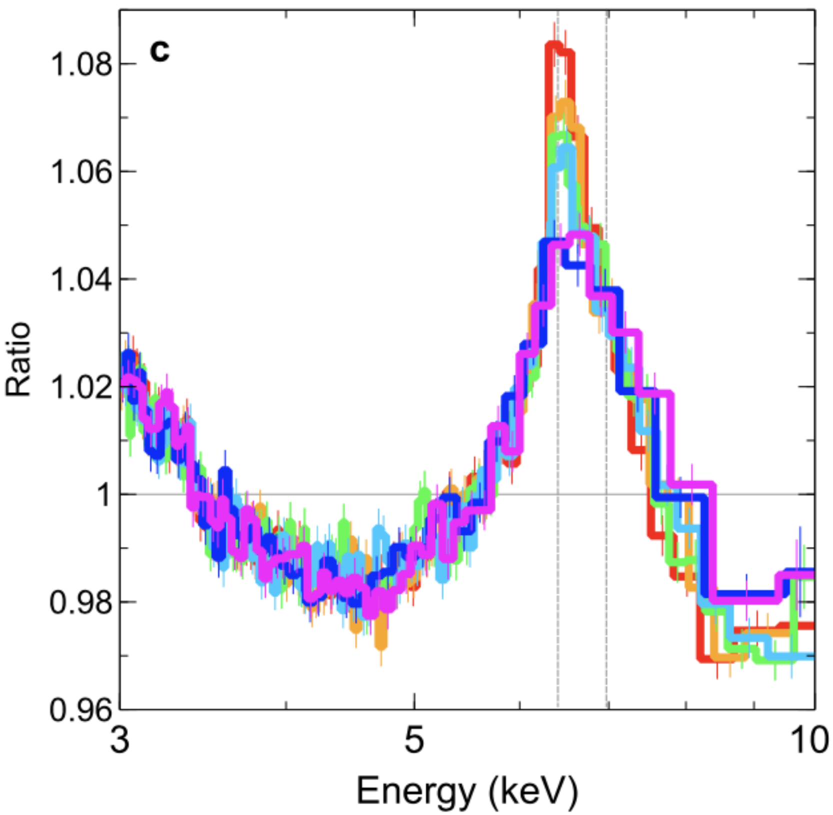
Tomaru et al 2026
Xrism+ 2025

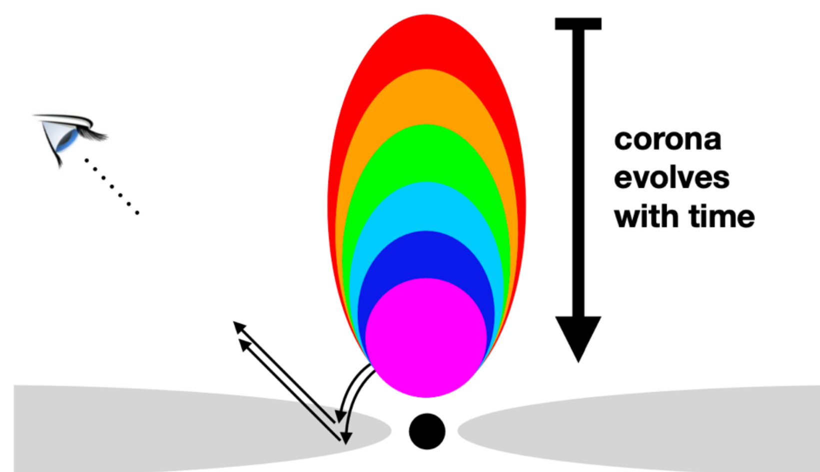
Conclusions

- ADAF-disc framework to think about XRB outbursts
- Truncated disc/hot flow gives framework for spectra, jet, fast variability and pol direction (perp to disc)
- Central irradiation heats surface – thermal atm/wind
- Approx. model OK but need better (or hydro) for XRISM
- Atm/wind scatters source flux into diffuse component- changes outburst lightcurve and adds polarisation (IXPE)
- PROBLEMS
- REFLECTION spectra require disc in bright hard states?
- Nature of viscosity/magnetic field configuration??
- Jet???

Bright low/hard state geometry!

Reflection models for iron line show disc inner radius small throughout transition – broad base





Kara et al 2019

Bright low/hard state geometry!

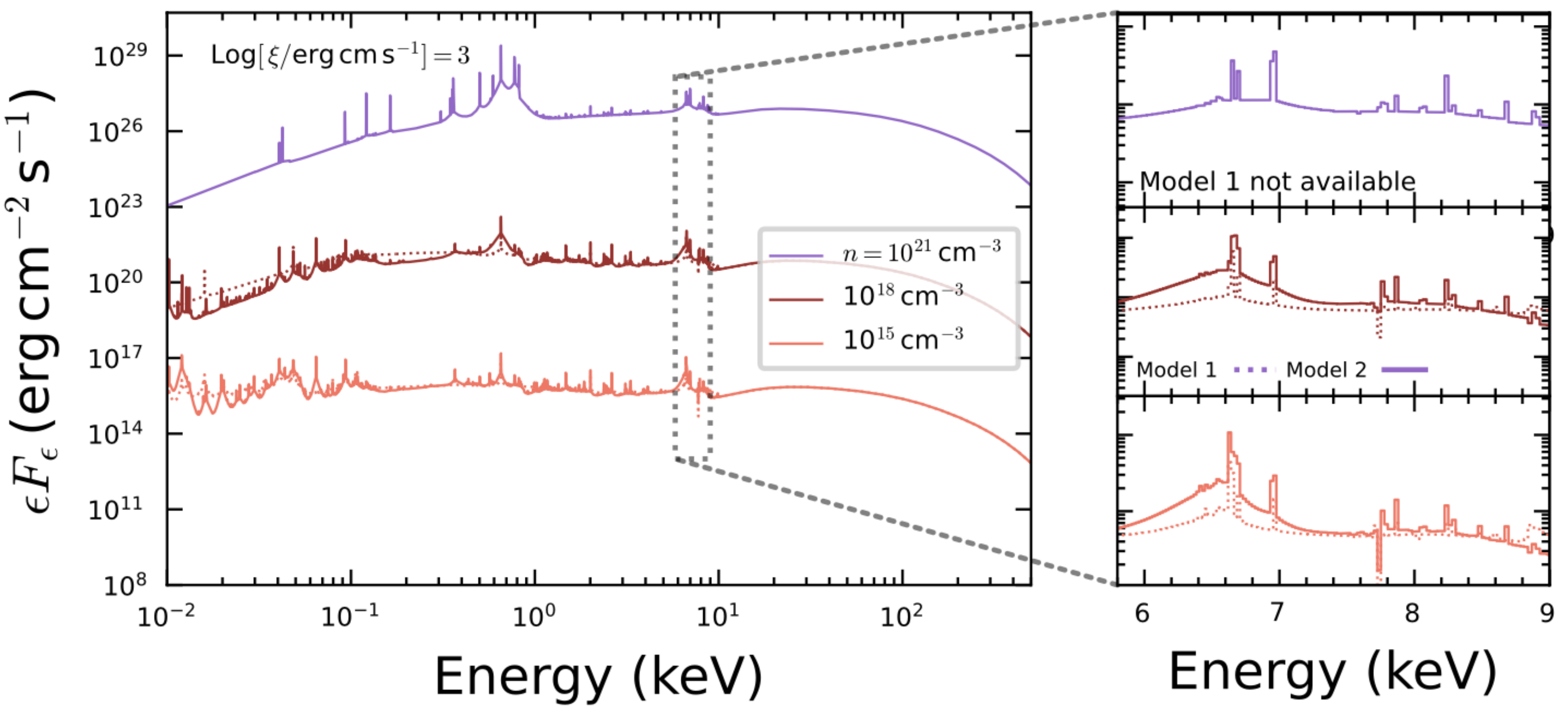
But current reflection models ASSUME

1) constant density with height
Yet irradiation of gives thermal instability and highly ionized atmosphere/wind.

