# Accretion flow, pair production and jet in MAXI J1820+070

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# Evolution of discs and coronae in BH LMXBs

- Quiescence, years to tens of years, and outbursts (hard-soft-hard), months to years.
- Observed properties of outbursts in conflict with the disc instability model if the disc extends to the ISCO in quiescence. Also, a disc extending to ISCO cannot explain the observed quiescent X-ray luminosities (Dubus+01).
- ⟶ the disc should be truncated at $R_{\rm in}$~$10^{10}$ cm (~$10^4$ $R_{\rm g}$, $R_{\rm g}$=gravitational radius), with a hot accretion flow at $R<R_{\rm in}$.
- Confirming it, Bernardini+16 found (from the width of the Hα line) $R_{\rm in} \gtrsim 3\times10^4 R_{\rm g}$ during the quiescence of V404 Cyg.

# Disc truncation during an outburst

- If the disc remains truncated during the hard state, what can prevent the disc to reach the ISCO?
- We are not sure. It could be emission of a jet through the Blandford-Payne mechanism (Ferreira, Petrucci, Marcel), or formation of a hot corona and disc evaporation (Różańska; Meyer, Meyer-Hofmeister, Liu, ...), or winds.

# MAXI J1820+070

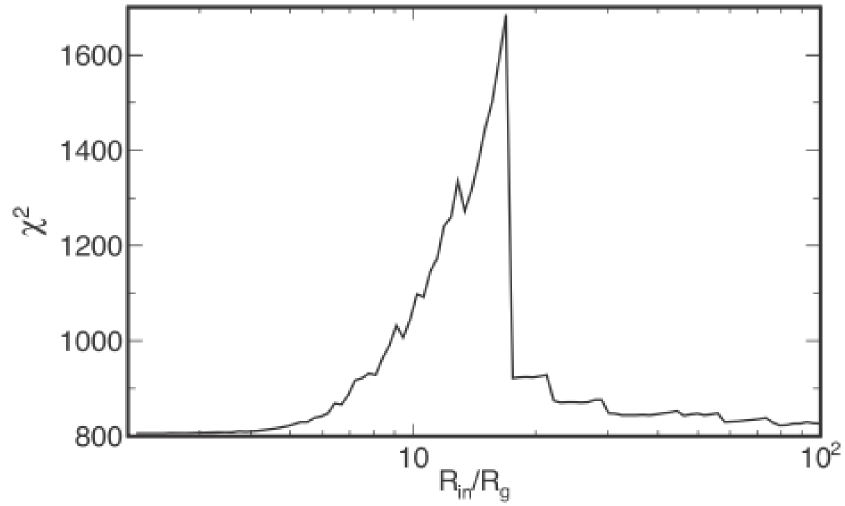
- A transient low-mass X-ray binary with a black-hole accretor, $P \approx 0.7$ d, $M_{BH} \approx 6–8\ M_{\odot}$ (Torres+20).
- A major outburst in 2018, the hard, intermediate, soft, intermediate and hard states and quiescence.
- The jet inclination 64±5° (Wood+21), the binary one 66–81° (Torres+20), misalignment (Poutanen+22).
- $D \approx 3 \pm 0.5$ kpc, $D_{max} \approx 3$ kpc from radio ejecta (Wood+21).
- A lot of observations by various instruments including NICER, *NuSTAR*, *HXMT* and *INTEGRAL*.

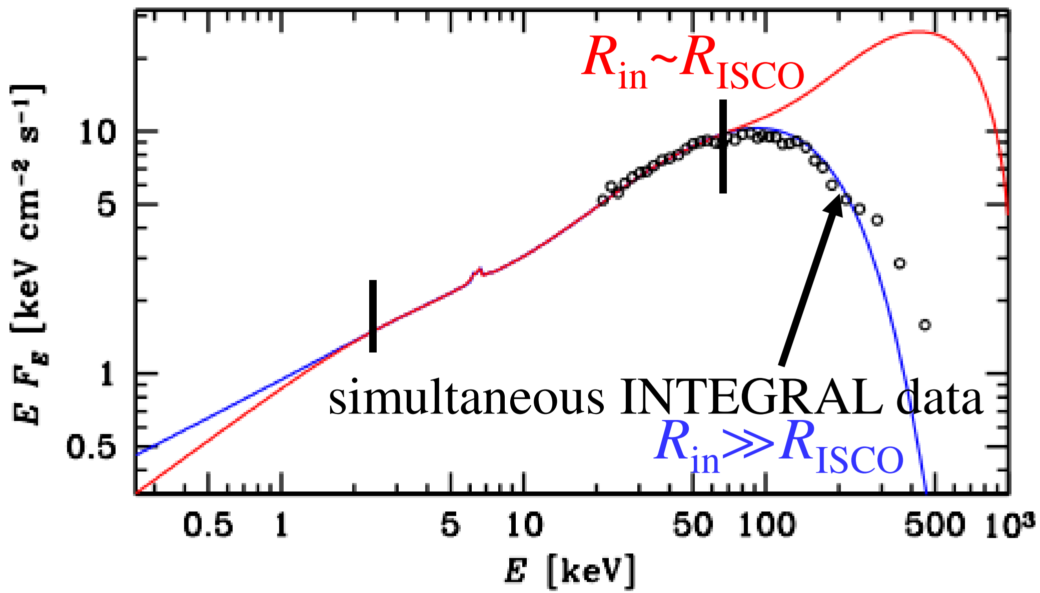
# Our studies of MAXI J1820+070

1. AAZ+21a: spectral fitting of *NuSTAR* data, $R_{\rm in} \gg R_{\rm g}$, at least two Comptonization zones present.
2. AAZ+21b: *NuSTAR+INTEGRAL* data, $R_{\rm in} \gg R_{\rm g}$, two zones + hybrid Comptonization, pair production.
3. Dziełak+21: spectro-timing studies of NICER data, Lorentzian-resolved spectroscopy. The continuum is complex, at least two zones.
4. De Marco+21: timing studies of NICER data, long reverberation lags, Fourier-resolved spectroscopy, $R_{\rm in} \gg R_{\rm g}$.
5. AAZ, Tetarenko & Sikora 22a: modelling the radio-to-optical jet in the hard state.
6. AAZ+22b, *NuSTAR+HXMT+INTEGRAL* data confirm $R_{\rm in} \gg R_{\rm g}$.
7. Mikołajewska+22, the parameters of the donor.

