# Measuring Black Hole Spin from X-ray Data: Simulations and Observations

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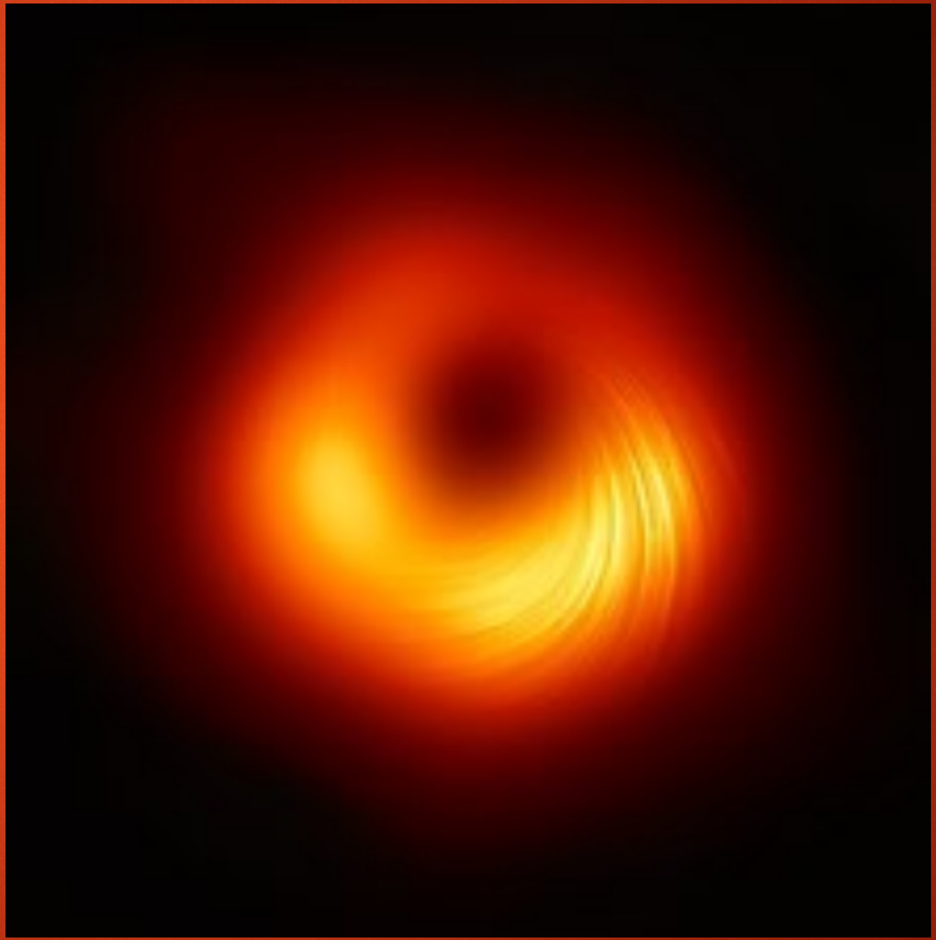
# Black holes

- No-hair theorem: BH can be described by mass, spin and charge (M, a, Q)
- We can measure mass and spin from observations
- Necessary for modelling the evolution of galaxies, processes in the close vicinity of BH, the formation of BHs and supernovae

# Measuring mass


Wiki



The Event Horizon Telescope (EHT)

# How fast can a BH spin?

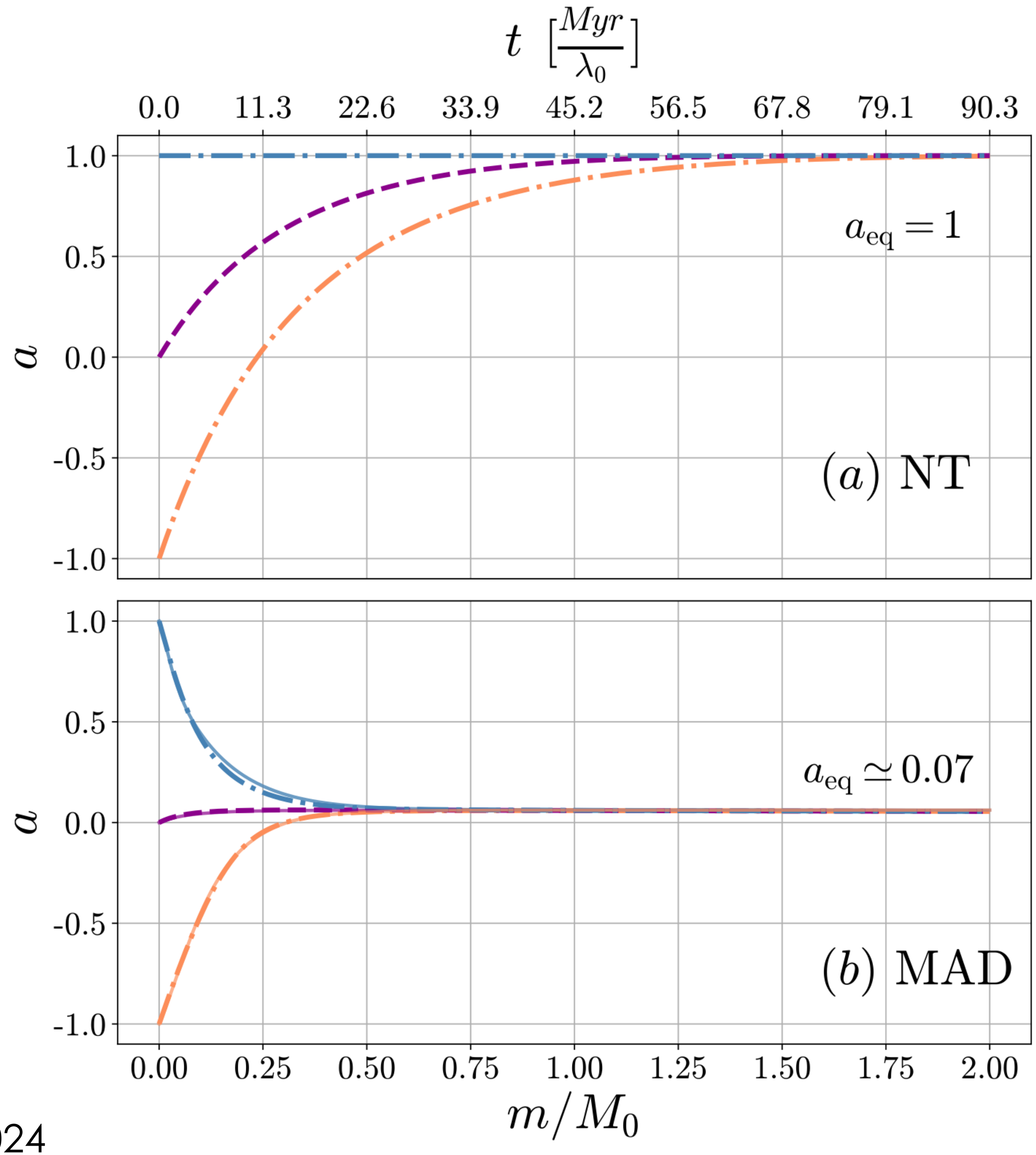
- From core-collapse supernova: max 0.75 (Baumgarte&Shapiro 1999)
  - Spherical collapse on mass-shedding limit
- NSs merger: max 0.9 (e.g. Shibata+ 2002)
  - Gravitation wave radiation – angular momentum loss
- BH mergers:
  - Comparable masses: a > 0.8 (Gammie+ 2004, Smarr 1979, …)
  - Merger with smaller BH leads to spin-down (Hughes & Blandford 2003)

# Change of spin by accretion

- Bardeen 1970: BH can spin-up to $a = 1$
- Thorne 1974: thin disc, $a = 0.998$
  - Radiation torque counteract the angular momentum accumulation
- Abramowicz+ 1978: Thick disc, $a > 0.998$
- Popham&Gammie 1998: ADAF, $a \sim 0.7$