2) Ionisation ALL from irradiation
Yet disc is observably hot – kT>0.2 keV will contribute to ionization of Fe

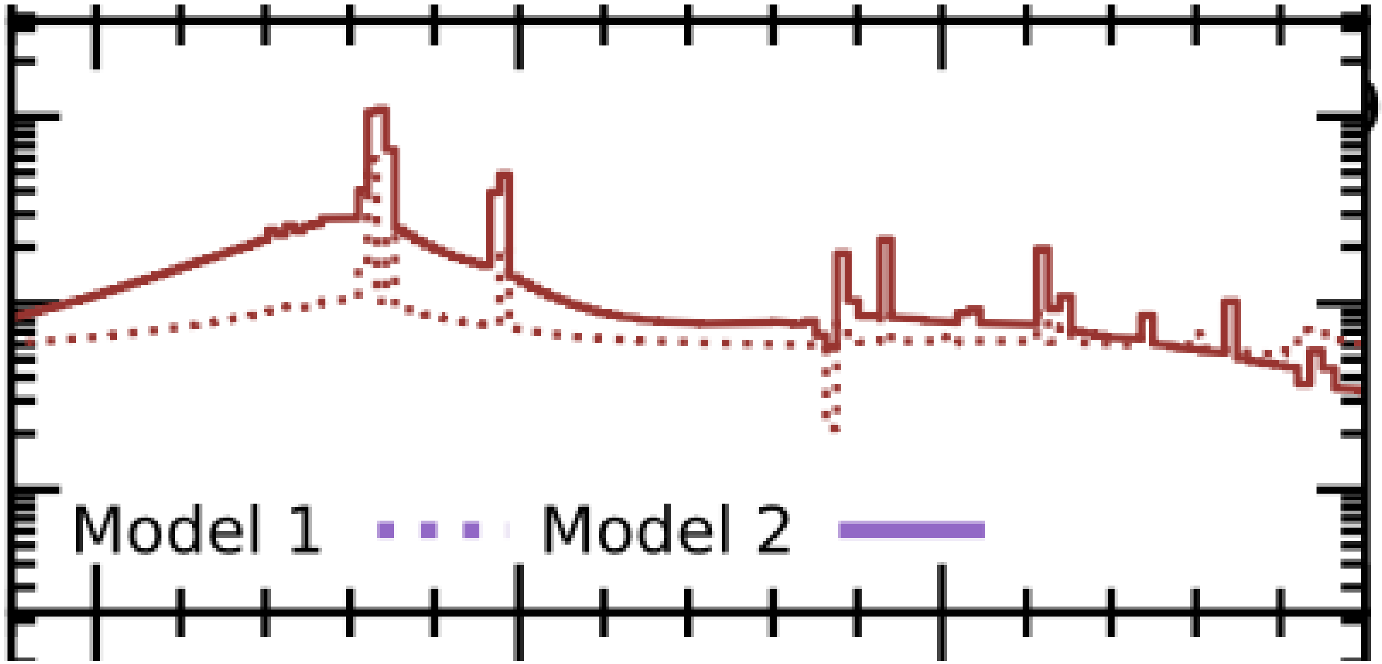
the result may be especially problematic in the BHXRBs' soft or intermediate states where a strong thermal spectrum dominates the continuum… Ding, Garcia+ 2024

New high density reflection models!!



Ding, Garcia al 2024

New high density reflection models!!



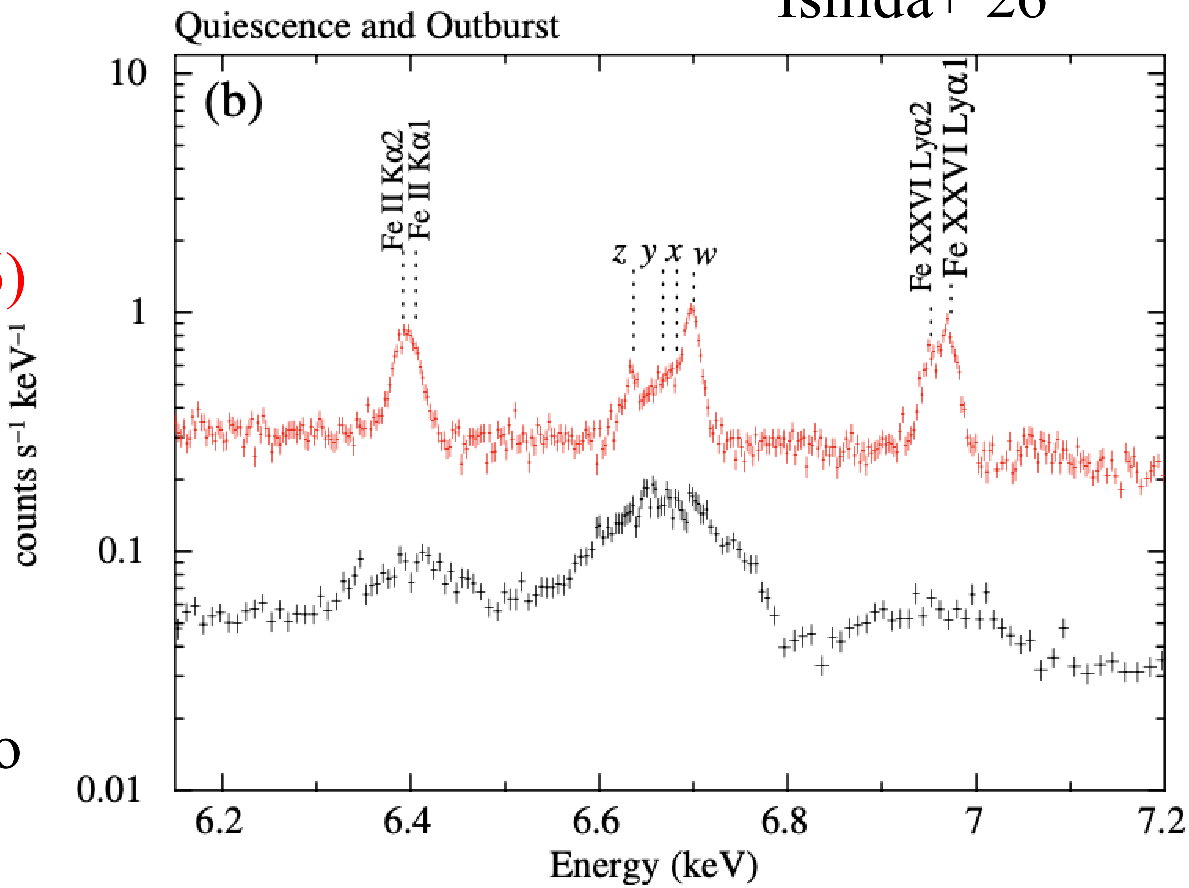
Ding, Garcia al 2024

Dwarf novae show hole in disc!!

Dwarf novae show hole in disc!!