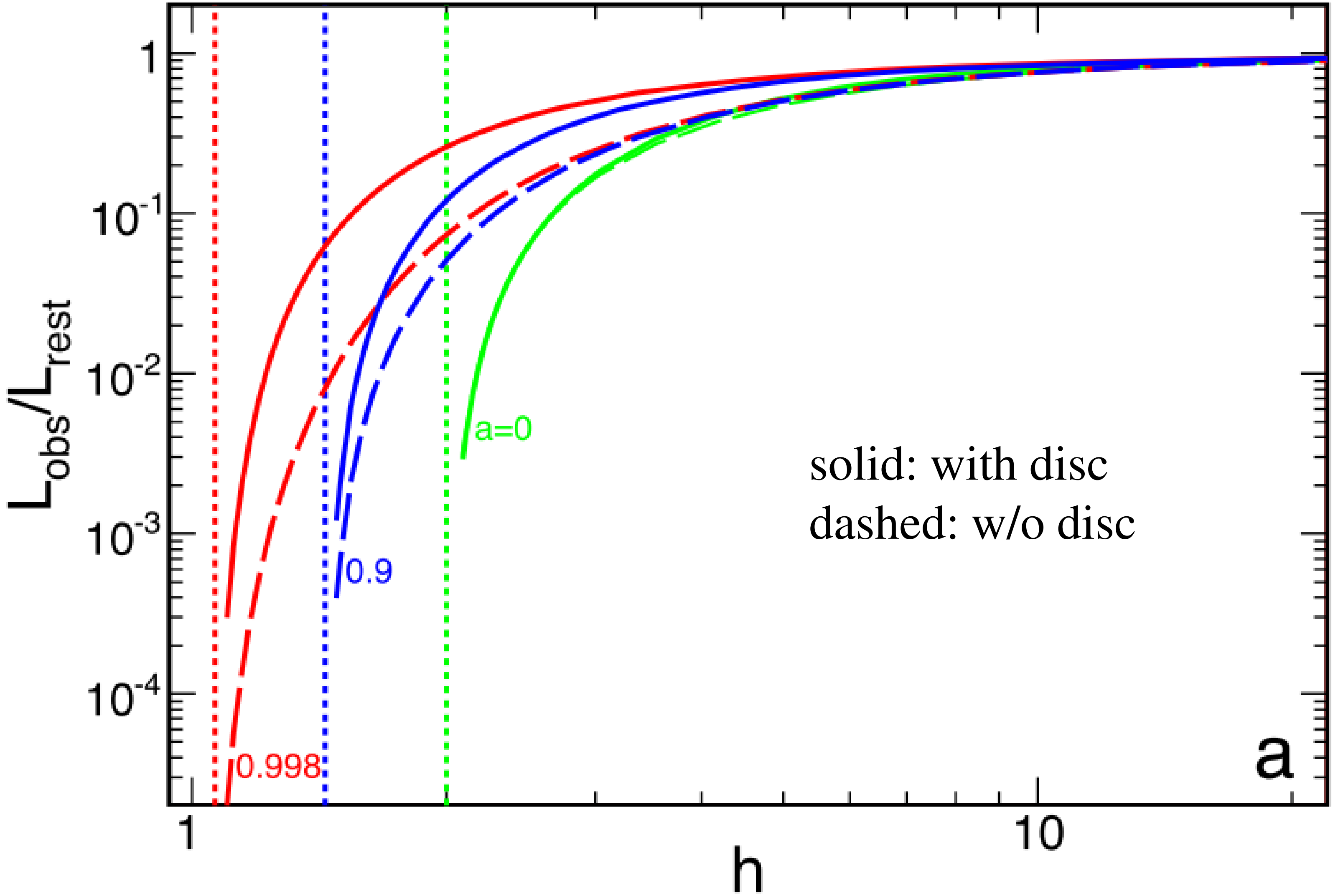
# The lamppost model for MAXI J1820+070

- Buisson+19 fitted the 3–78 keV NuSTAR data with two lampposts and $R_{\rm in}$~$R_{\rm ISCO}$, finding the disc inclination of $i$~30º and the Fe abundance of $Z_{\rm Fe}$≈4–7.
- However, both the binary and the jet have $i$ ~60–80º, and the donor has a low metallicity (Mikołajewska+22).
- AAZ+21a found two solutions separated by a wall in $\chi^2$, the 2nd one with $R_{\rm in} \gtrsim 20R_{\rm g}$, $i$~60–70º and $Z_{\rm Fe}$~1;
- Solution of Buisson+19 disagrees with the INTEGRAL data.



# Flux reduction of the lamppost radiation – can be extreme for small heights




Niedźwiecki & AAZ 2018

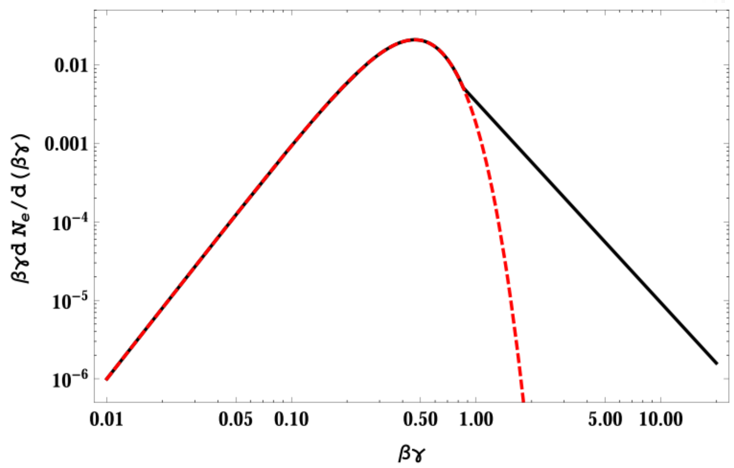
# Electron-positron pair production in the lamppost