# Magnetic field - simulations

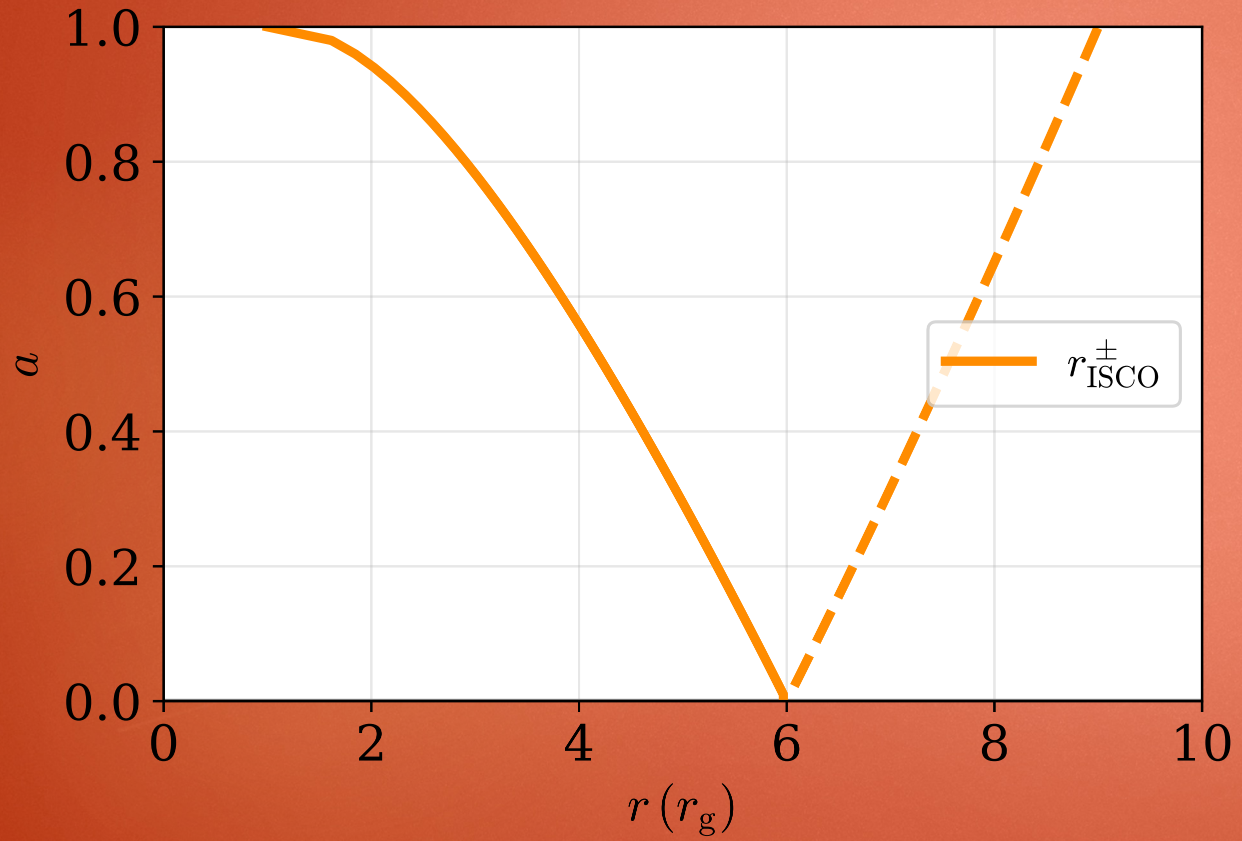
- While thin disc accretion spins-up the BH, the accretion of magnetically arrested disc slows it down very rapidly
- Are most of the discs MAD?



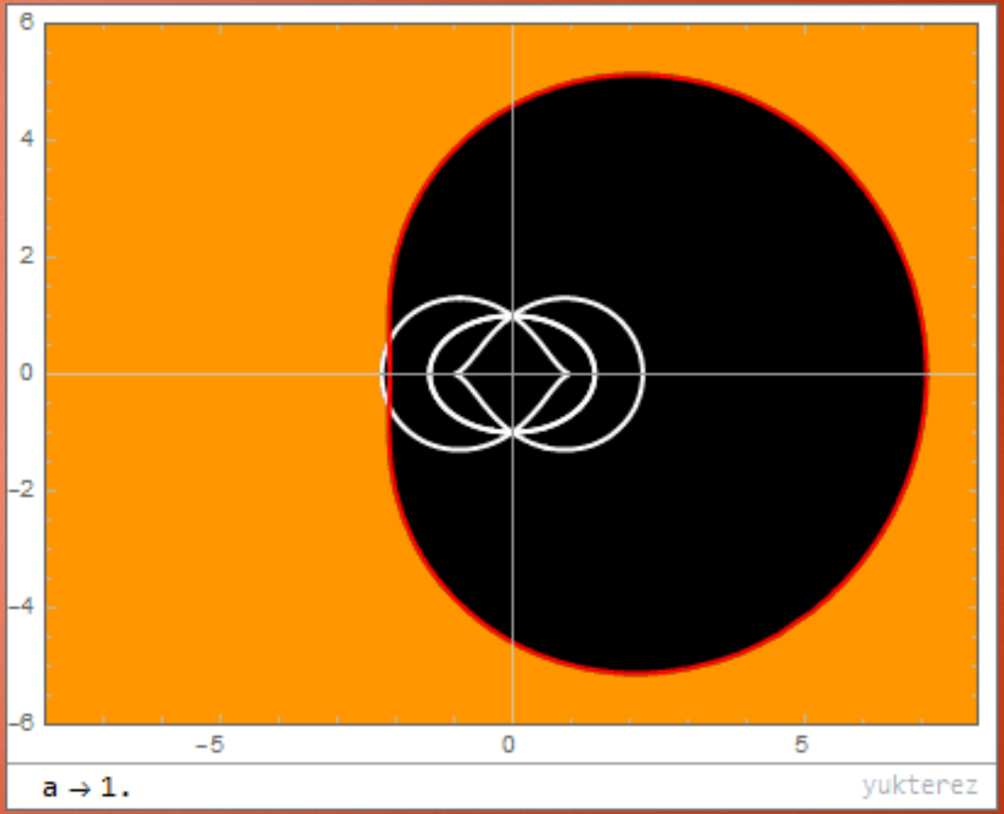

Lowel+ 2024

# How to measure spin

Position of innermost stable circular orbit (ISCO)



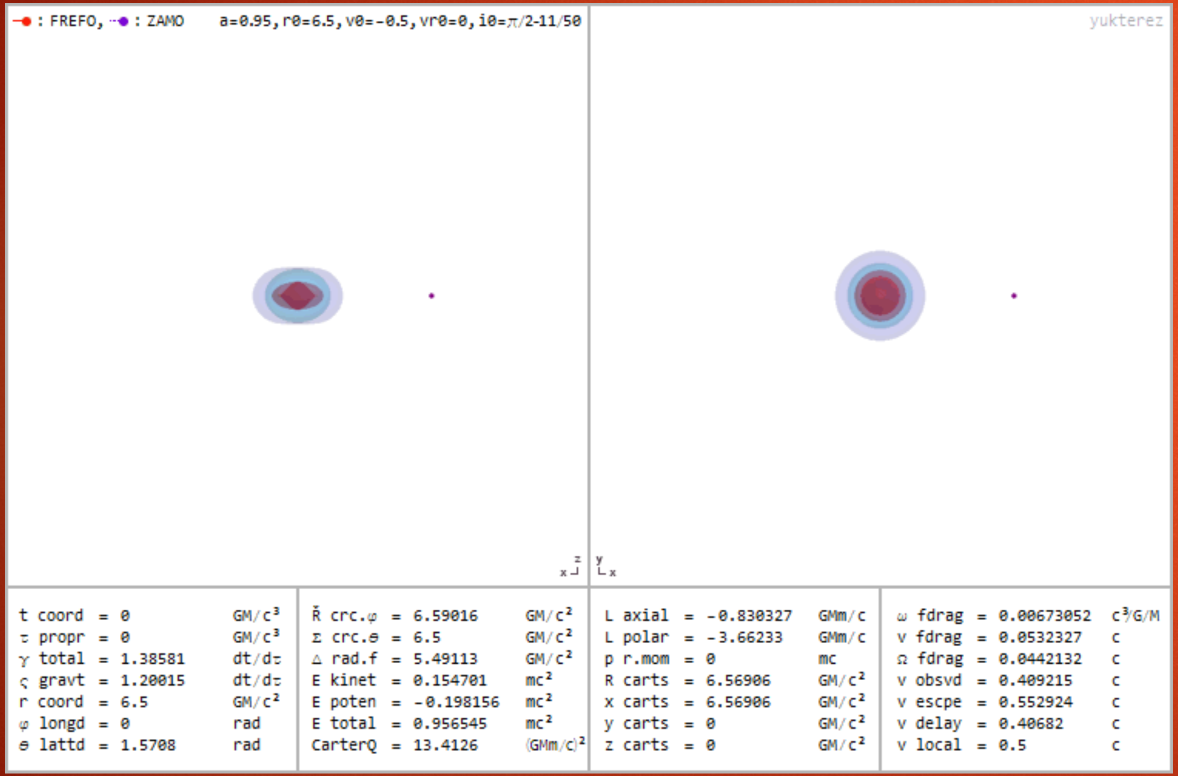

Shape (ngEHT)