NARROW line in quiescence! WD surface and NO inner disc (Kimura, CD+26)

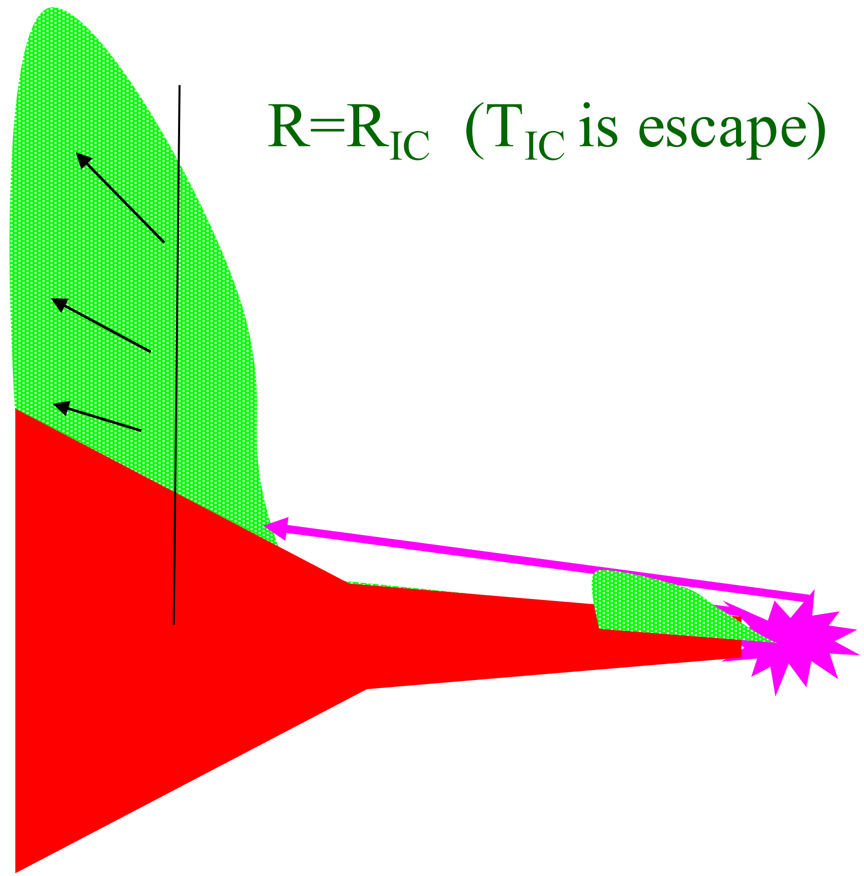
Ishida+ 26



Broad Fe Ka in outburst shows disc to WD and BL

Plus maybe structures on inner disc casting shadow!

- Goes optically thick in radial direction
- Corona over inner disc forms SHADOW
- Until outer disc curves up out of the shadow