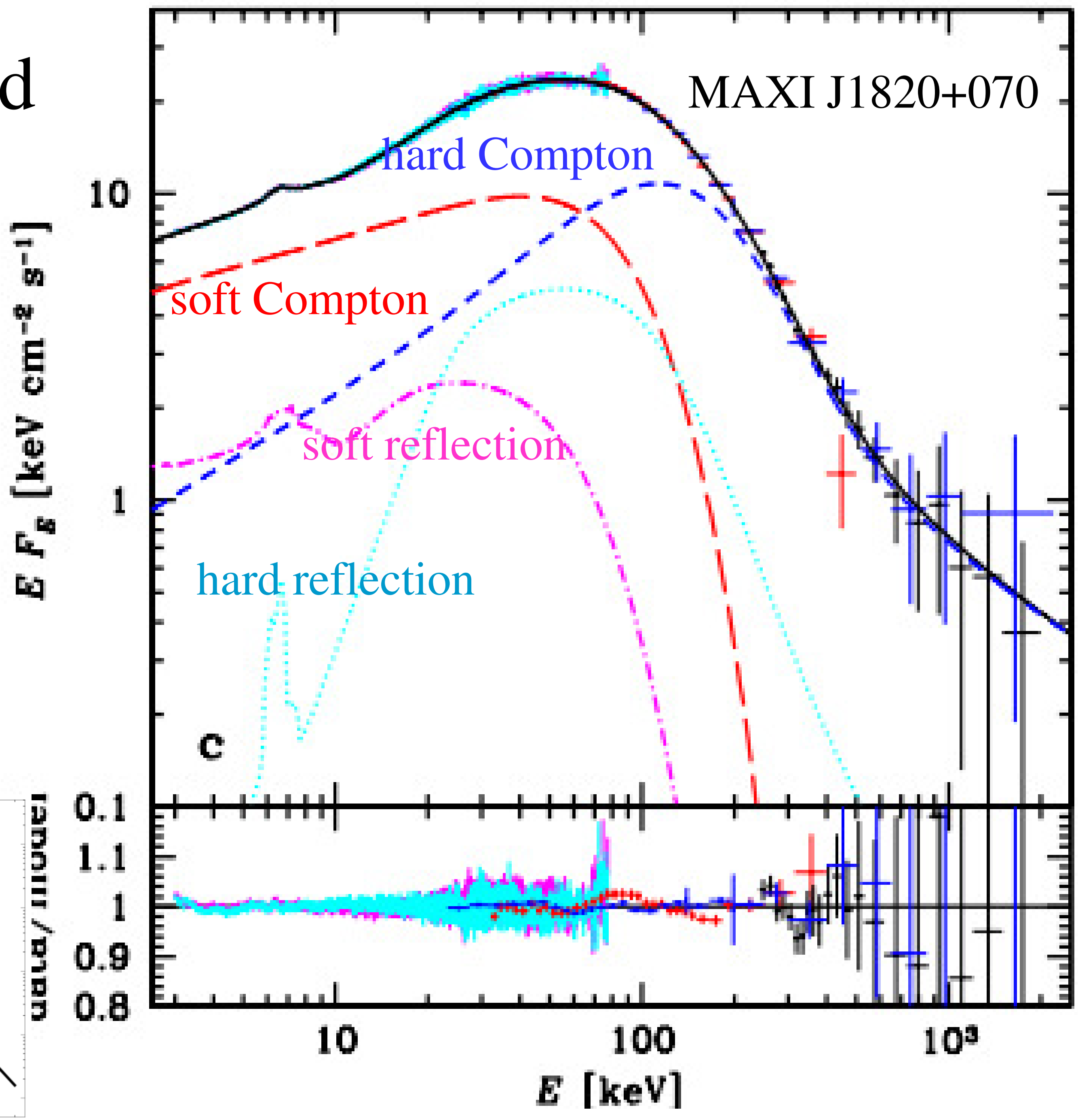
- The parameters in the source frame are extreme. Photons in that frame have (1+$z$) higher energies than those observed; e.g., $z \approx 6$ for the model of XTE J1752–223 of Garcia+18. The redshift, time dilation and light bending increase the locally-measured luminosity with respect to that observed (e.g., by a factor of 2000 for the model of XTE J1752–223).
- The observed high-energy cutoffs in the hard state of BH binaries are at ~100 keV. (1+$z$)100 keV>511 keV in the lamppost frame, with a lot of photons above the threshold for $e^{\pm}$ pair production.
- Niedźwiecki+16: such sources would be much above the pair equilibrium limit, with the pair production rate exceeding the annihilation rate by orders of magnitude.

# Two-component Comptonization and reflection

$R_{\rm in} \gtrsim 20 R_{\rm g}$,
$i$ ~65°, $Z_{\rm Fe}$~1,
$kT_{\rm e,soft}$~12–20 keV,
$kT_{\rm e,hard}$~20–30 keV,
very good fits

Comptonization by hybrid electrons: Maxwellian + a high-energy tail:

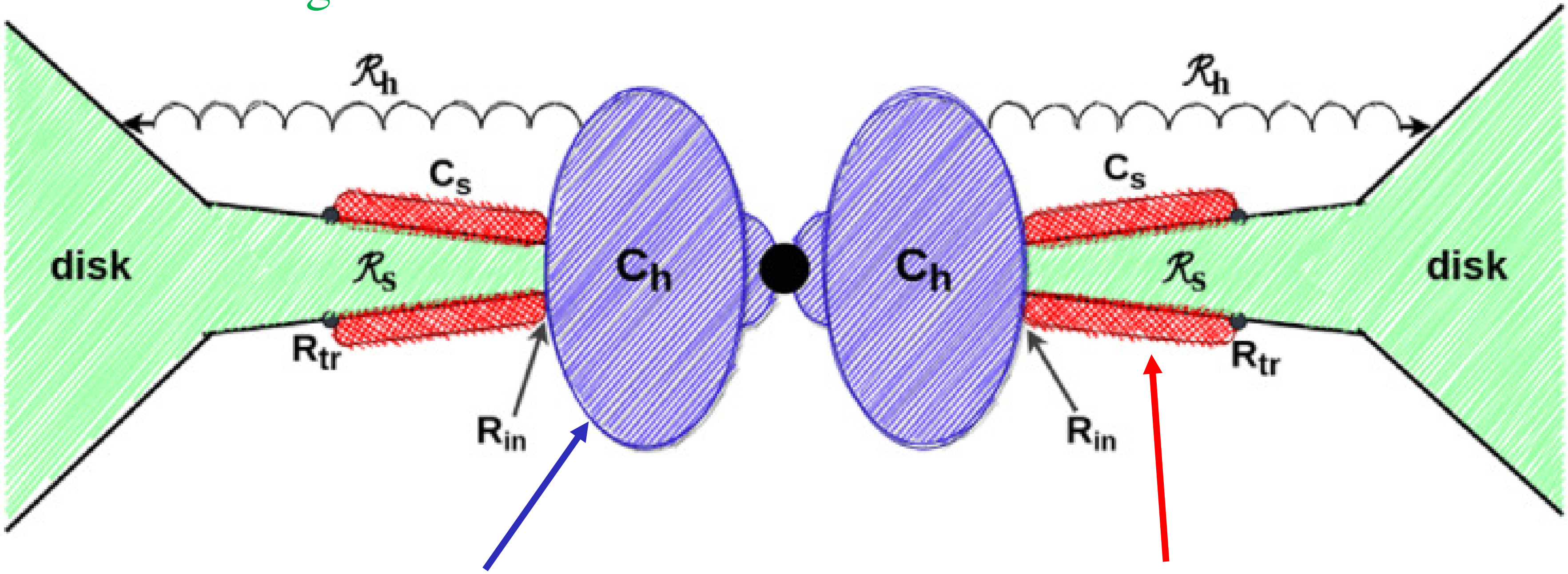



NuSTAR+INTEGRAL data; AAZ+21

# An accretion flow geometry implied by our fits

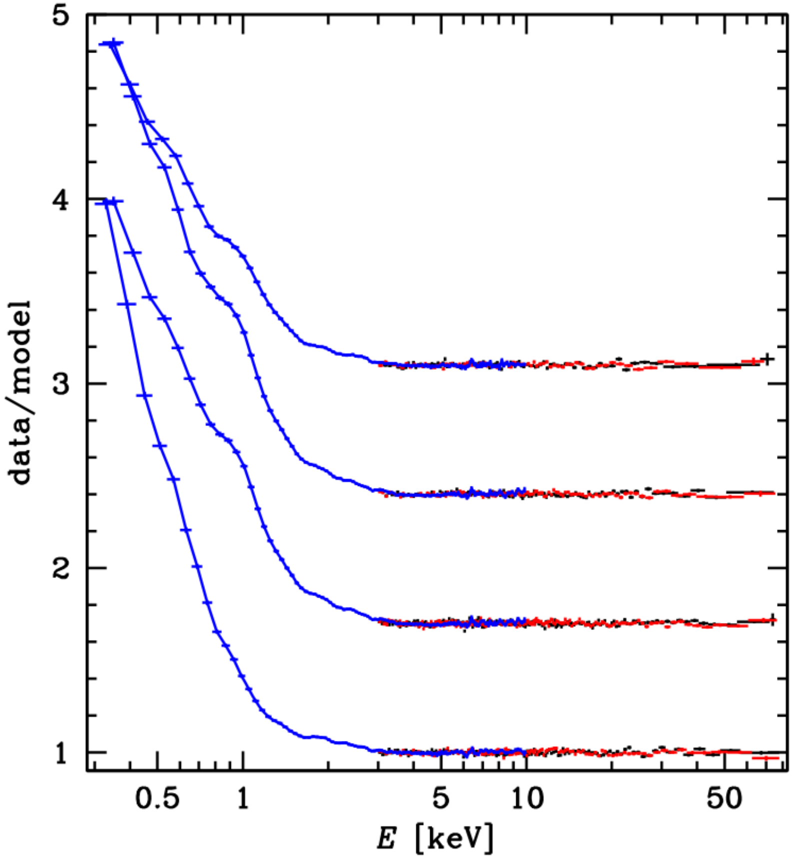
possible disc flaring




Hard hybrid Comptonization in an inner flow reflecting from remote parts of the disc

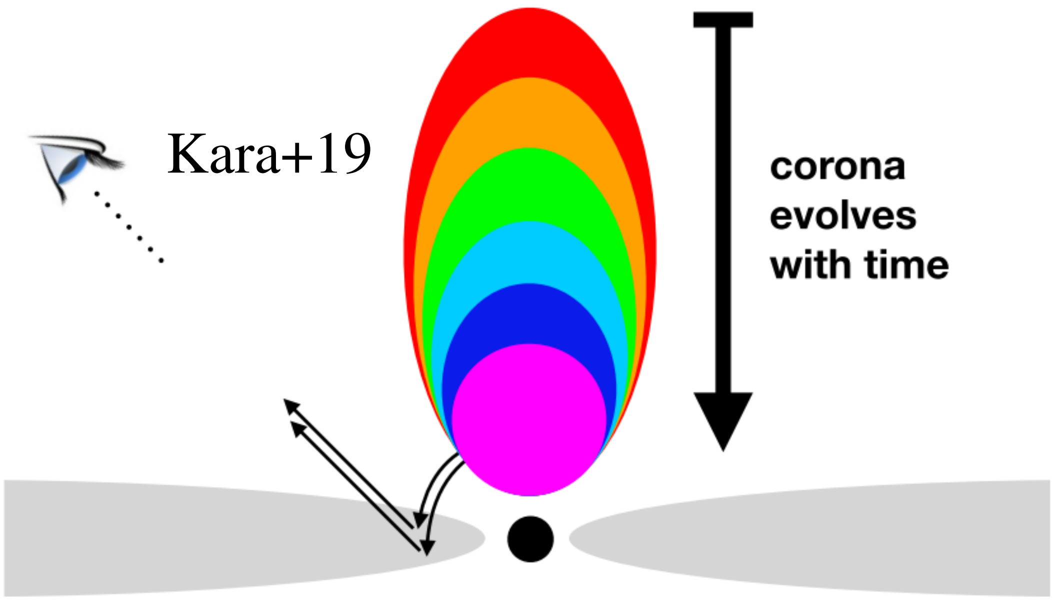
Soft Comptonization forming a corona above the disc

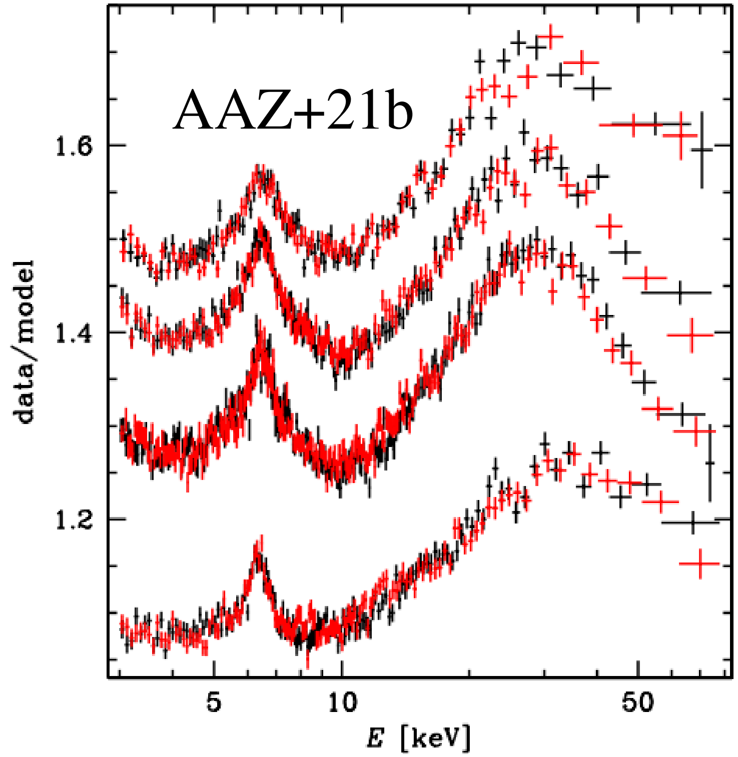
# Further complexity implied by the NICER soft X-ray data




The ratios of the NICER+NuSTAR data fitted to NuSTAR. The soft excess not explained just by a disk blackbody. Another Comptonization component.

Kara+2019 interpreted the lags as caused by an evolving corona at a constant $R_{\rm in}$, since the broad Fe K component was almost constant in the NICER spectra.