Wiki

# How to measure spin

## Orbital motion

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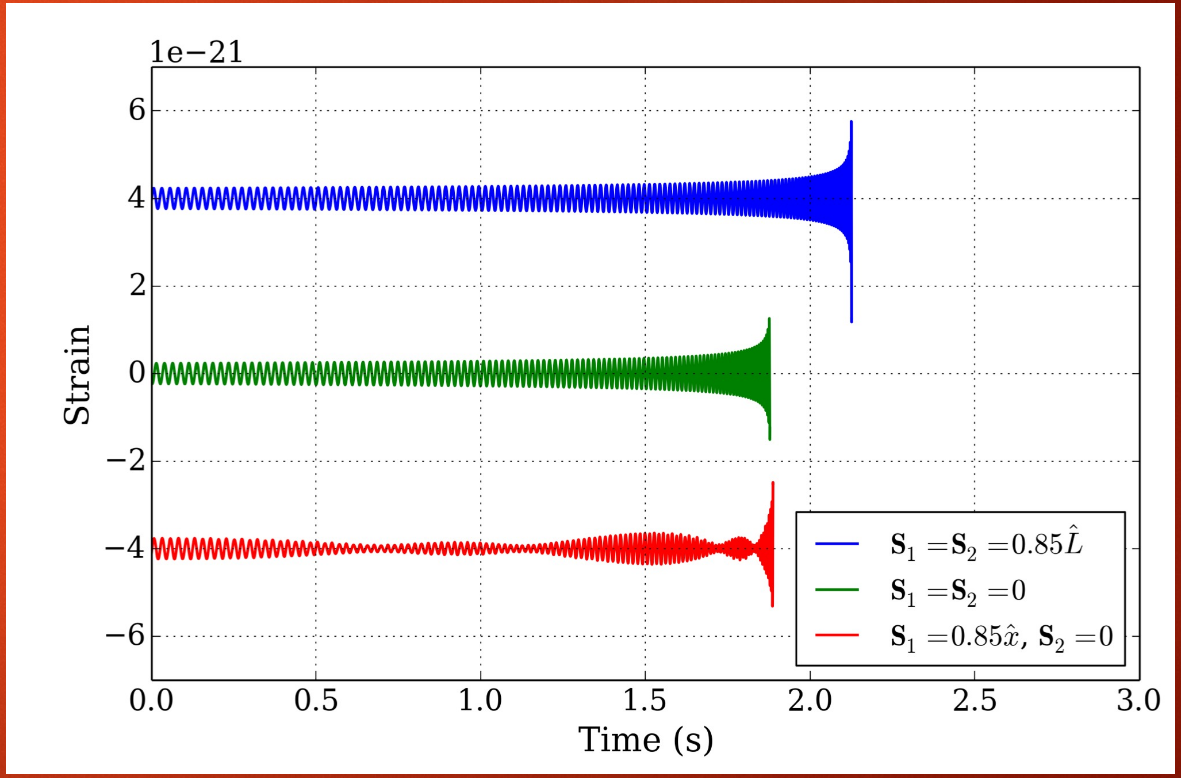
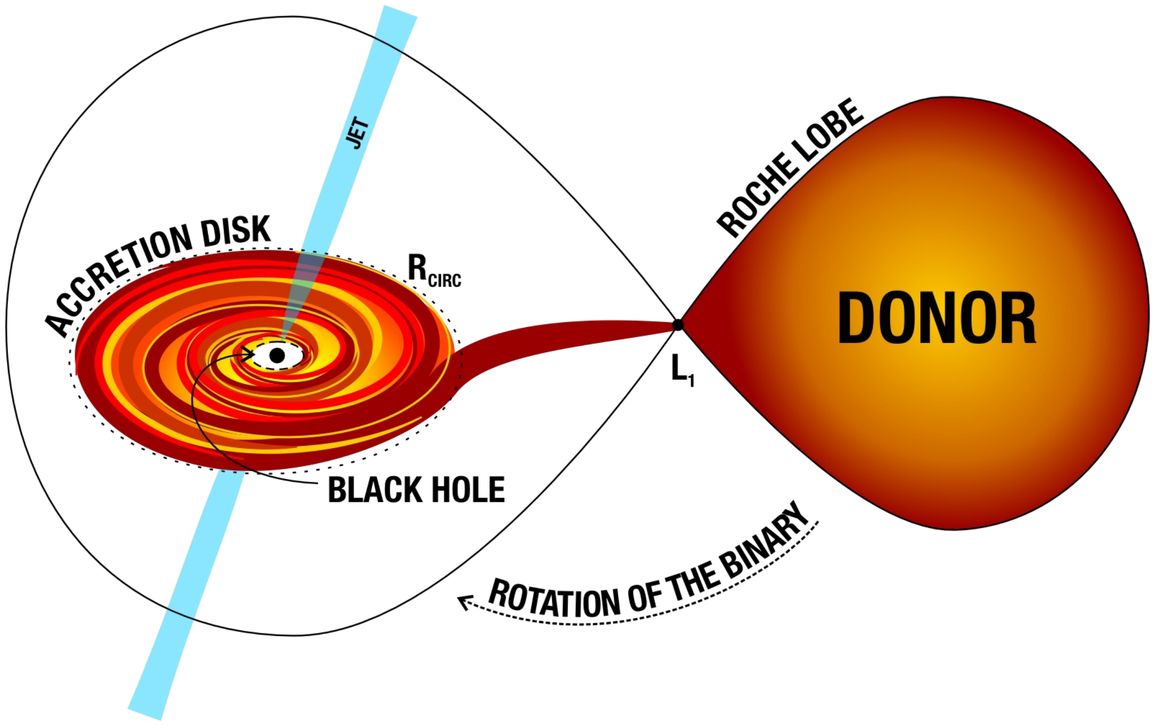
## GW




Privitera 2014

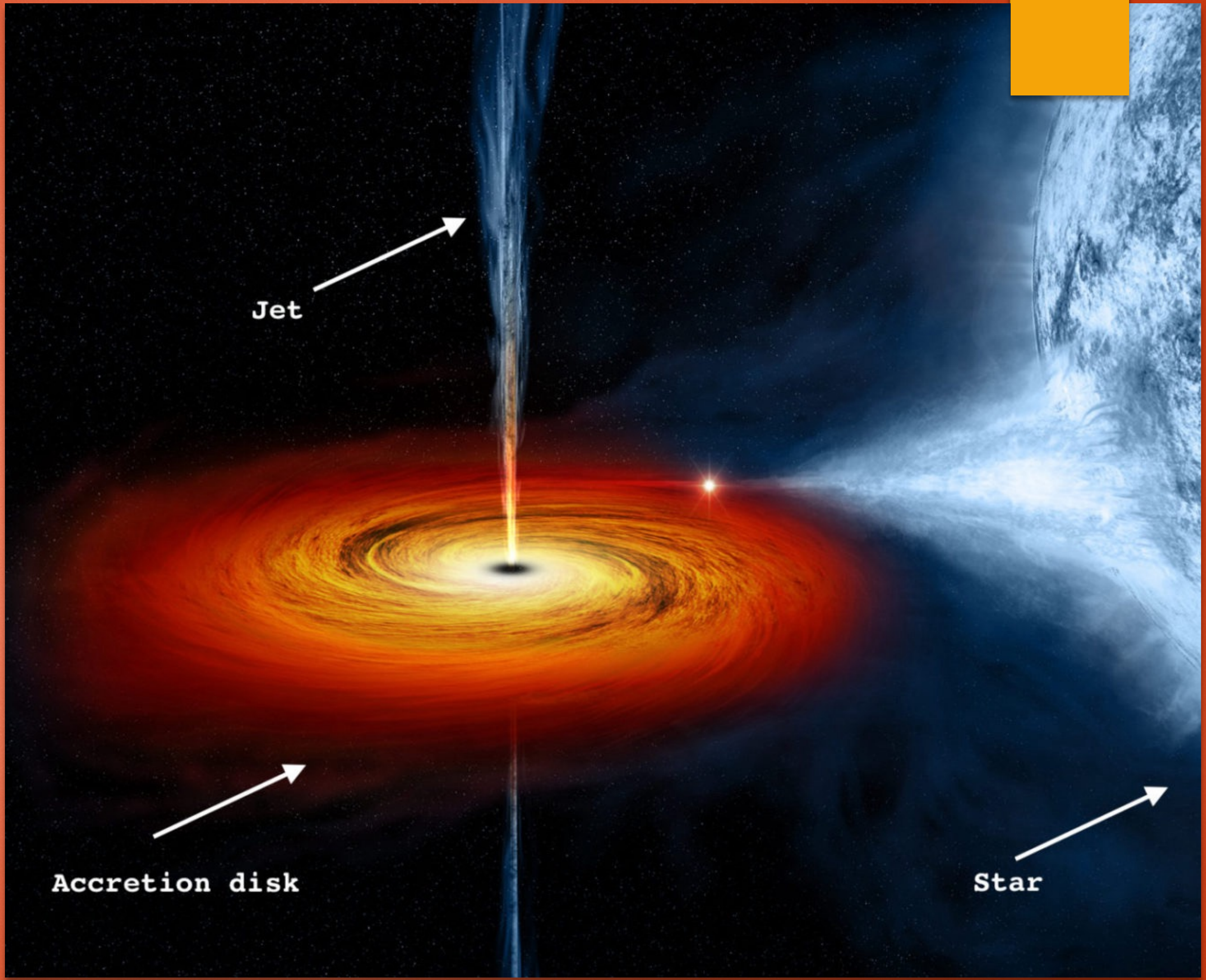
# X-ray binaries

- Compact object
- Accretion disc luminous in X-ray
- Sometimes radio-loud jet
- Donor – not observed (Low Mass) or bright in UV/Optical (High Mass)