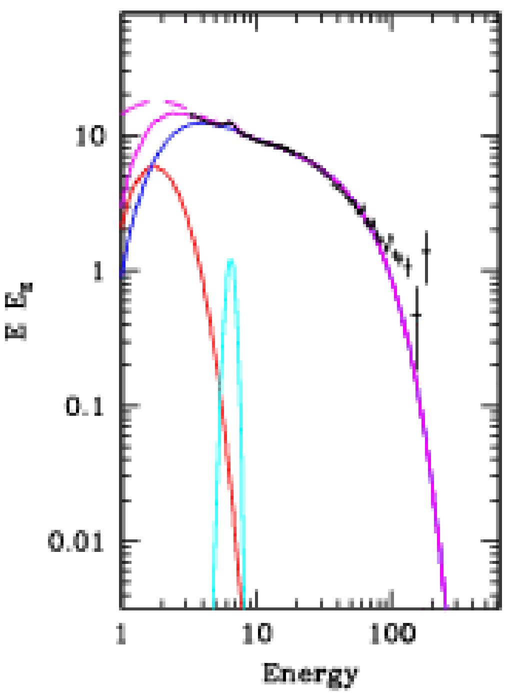


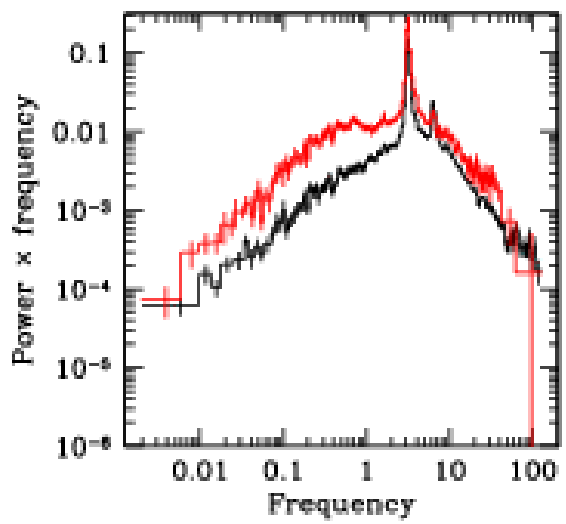
Begelman & Shields 1983

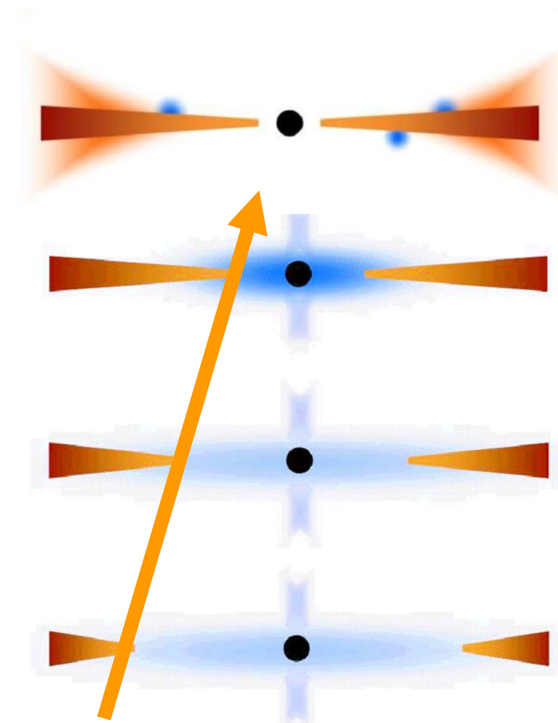
Moving disc – moving QPO

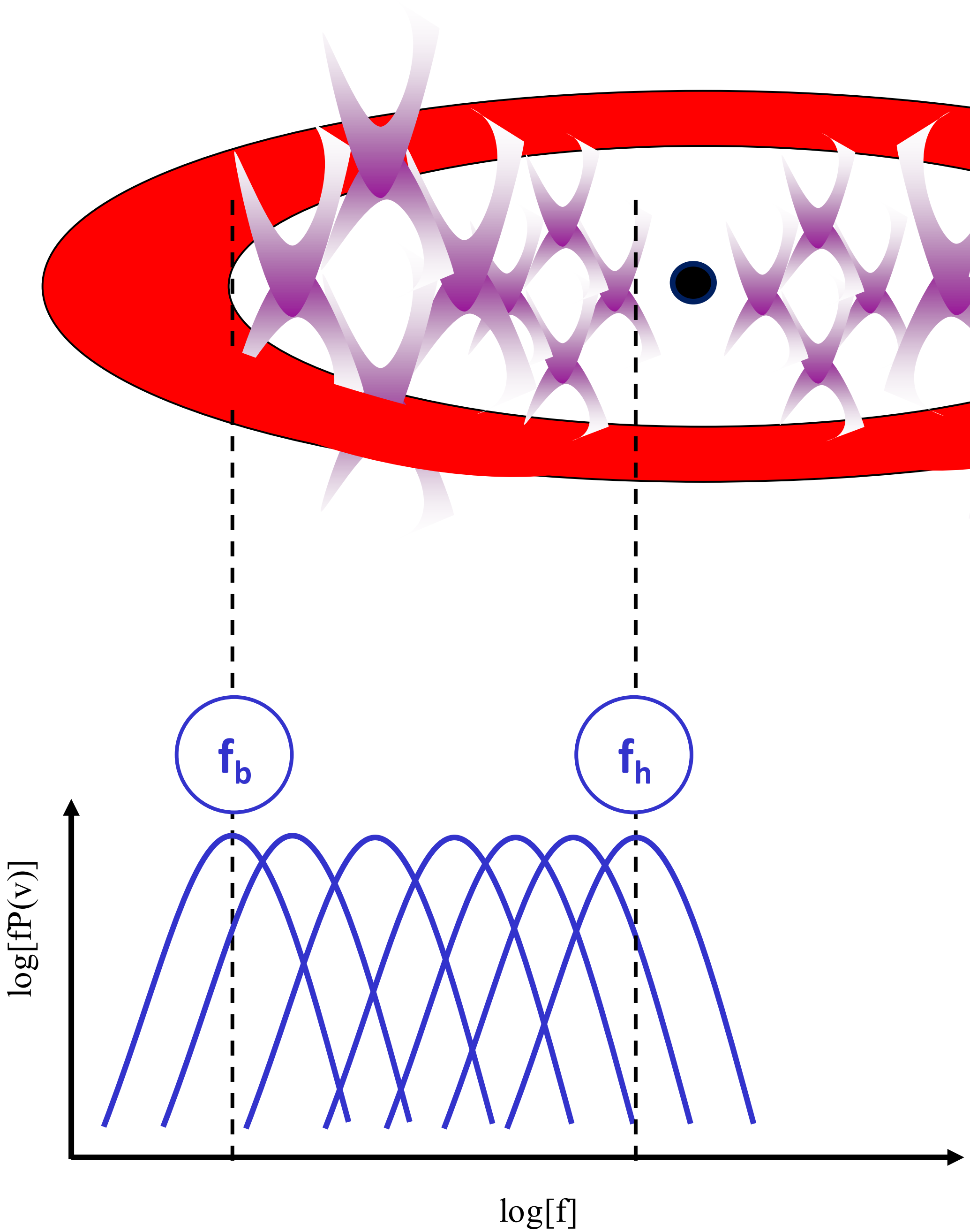
- Energy spectra need disc to move from 50-6ish Rg as make transition
- Power spectra: low frequency break moves, high frequency power more or less constant! Large radius moves, Small radii constant
- Need a way to transition from disc to hot flow!!