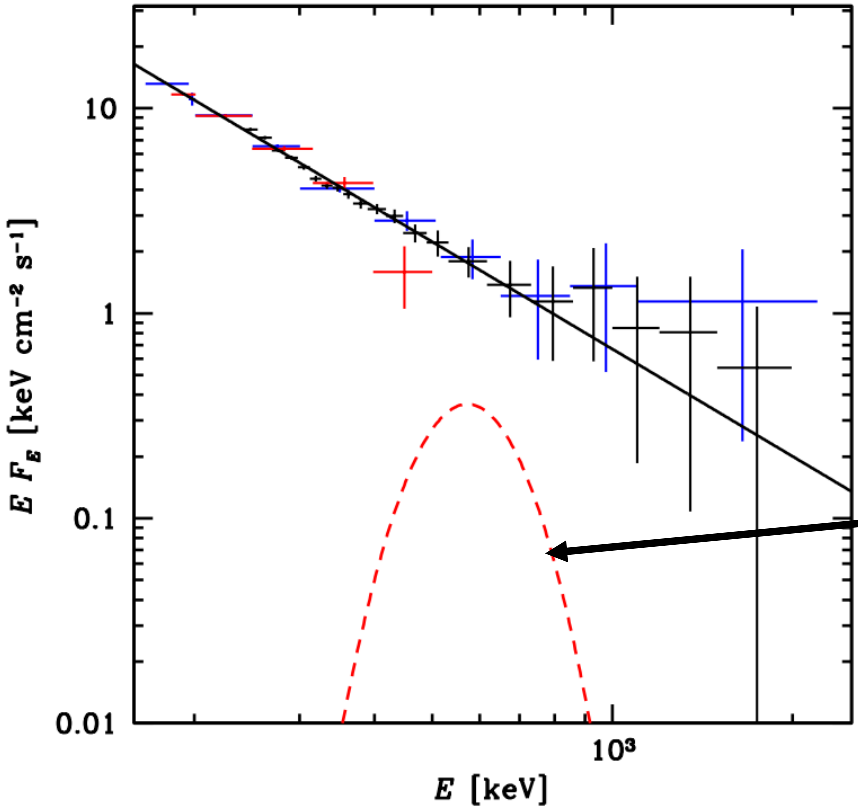



The apparent constancy also appeared in the *NuSTAR* data, which, however, were fitted with $R_{\rm in}$ changing from ≈10 to ≳100 $R_{\rm g}$ (AAZ+21).

Thus, while the lags can be interpreted as changing of either $R_{\rm in}$ or the coronal height, the Fe K data show the lags are due to a moving $R_{\rm in}$ ($\gg R_{\rm g}$).