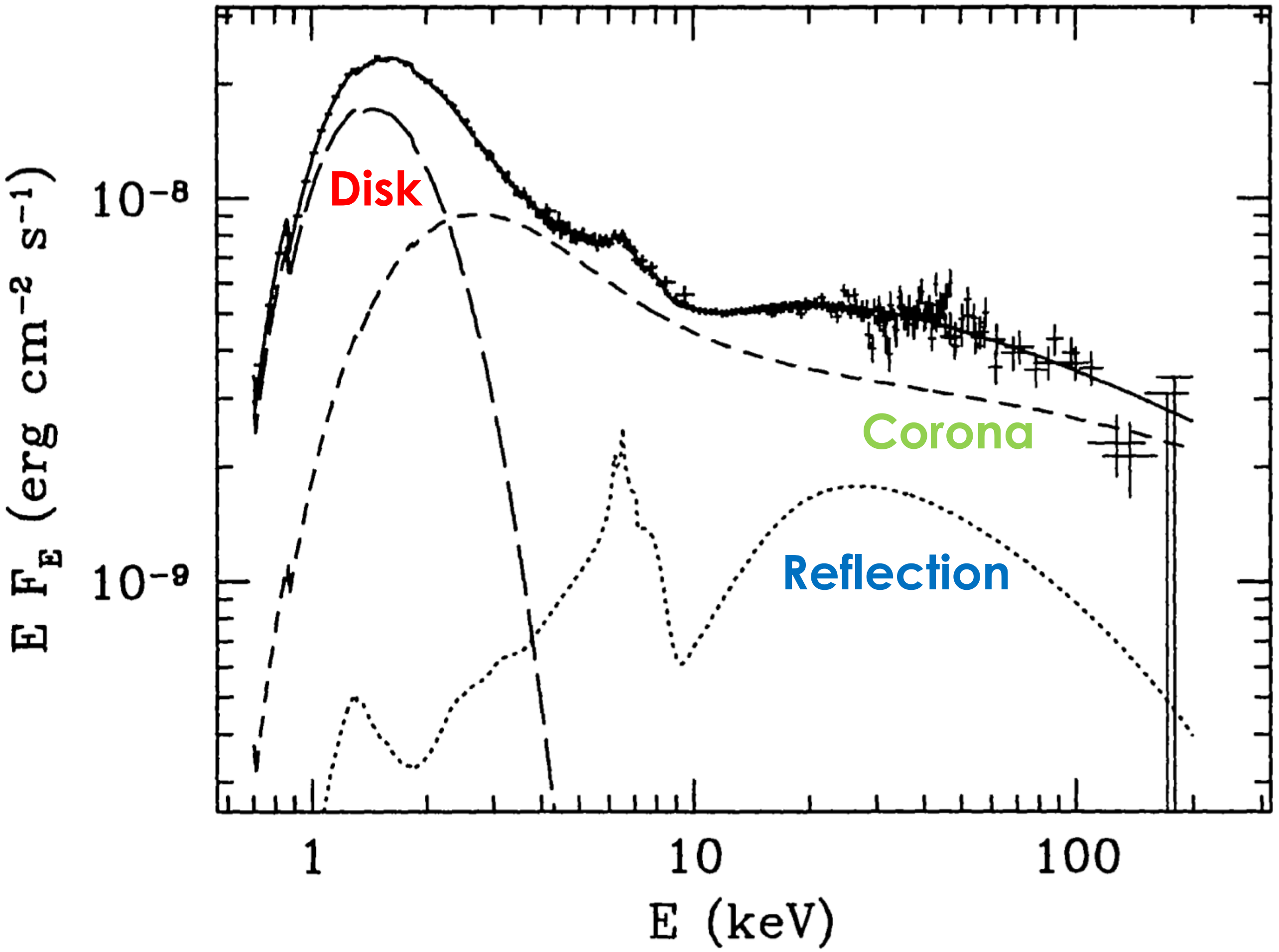
# Accretion disc in X-ray binaries

- Standart thin disc – Shakura&Sunyaev, Novikov&Thorne 1973
- Thermal radiation – 10^6 K - 1 keV – soft X-rays
- Compton up-scattering of thermal photos – hard X-rays