DGK07

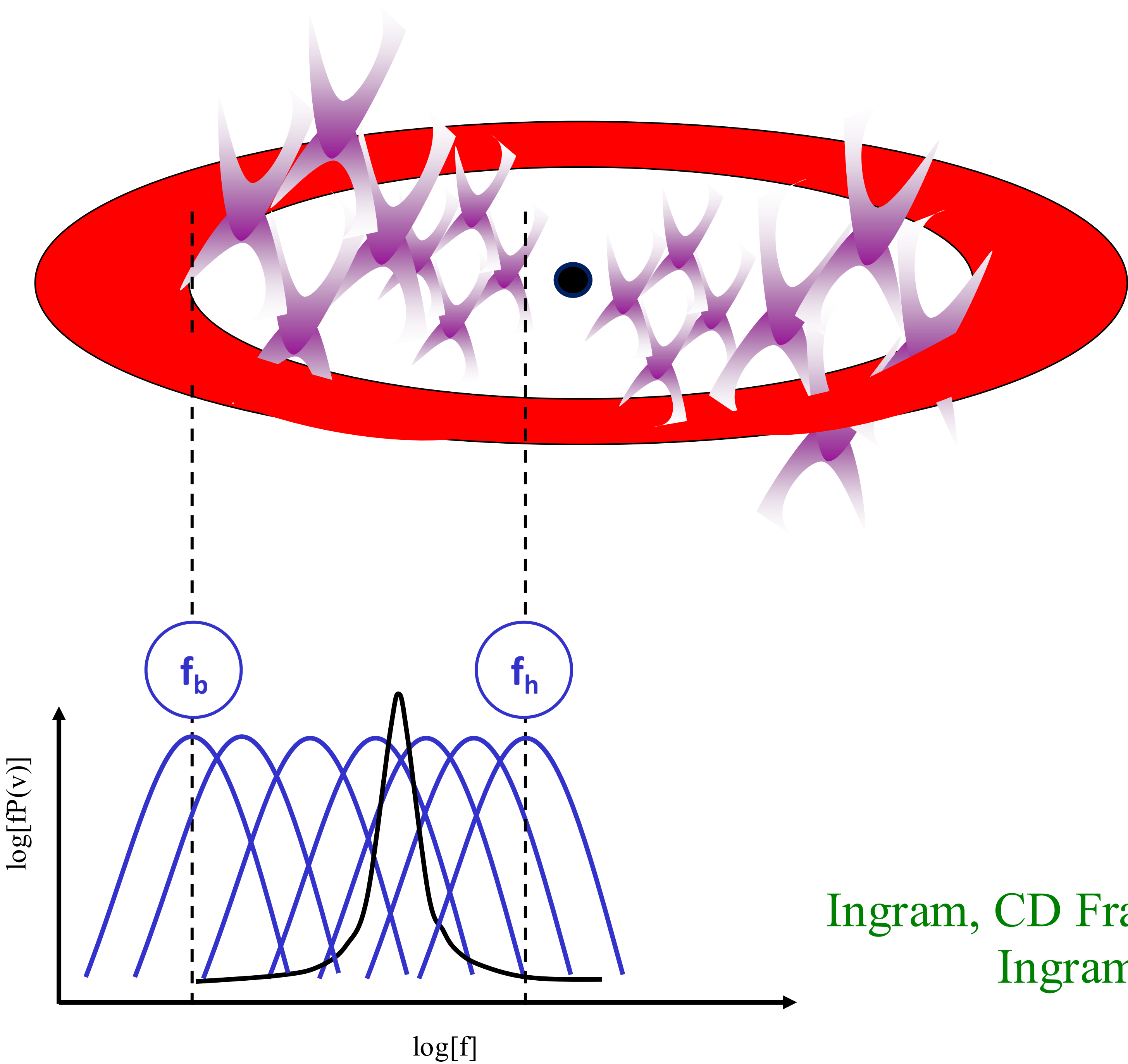




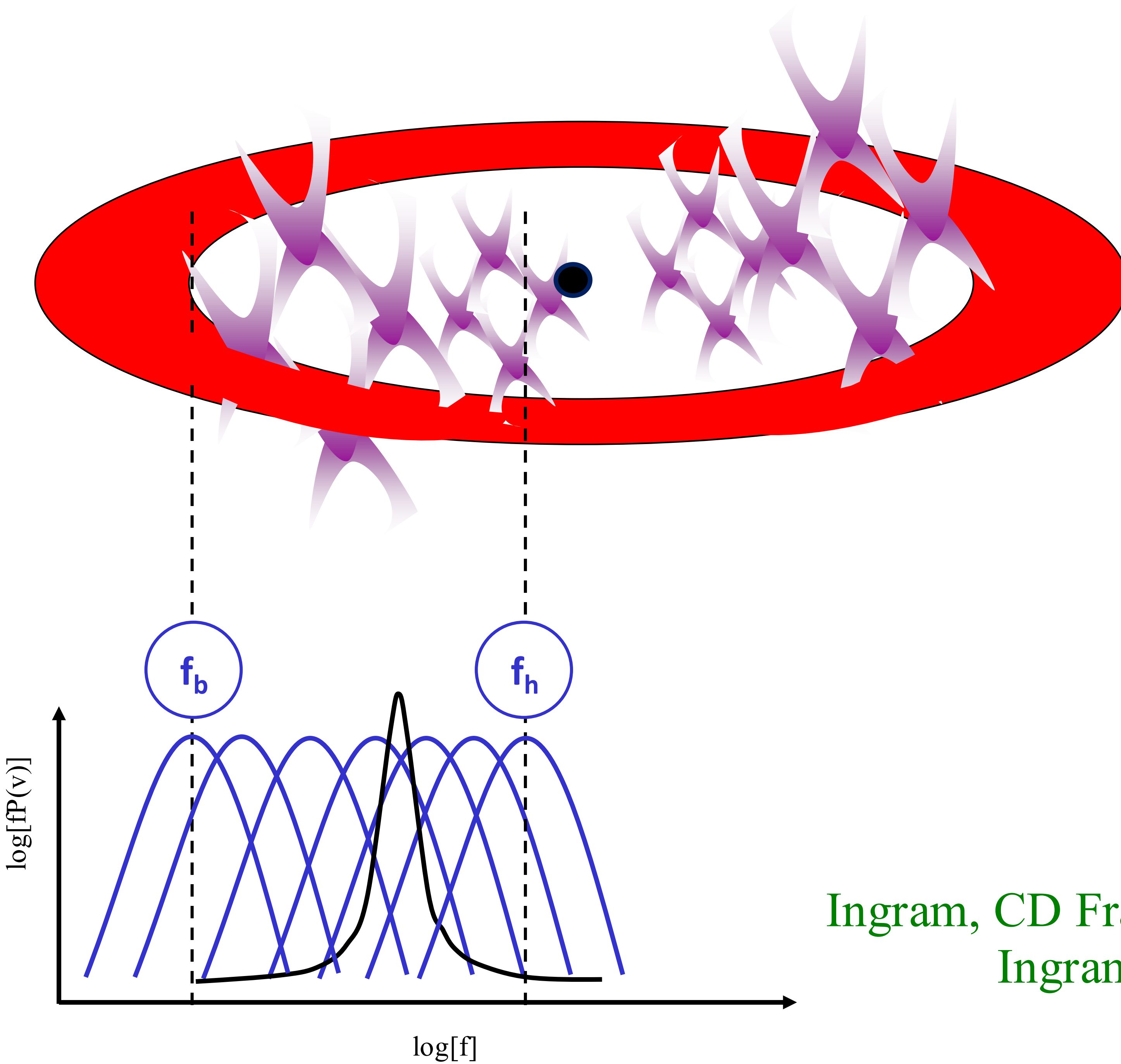




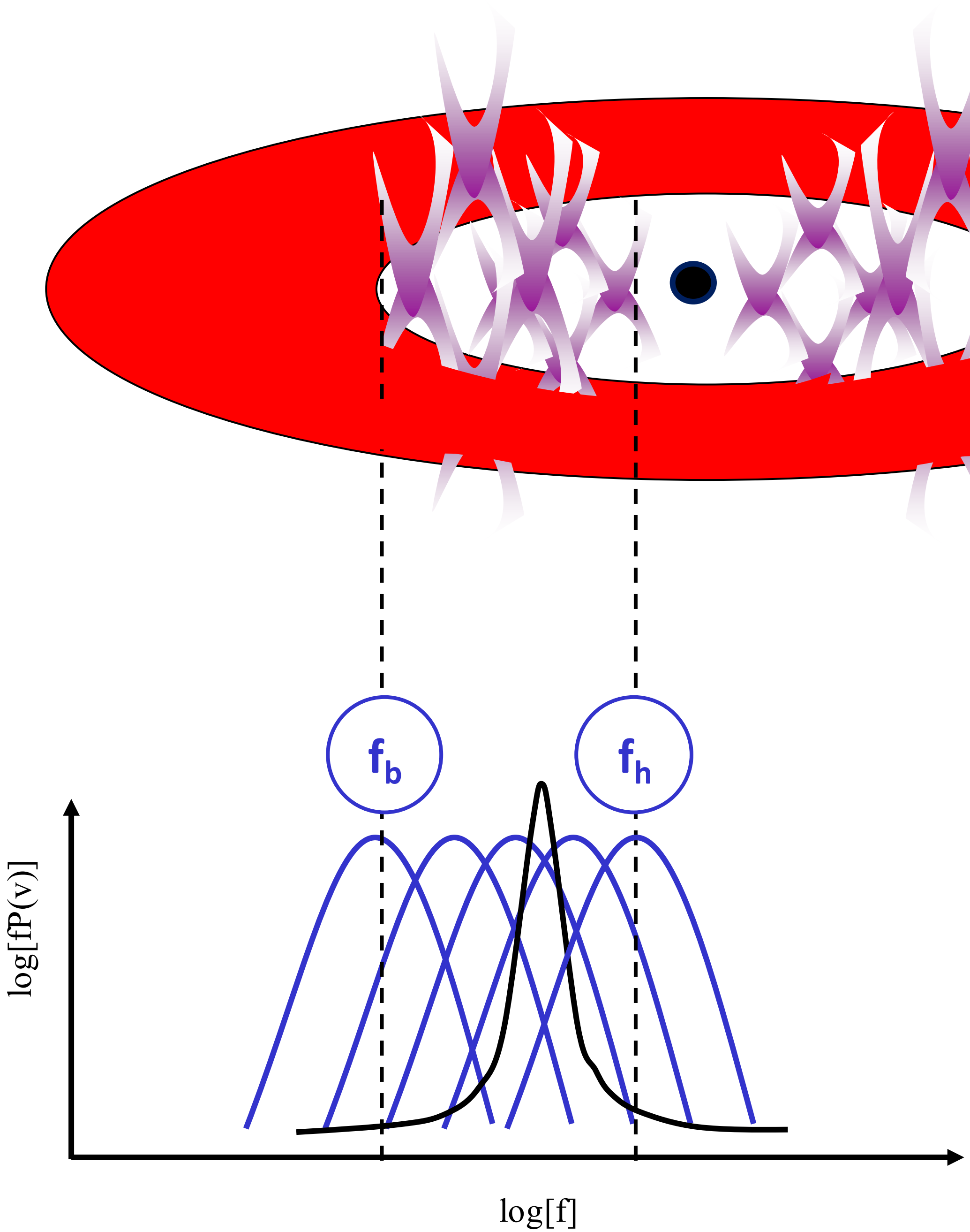
Ingram, CD 2012



Ingram, CD Fragile 2009
Ingram, CD 2012



Ingram, CD Fragile 2009