# A low pair density in the accretion flow




The 2σ upper limit on an annihilation line

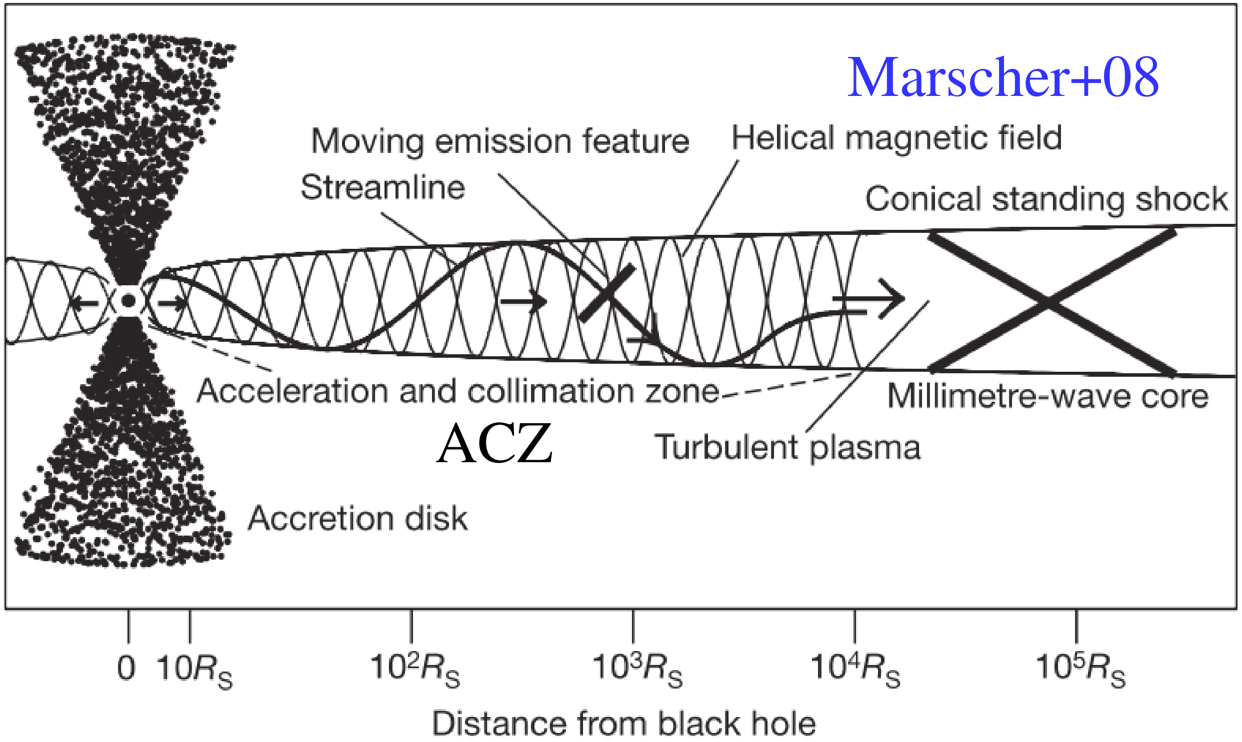
AAZ+21

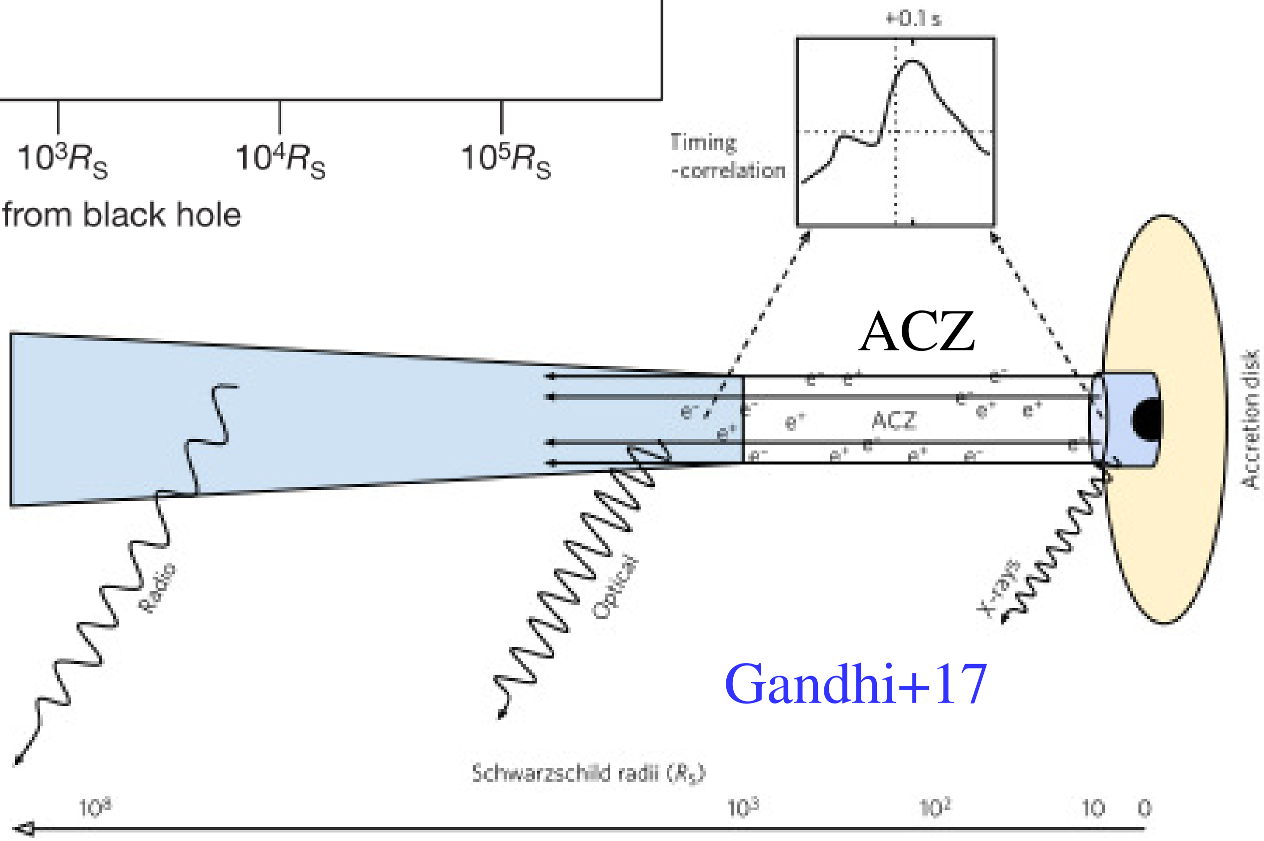
The continuum is detected up to ≈2 MeV; thus $e^{\pm}$ pairs are produced in γγ collisions. However, the Thomson optical depth of the flow is large (several), pair annihilation is fast and the equilibrium fractional pair density found ≪1.

# The hard-state jet in MAXI J1820+070

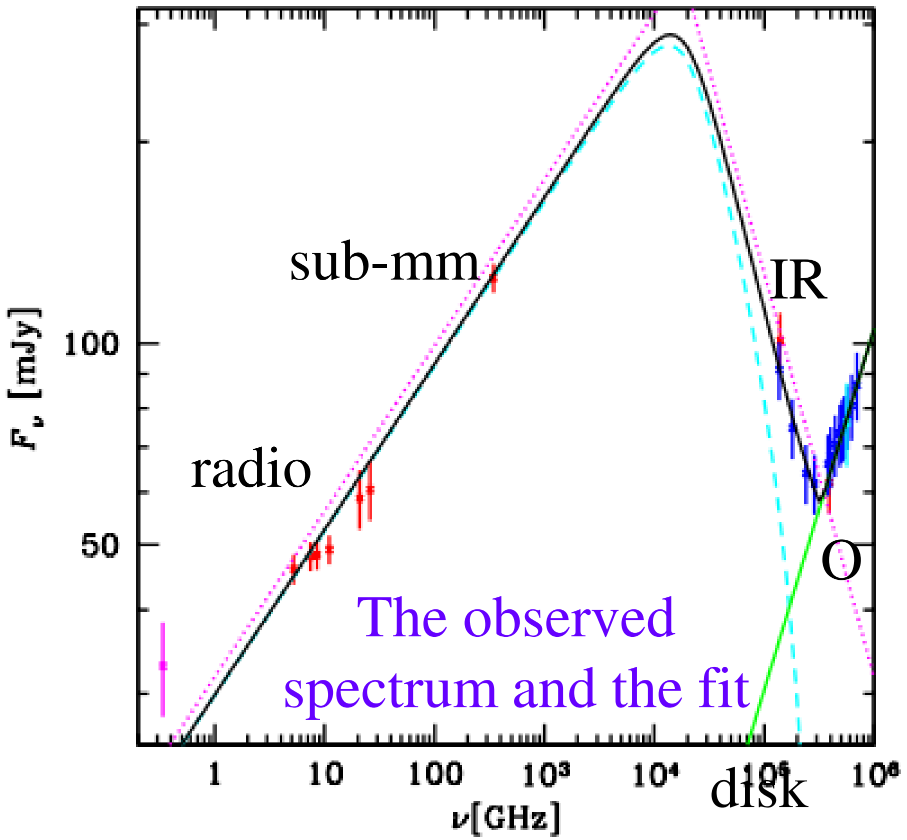
- A unique data set acquired during a bright hard state on 2018 April 12: VLA, ALMA, VLT, NTT, NICER and INTEGRAL; spectral and timing data.
- An analysis by AAZ, Tetarenko & Sikora 22.
- We find $\Theta \approx 1$–$1.5°$, $\Gamma \approx 1.8$–$4$, i.e. more typical values.
- Model: a conical jet with a constant velocity and partially self-absorbed synchrotron emission from power-law electrons, $B$ parametrized by equipartition, power-law dependencies on the distance.