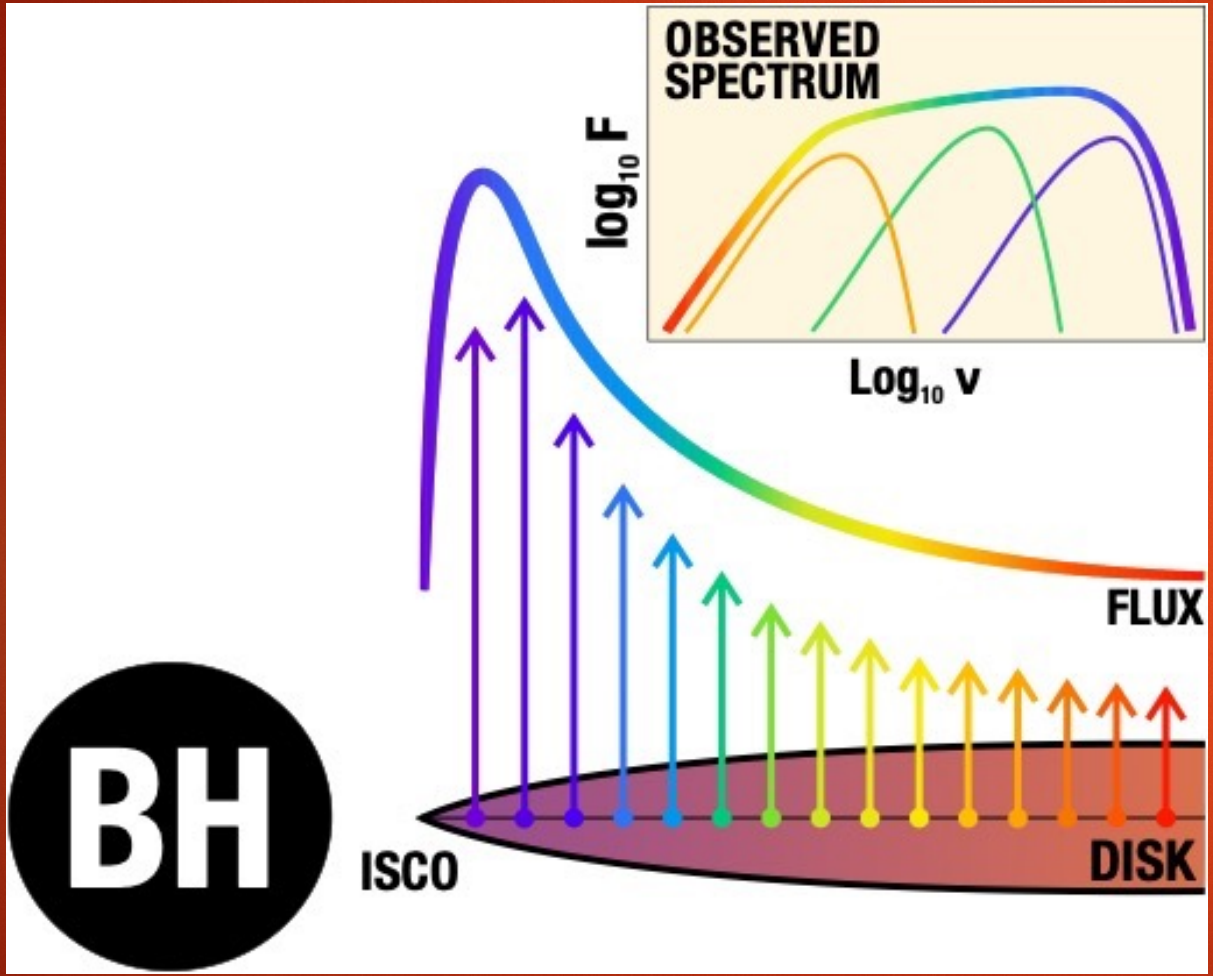


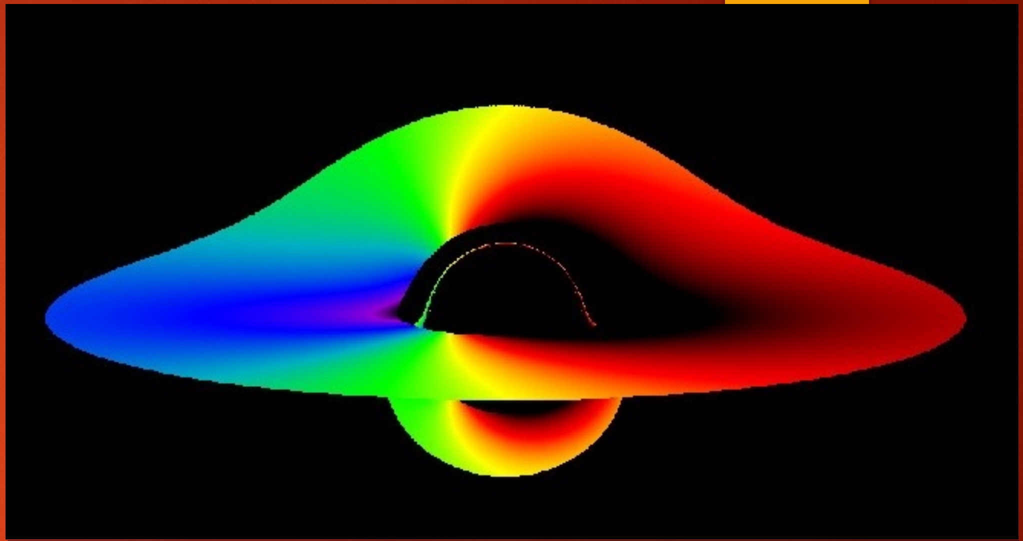
# X-ray spectrum

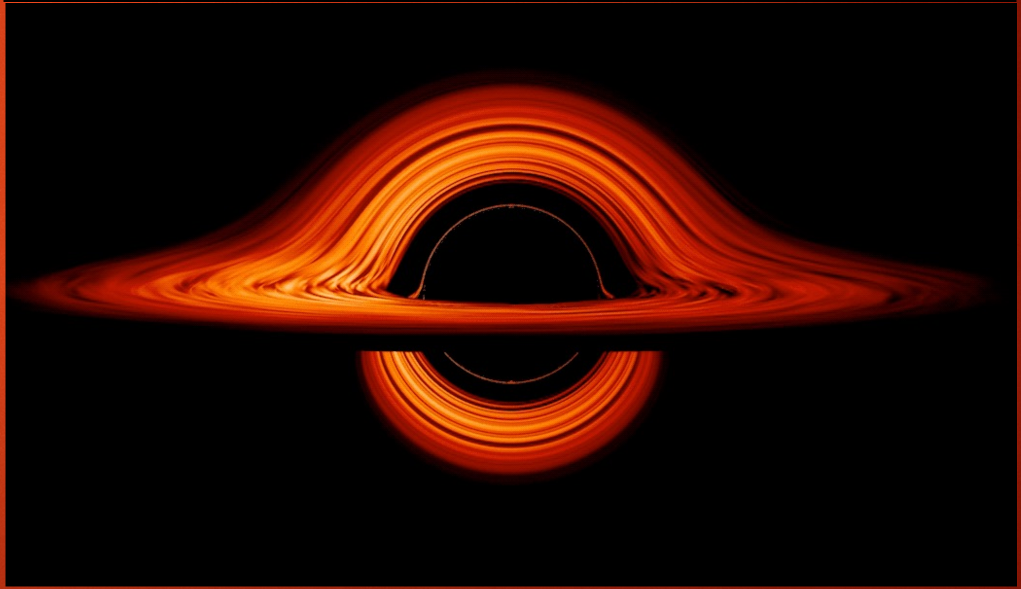
- Cyg X-1
- Gierlinski&Zdziarski 1999



# Where does the disc ends?

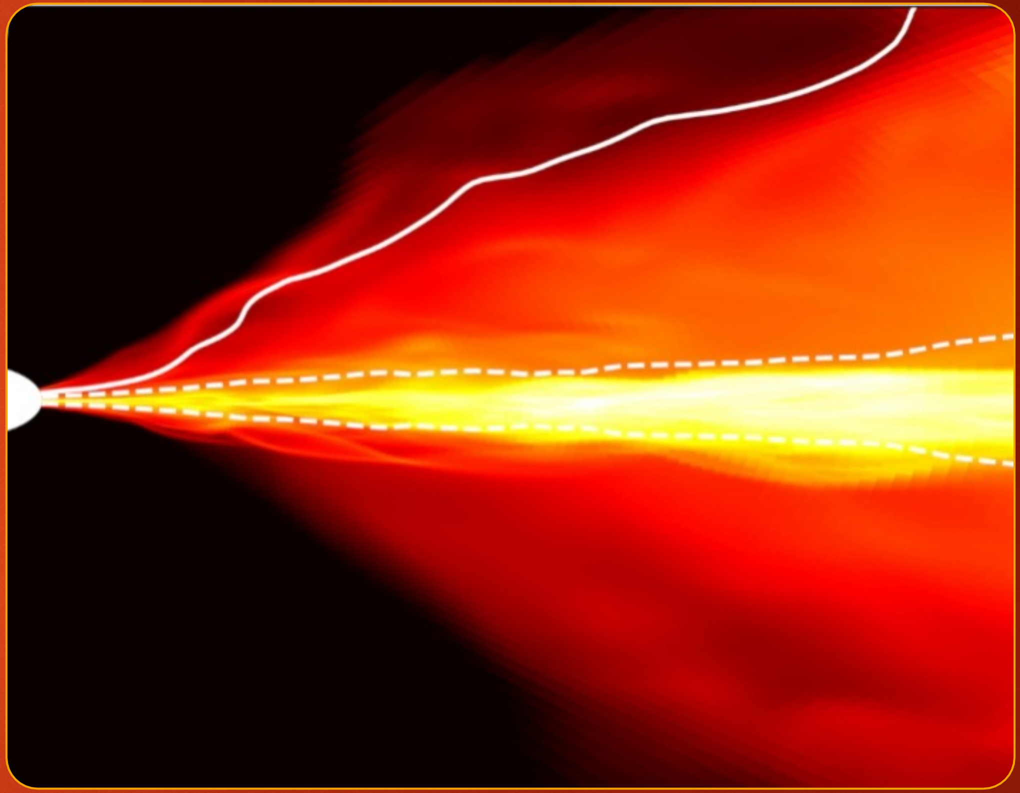


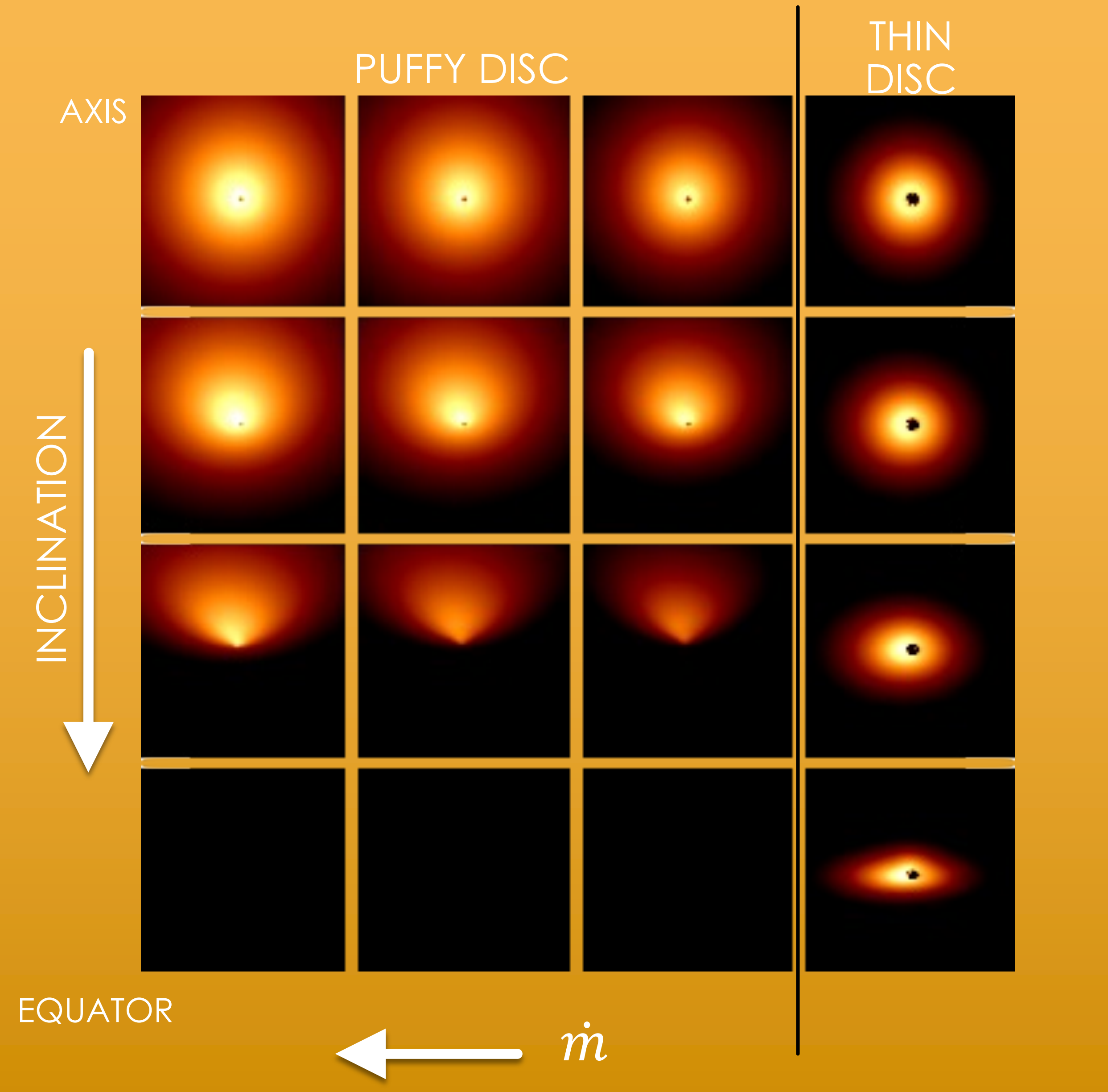



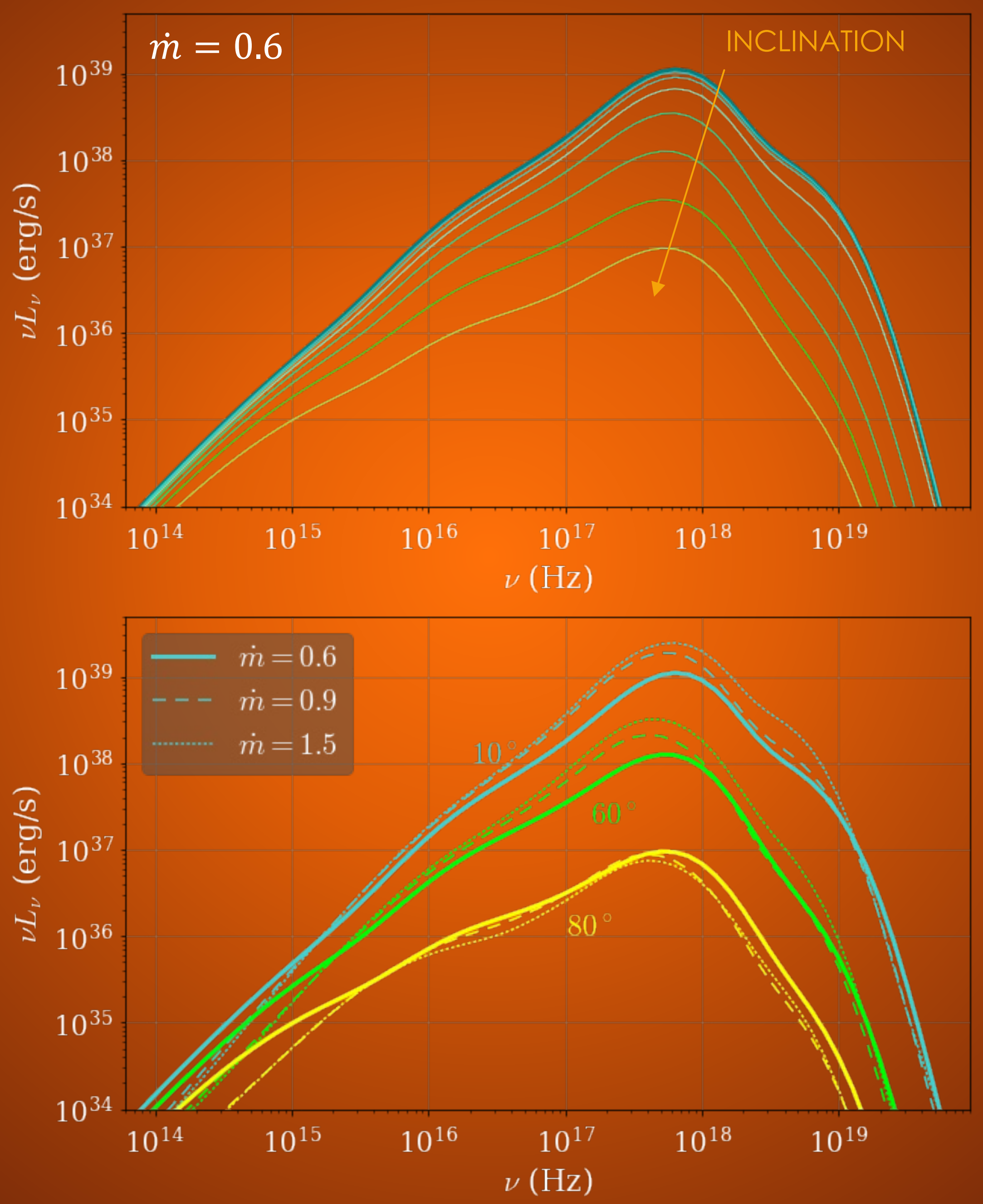


# Does ISCO matter?

- Recent studies show that the ISCO boundary condition is not correct (Wielgus+ 2022, Lančová+ 2023, Mummery+ 2024)
- Magnetic torques act on plasma under ISCO and keep it stable
- Puffy accretion disc (Lančová+ 2019)
  - Sub-Eddington accretion on stellar-mass non-rotating BH
  - GRRMHD simulations
  - Stable in radiation-pressure-dominated regime
  - Optically thick all the way to the horizon, sonic point deep under the ISCO






WIELGUS+ 2022

FIT IT!