Ingram, CD 2012



Ingram, CD Fragile 2009
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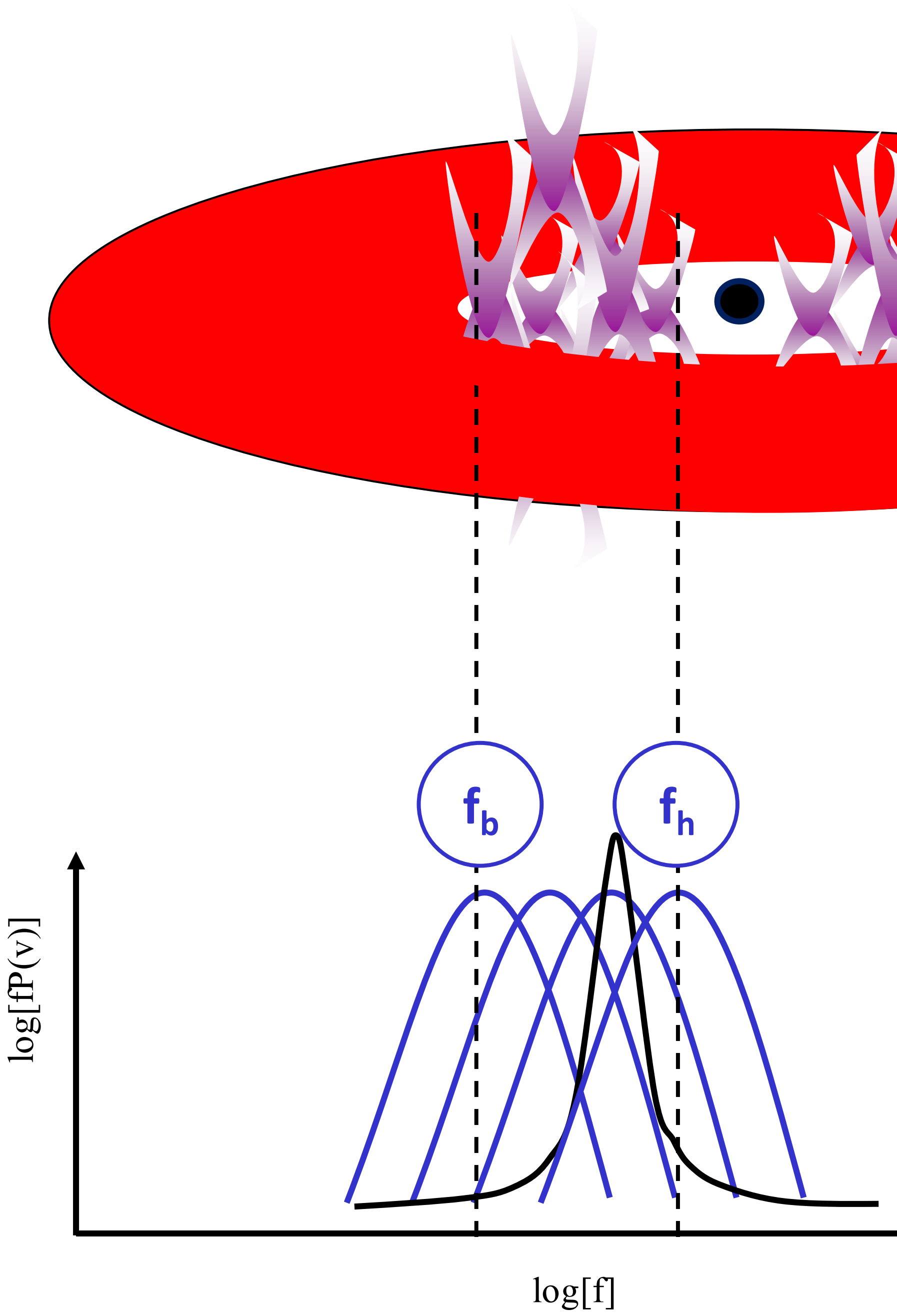
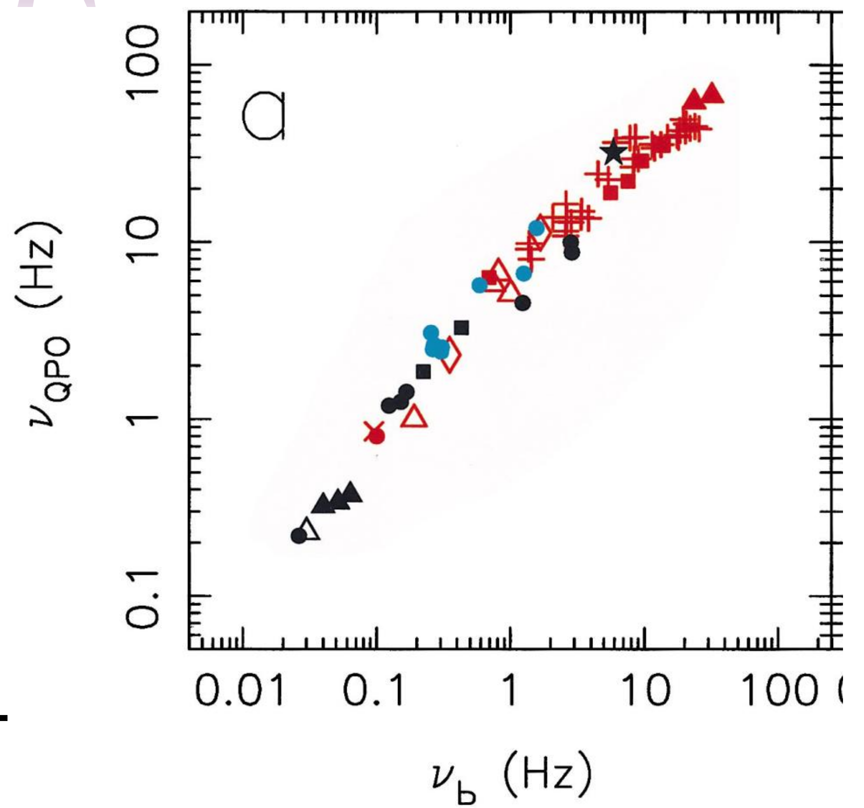
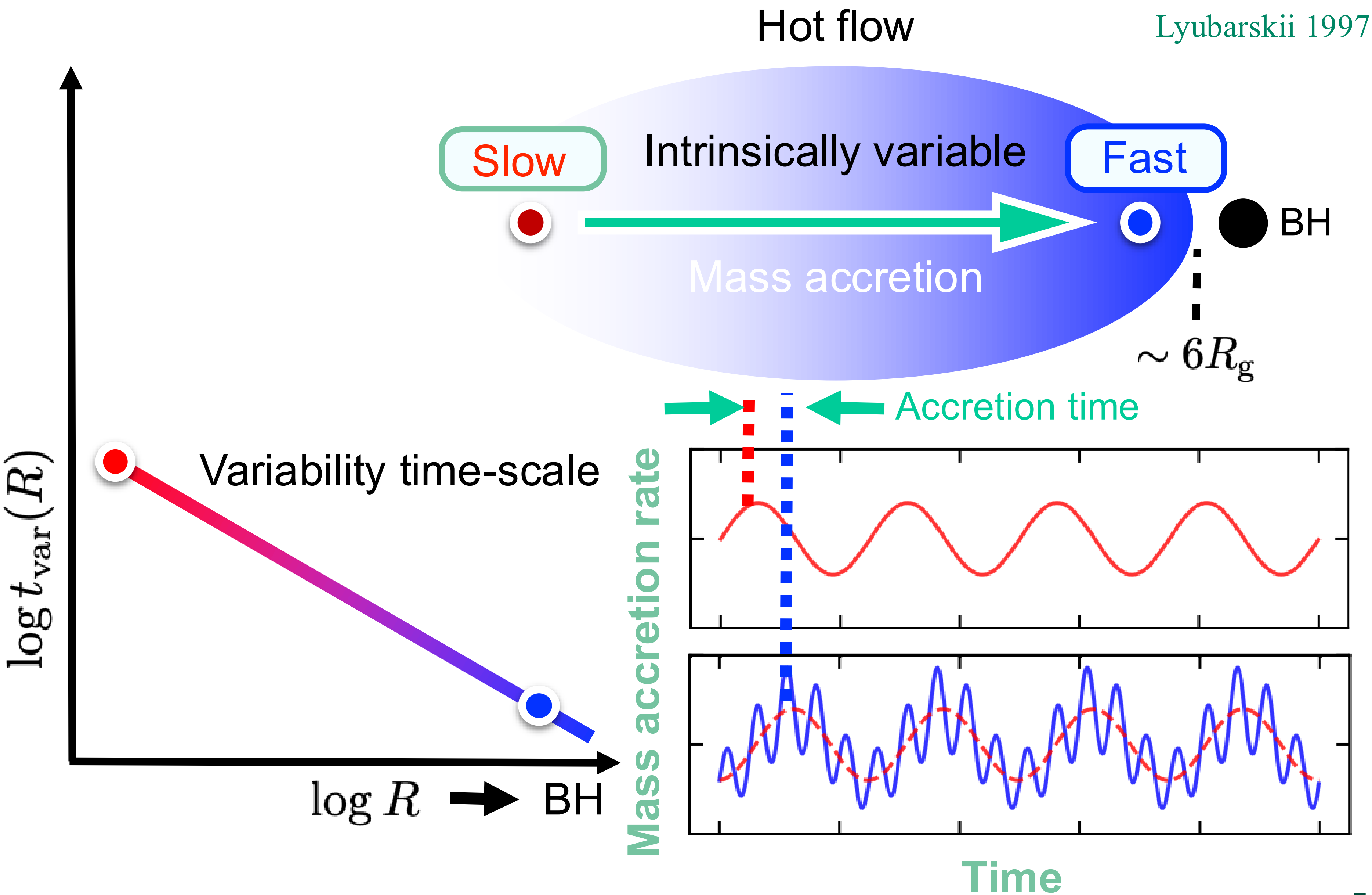