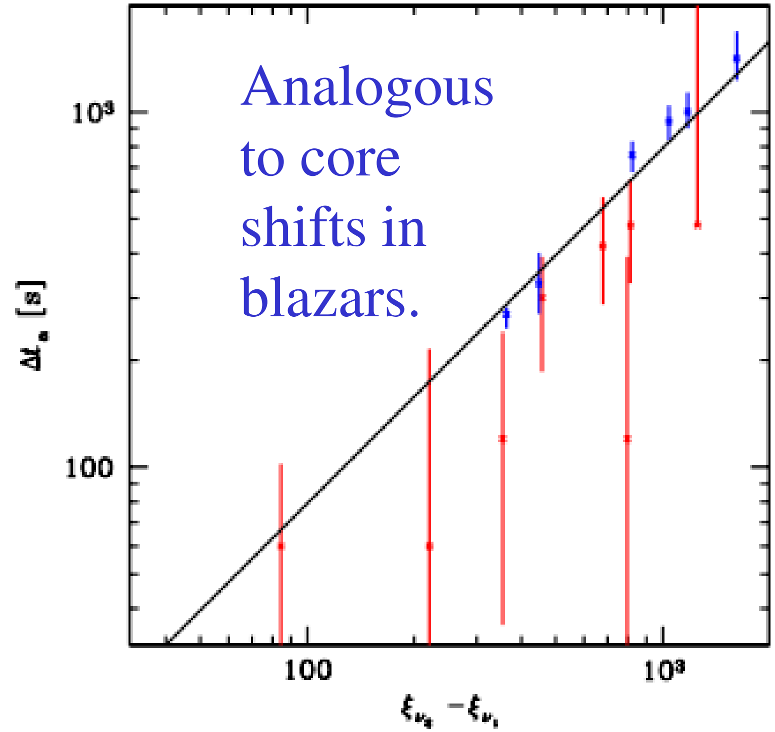
# The jet structure and time lags



# Fits to the spectrum and lags

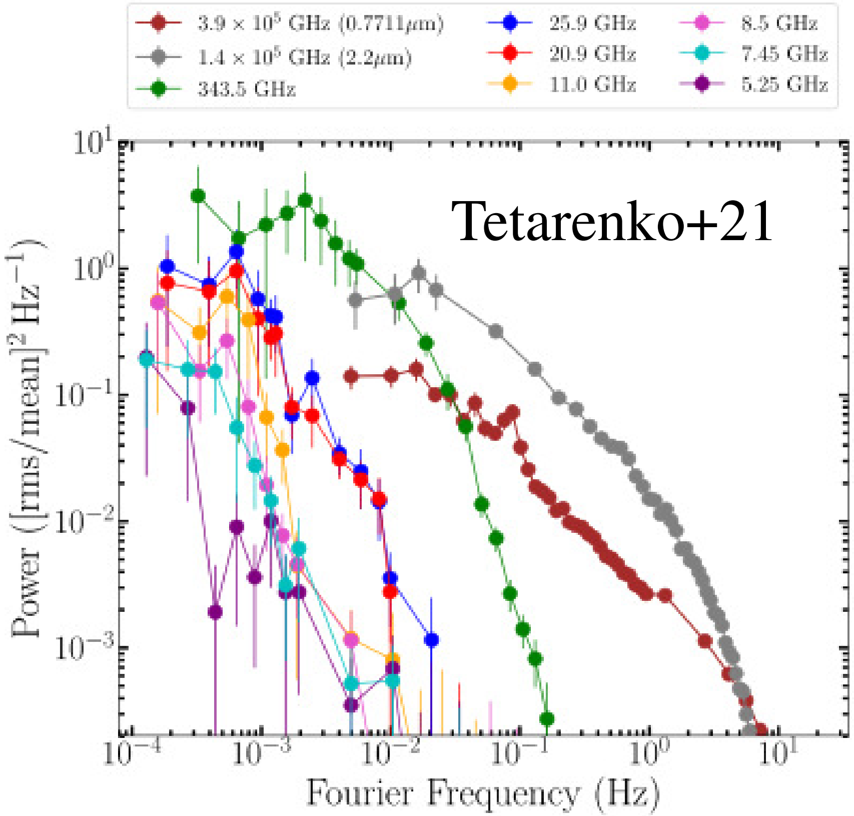



Time lags between various radio and sub-mm frequencies vs. the separation in units of $z_0$.

The solution: the onset of emission (the end of ACZ) at $z_0 \approx 3\times10^4\ R_g$, the jet opening angle $\Theta \approx 1$–$1.5°$, the bulk Lorentz factor $\Gamma \approx 1.8$–$4$.

# Break frequencies of power spectra



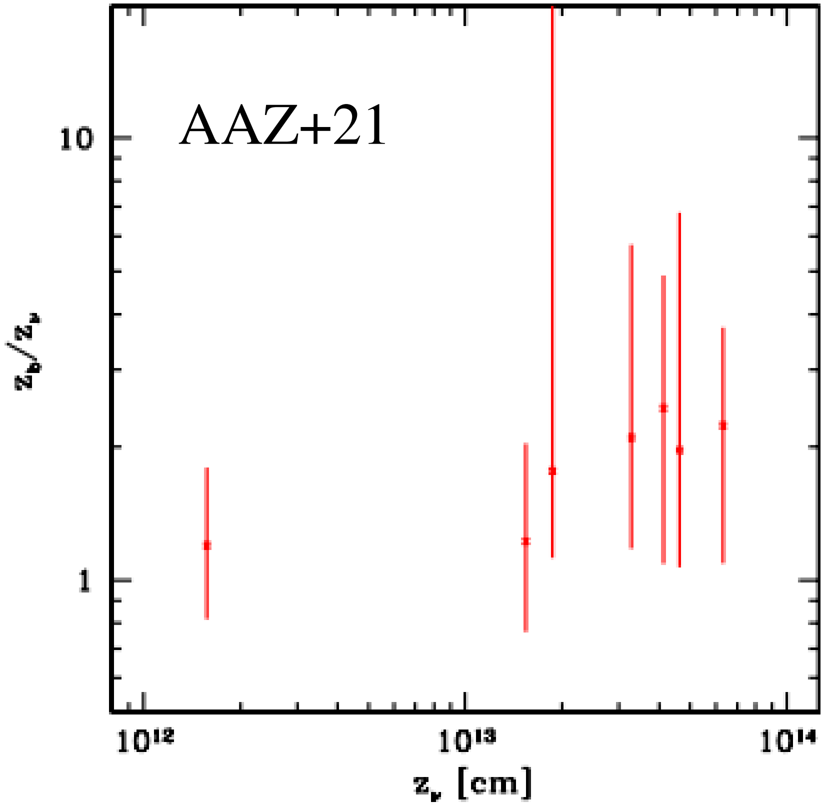




**Figure 7.** The locations of the emission at the observed frequencies based on the break in the power spectra as $z_\mathrm{b} = \beta c/f_\mathrm{break}$ for $\Gamma = 3$ and $i = 64°$, shown as their ratio to the locations based on time lags and the slope of the partially self-absorbed spectrum, $z_\nu \approx z_0(\nu/\nu_0)^{-0.88}$.

The distances corresponding to the jet propagation during the break time scales, $z_\mathrm{b}$, found to be roughly equal to the distances of the maximum emission at a given frequency, $z_\nu$. It may be due to viscous damping during perturbation propagation.

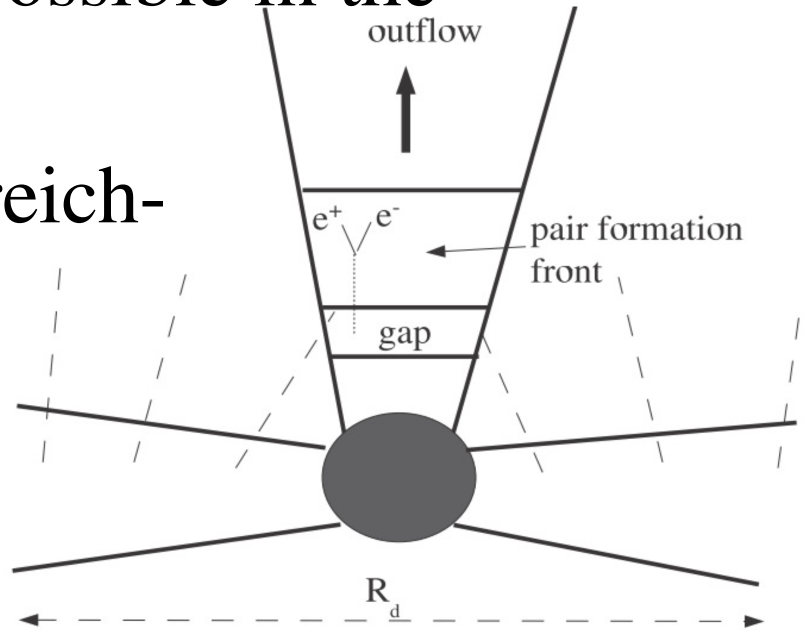
# Are there $e^{\pm}$ pairs in jets, and if yes, how are they produced?