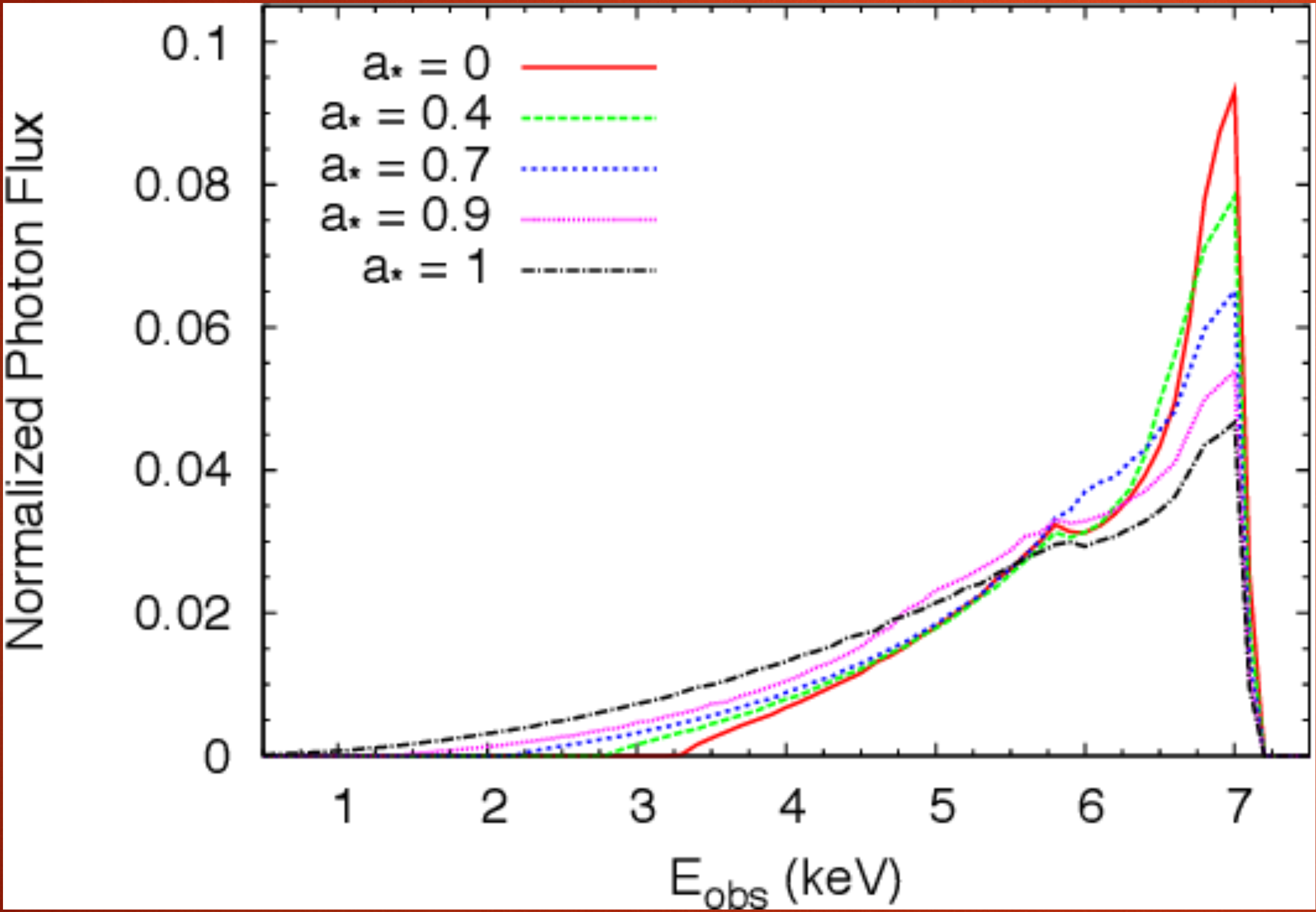
| | puffy $\theta = 10^\circ$ | | puffy $\theta = 60^\circ$ | |
|---|---|---|---|---|
| | **slimbh** | **kerrbb** | **slimbh** | **kerrbb** |
| $a_*$ | $0.82^{+0.08}_{-0.16}$ | $0.86^{+0.08}_{-0.14}$ | $0.55^{+0.11}_{-0.29}$ | $0.48^{+0.12}_{-0.41}$ |
| $L_{\rm disk}/L_{\rm Edd}$ | $0.73^{+0.15}_{-0.16}$ | $0.79^{+0.1}_{-0.1}$ | $0.21^{+0.19}_{-0.24}$ | $0.17^{+0.05}_{-0.03}$ |
| $\Gamma$ | $2.85^{+0.17}_{-0.20}$ | $2.72^{+0.24}_{-0.24}$ | $3.62^{+0.27}_{-0.29}$ | $3.67^{+0.34}_{-0.27}$ |
| $T_{\rm e}$ (keV) | $14.95^{+5.31}_{-2.68}$ | $13.05^{+4.62}_{-2.43}$ | $19.51^{+17.34}_{-5.75}$ | $19.26^{+21.81}_{-5.58}$ |
| $T_{\rm bb}$ (keV) | $0.50^{+0.08}_{-0.07}$ | $0.67^{+0.22}_{-0.15}$ | $1.01^{+0.57}_{-0.31}$ | $0.97^{+0.48}_{-0.29}$ |
| $\chi^2/dof$ | $9.32/29$ | $8.51/29$ | $11.58/29$ | $27.97/29$ |