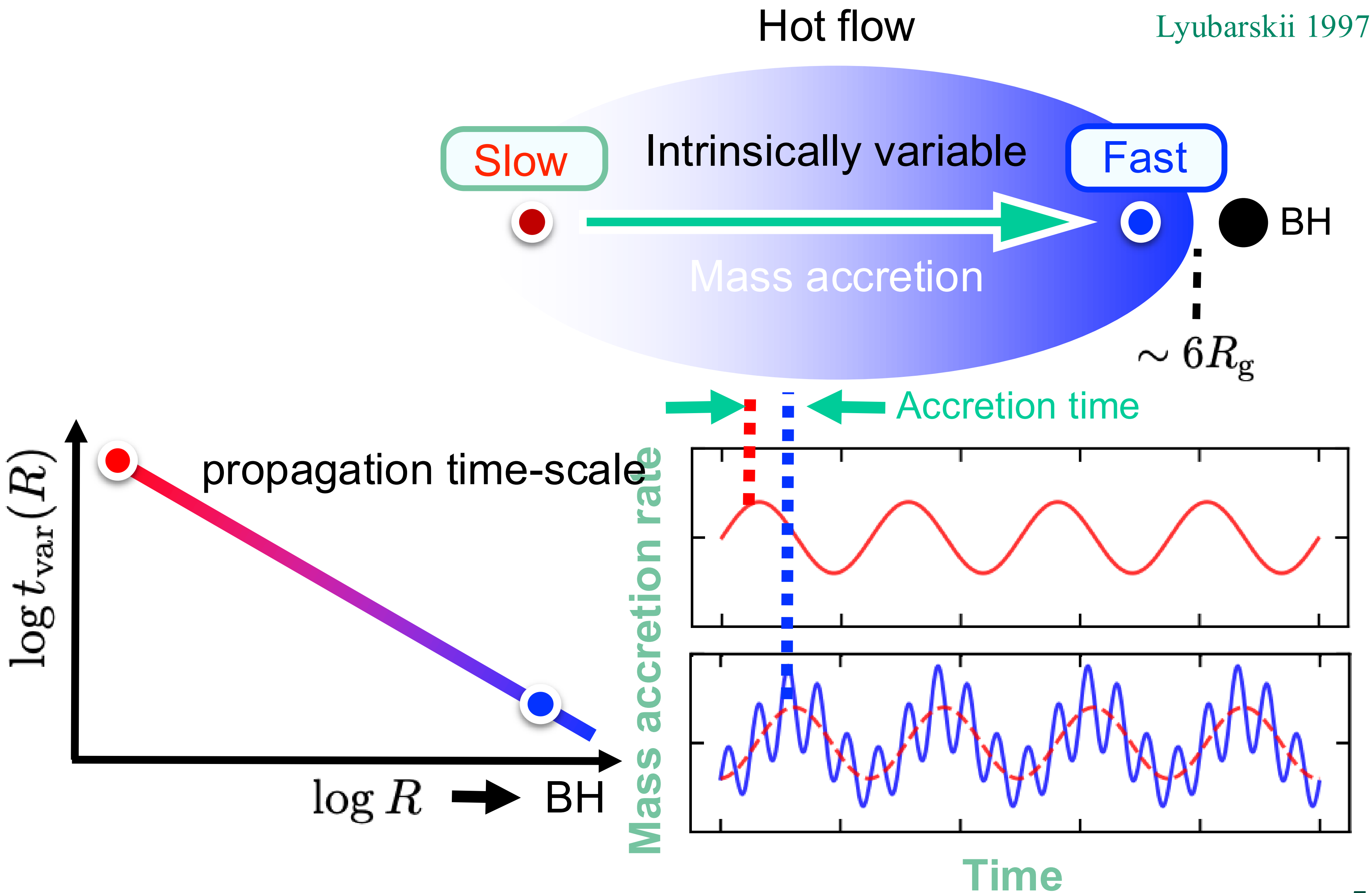
Wijnands & van der Klis 1989



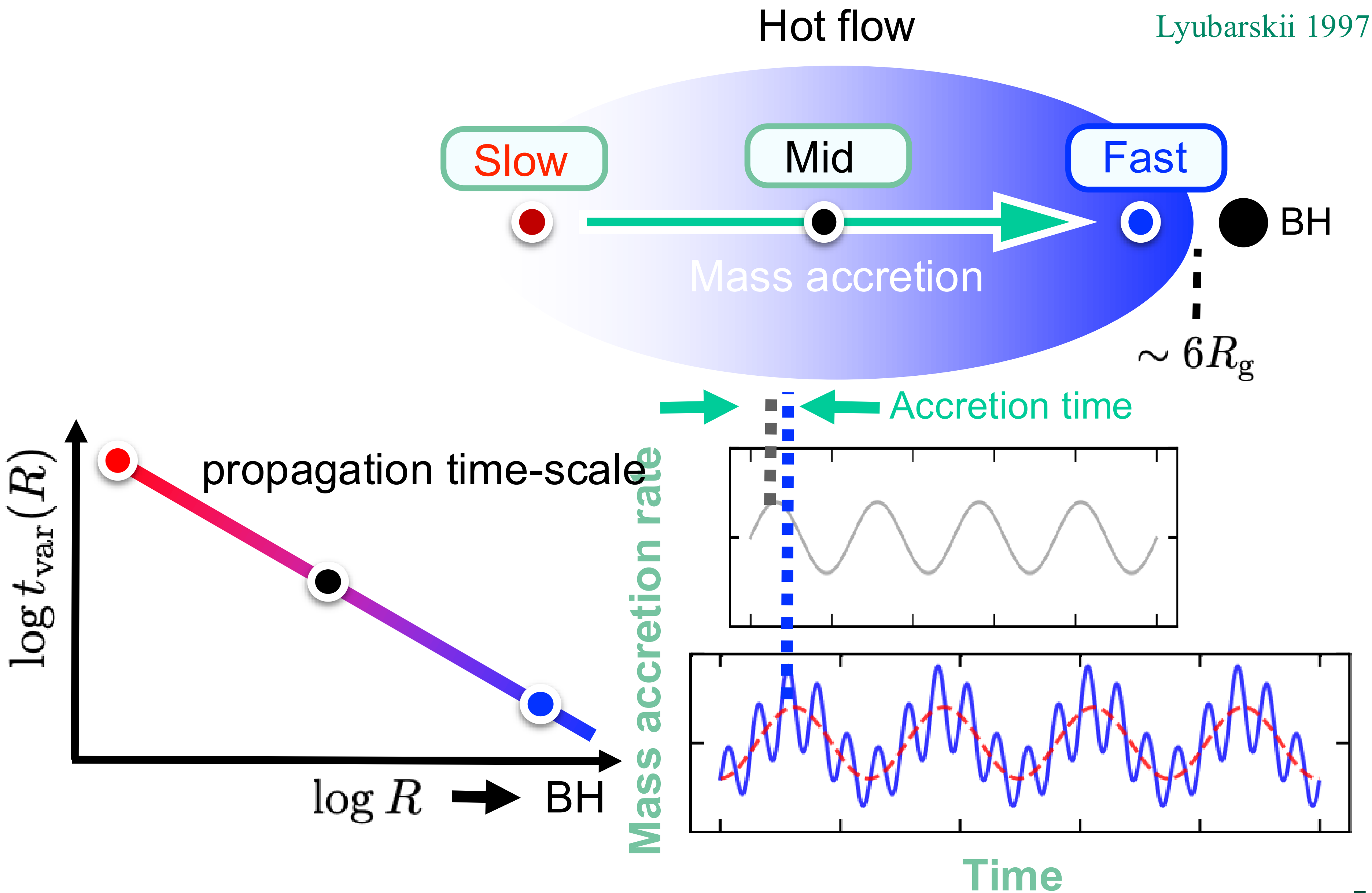
Hot flow propagating fluctuations model



Propagating fluctuations model

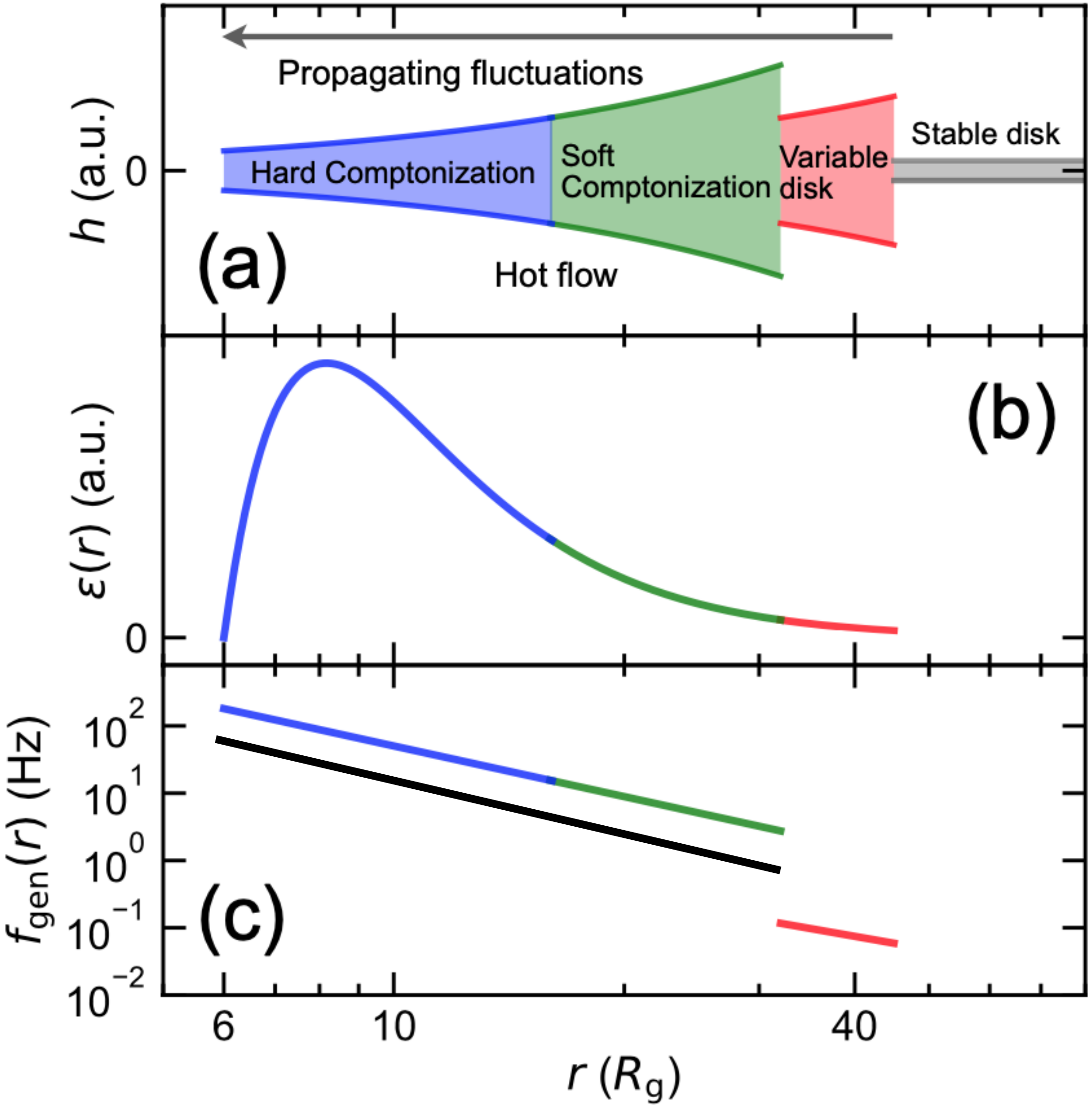


Propagating fluctuations model



So does it work?? 1D radial model

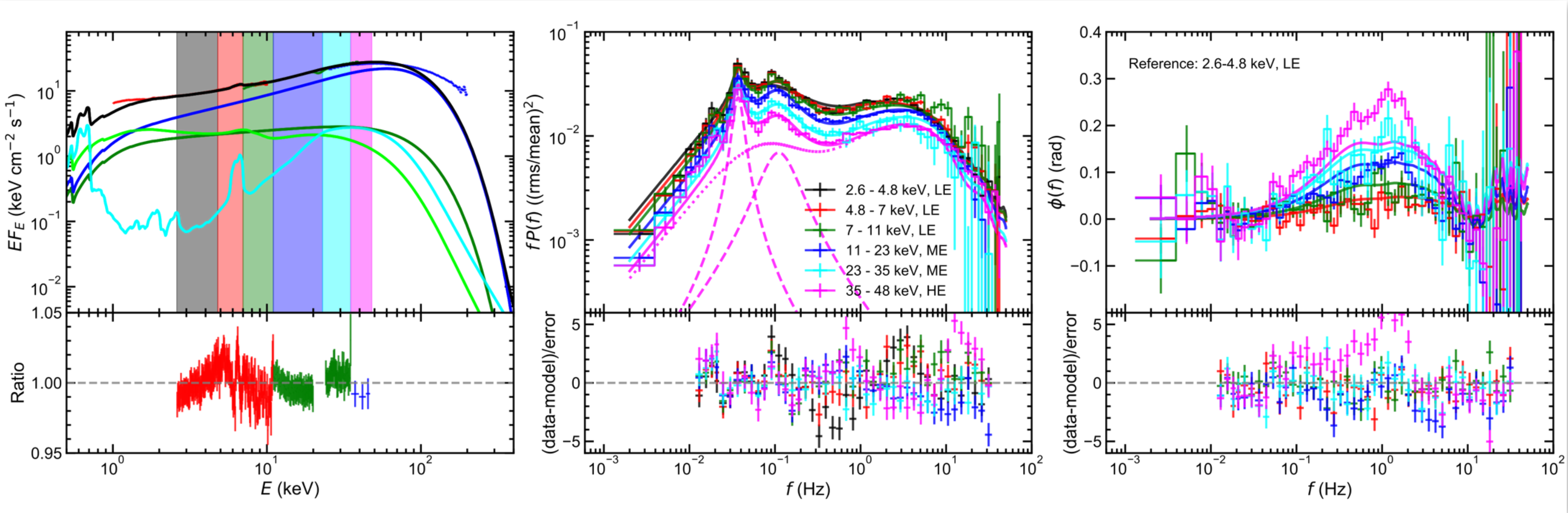
- Geometry
- spectra
- emissivity
- Fluctuation generator timescale
- Propagation timescale



Kawamura et al. 2023

Simultaneous spectral and short-time variability modelling

Simultaneous fitting of energy spectrum, six power spectra and five lag spectra



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Conclusions