- Arguments for $n_e \gg n_p$ in blazars and radio galaxies (e.g. Sikora+20).
- Pair production in spark gaps possible in the Blandford-Znajek mechanism:
- But this is limited by the Goldreich-

Julian density: $n_{GJ} = \dfrac{\Omega B}{2\pi e c}$

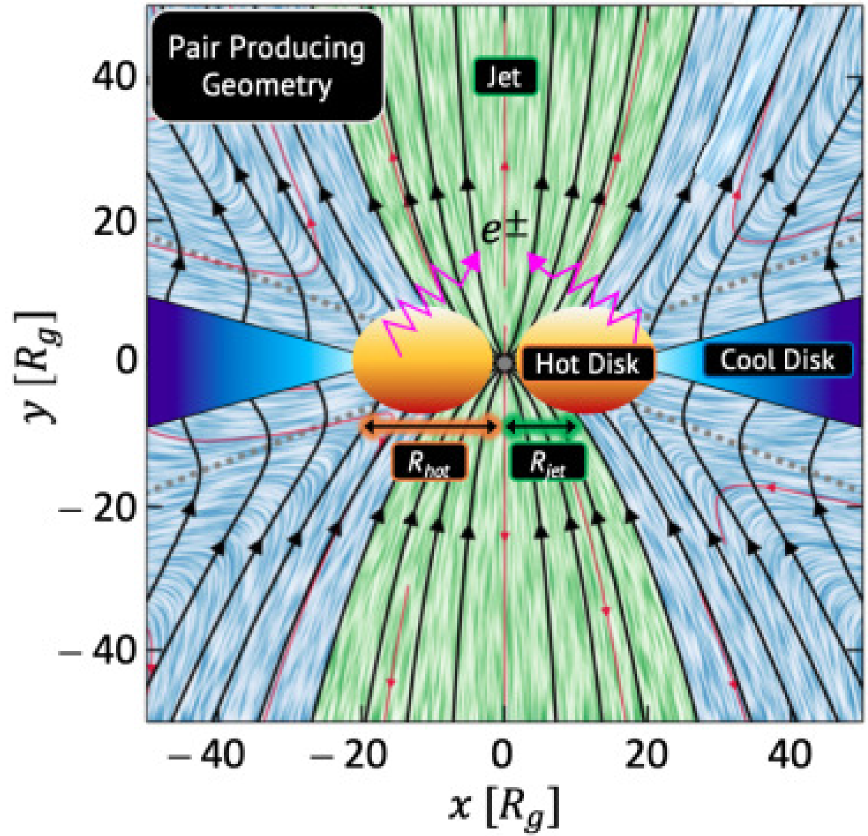
- Levinson & Rieger 2007 give

a limit of $n < 10^3 n_{GJ}$.

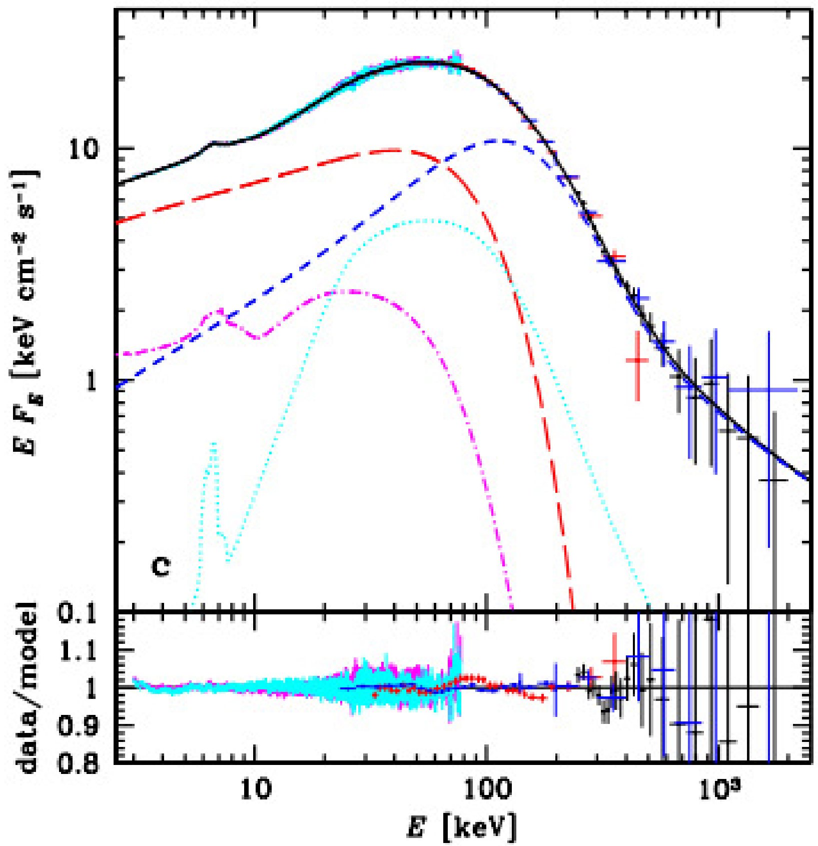



- Nokhrina+15 find $\sim 10^{12-15} n_{GJ}$ in blazars, and we find $> 10^7 n_{GJ}$ in MAXI J1820+070.

# γγ $e^{\pm}$ pair production




The assumed geometry shown on the jet simulation plot from Tchekhovskoy 2015.




The spectrum of the source from NuSTAR and INTEGRAL

The pair production rate within the (empty) jet base: $10^{40-41}\mathrm{s}^{-1} \approx$ the rate of the flow of $e^{\pm}$ calculated from the observed synchrotron emission. A remarkable coincidence, since both numbers are based on very different physics.

→ Pairs may dominate the jet by number.

# Conclusions

- $R_{\mathrm{in}} \gg R_{\mathrm{g}}$ in the hard state found in all our spectral and timing studies, in particular in MAXI J1820+070.
- The hot accretion flow is complex and consists of at least two Comptonization/reflection components.
- The electron distribution is hybrid, Maxwellian+a tail.
- Pairs are copiously produced, but the equilibrium pair density in the hot flow is low; no annihilation line seen.
- Pairs are also produced in the jet base, and can provide enough leptons for the synchrotron emission.
- Determination of jet parameters in MAXI J1820+070: $z_0 \approx 3\times10^4\, R_{\mathrm{g}}$, $\Theta \approx 1$–$1.5°$, $\Gamma \approx 1.8$–$4$.