- SLIMBH or KERBB + thermal comptonization NTHCOMP
- Spin overestimated – especially for high inclination – the innermost part of the disc

WIELGUS+ 2022

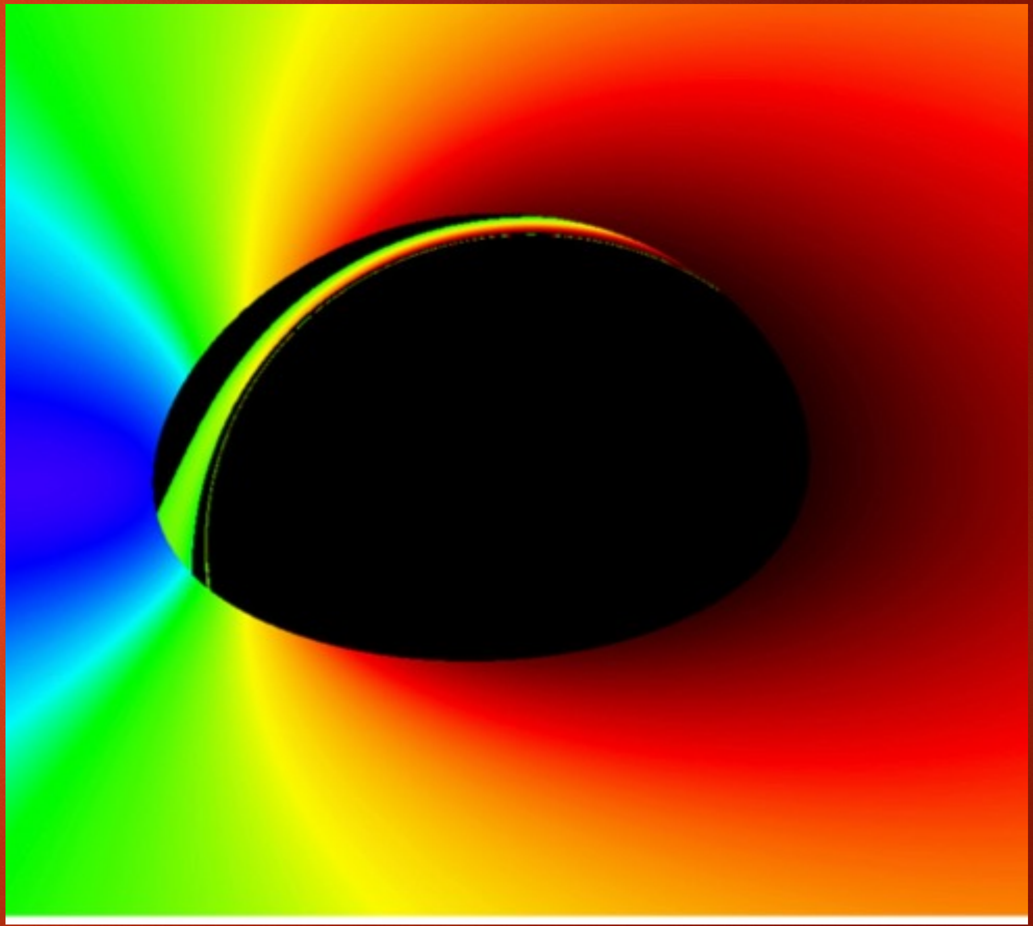
# Fitting the Fe line

Blue horn for high a



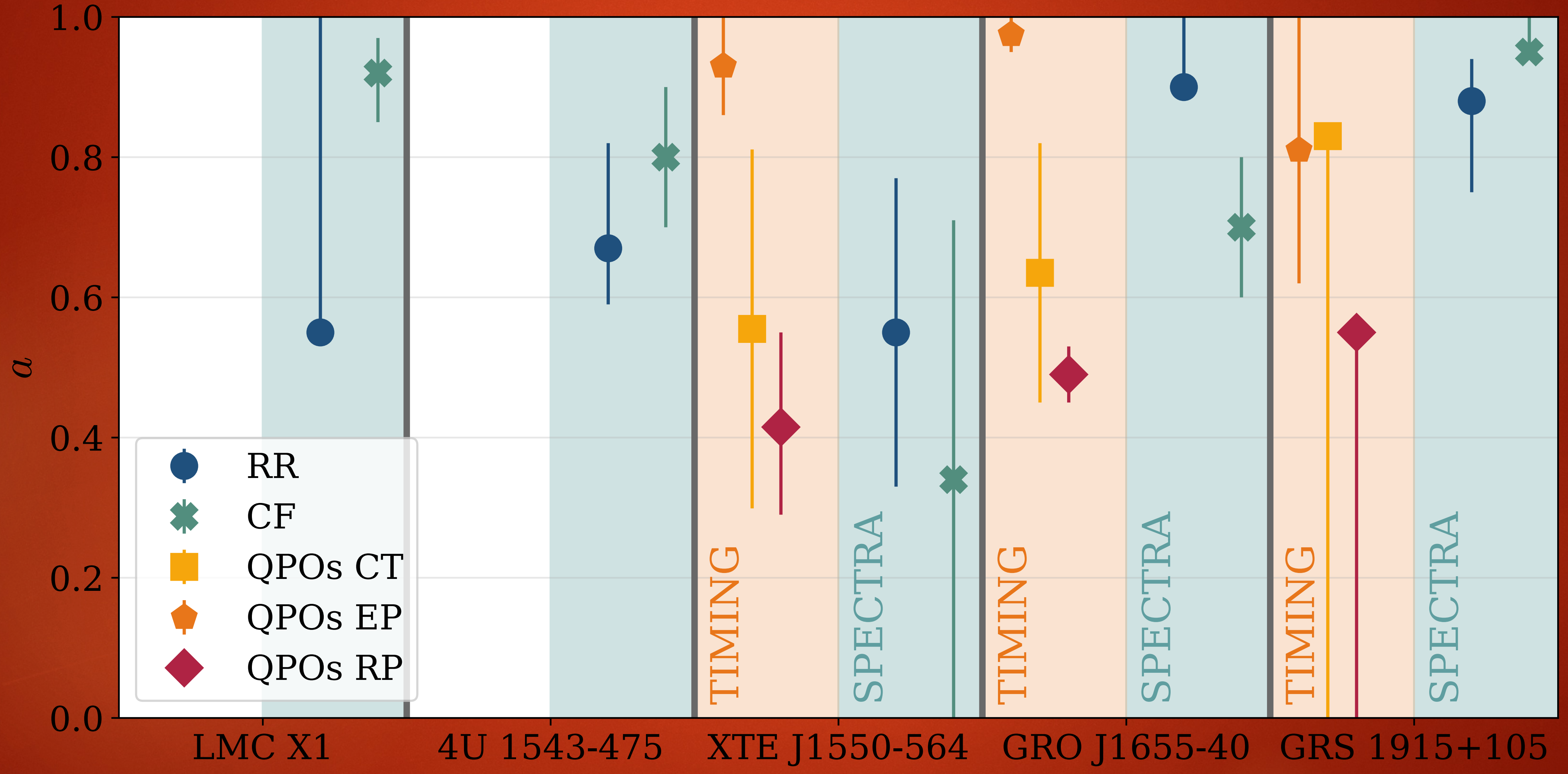

Bambi 2013

HOI leads to spin overestimation



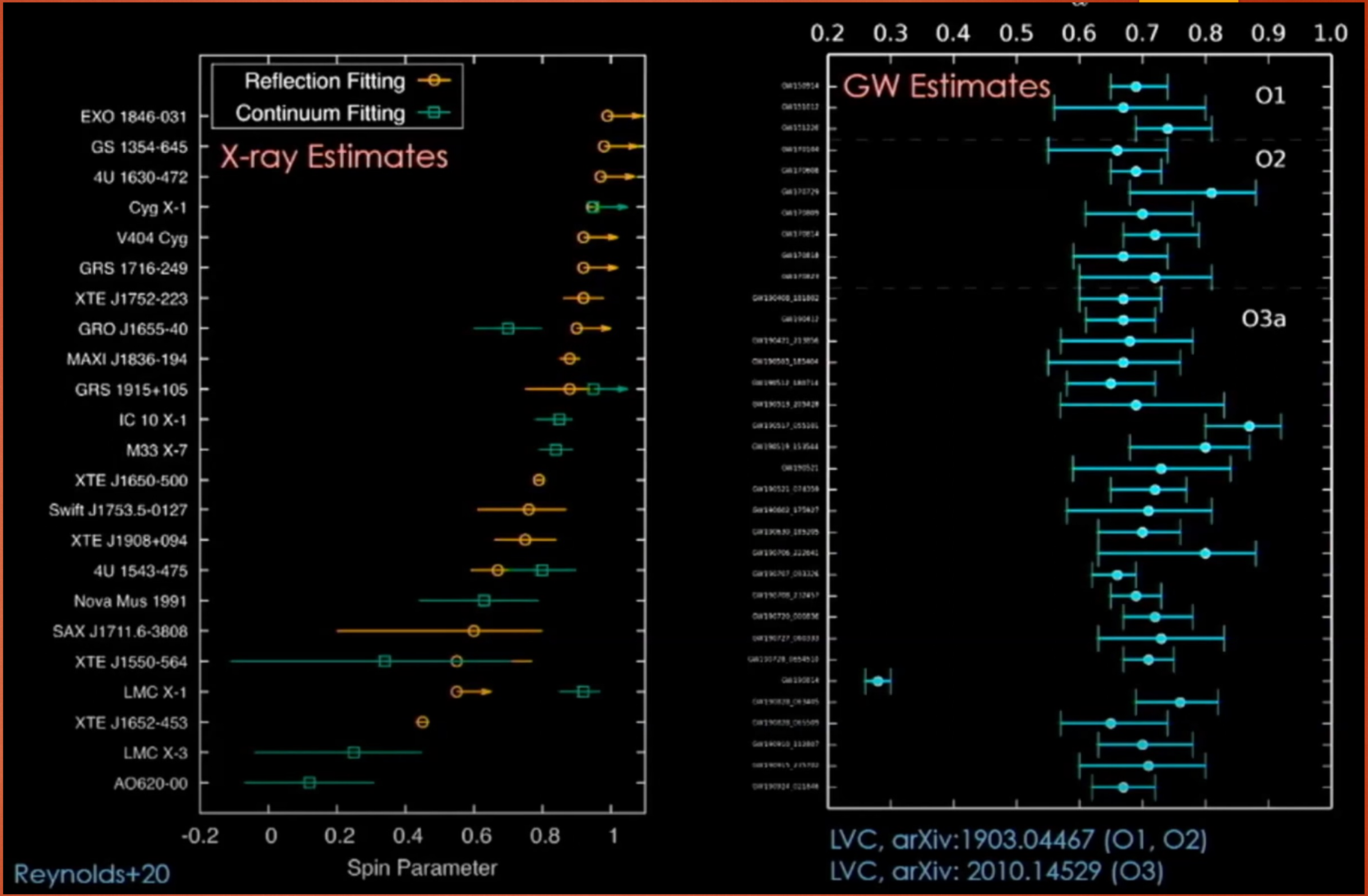
Falanga+ 2021

# BH binaries spin estimations




Kotrlová+ 2022, Reynolds 2020

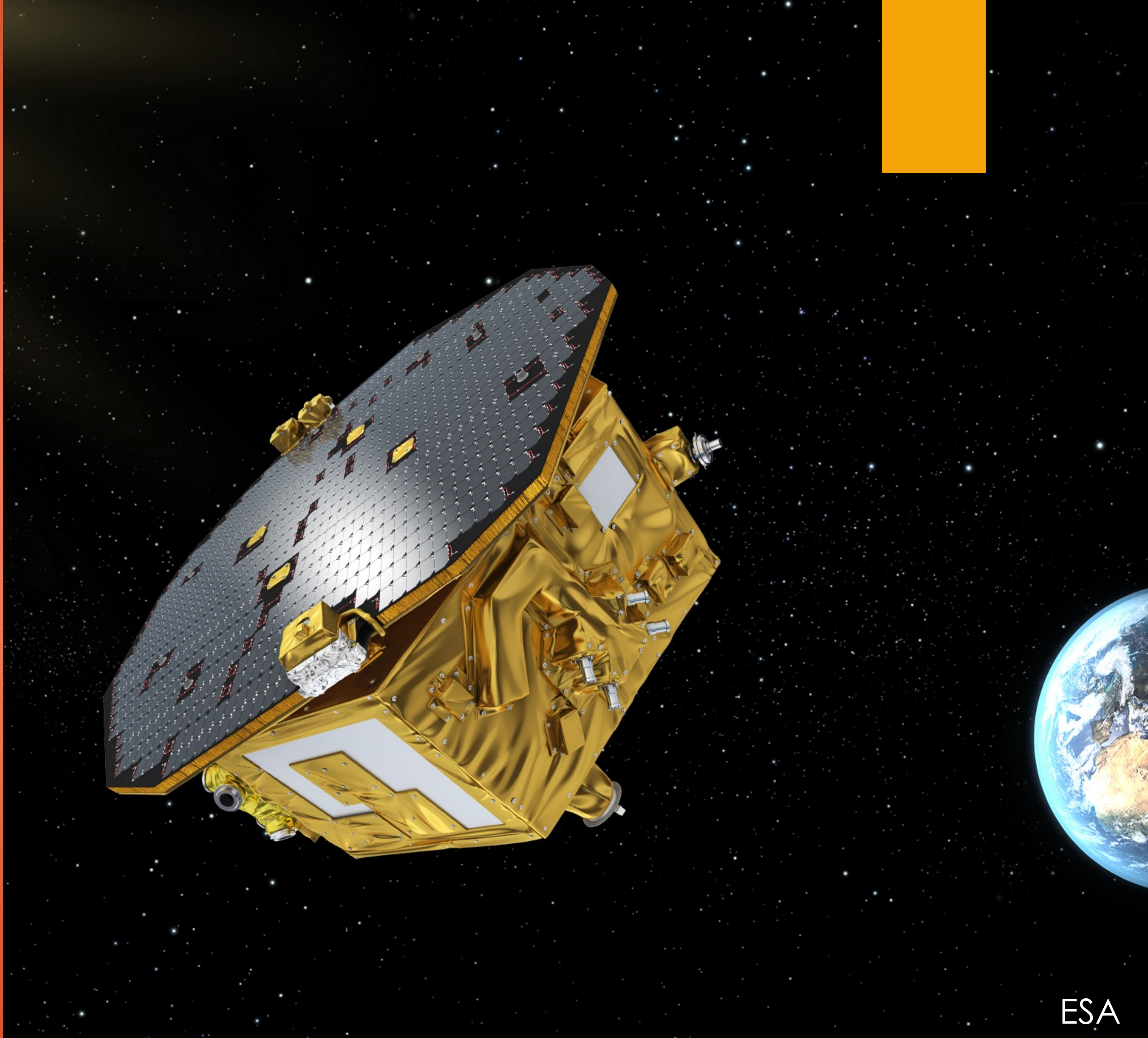
# X-RAYS VS GWS




PAUL DRAGHIS'S TALK AT 2022 MICROQUASAR WORSHOP

# LISA will help

- Minor mergers – ISCO measurement
- Galactic low-mass BH binaries
- In general, more methods to measure BH spin
- Better modelling of supernovae



ESA

# Thank you for your attention