A Multiwavelength Study of Cygnus X-1: the First mid-IR Spectroscopic Detection of Compact Jets

F. Rahoui, Harvard University & CfA

J.C. Lee, S. Heinz, D.C. Hines, K. Pottschmidt, J. Wilms & V. Grinberg

Rahoui et al, 2011, ApJ, 736, 63

Celebrating 50 years since the discovery of Sco X-1, July 10th 2012

Cygnus X-1

- BH, HMXB, 09.7Iab companion star (Walborn 1973)
- D≈1.86 kpc (Xiang et al. 2011 - X-ray scattering halo; Reid et al. 2011 - parallax)
- Focused-wind accretion, intermediate between Bondi-Hoyle and RLO (Gies et al. 1986, 2003; Hanke et al. 2009)
- 2/3 in the HS with many failed transitions to SS (IS, Wilms et al. 2006)

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2	53528.95922 - 53528.97367	53528.96981 - 53529.24333	53528.95935 - 53528.97375
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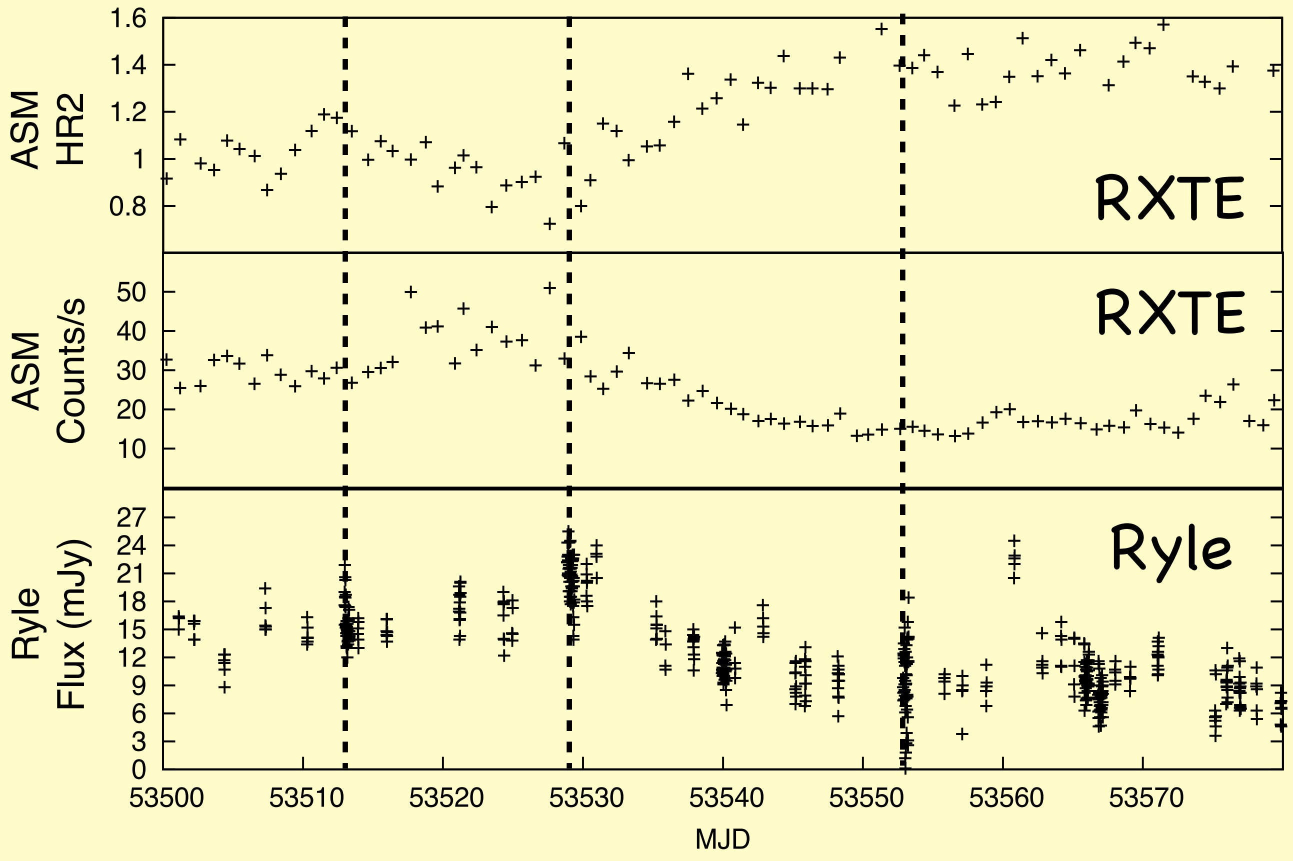
Goals

(1) constrain the spectral break (physical conditions within jet)

(2) origin of mid-IR continuum (variations?)

(3) dust (spectroscopic features, excess?)

Spectral States & Radio Activity



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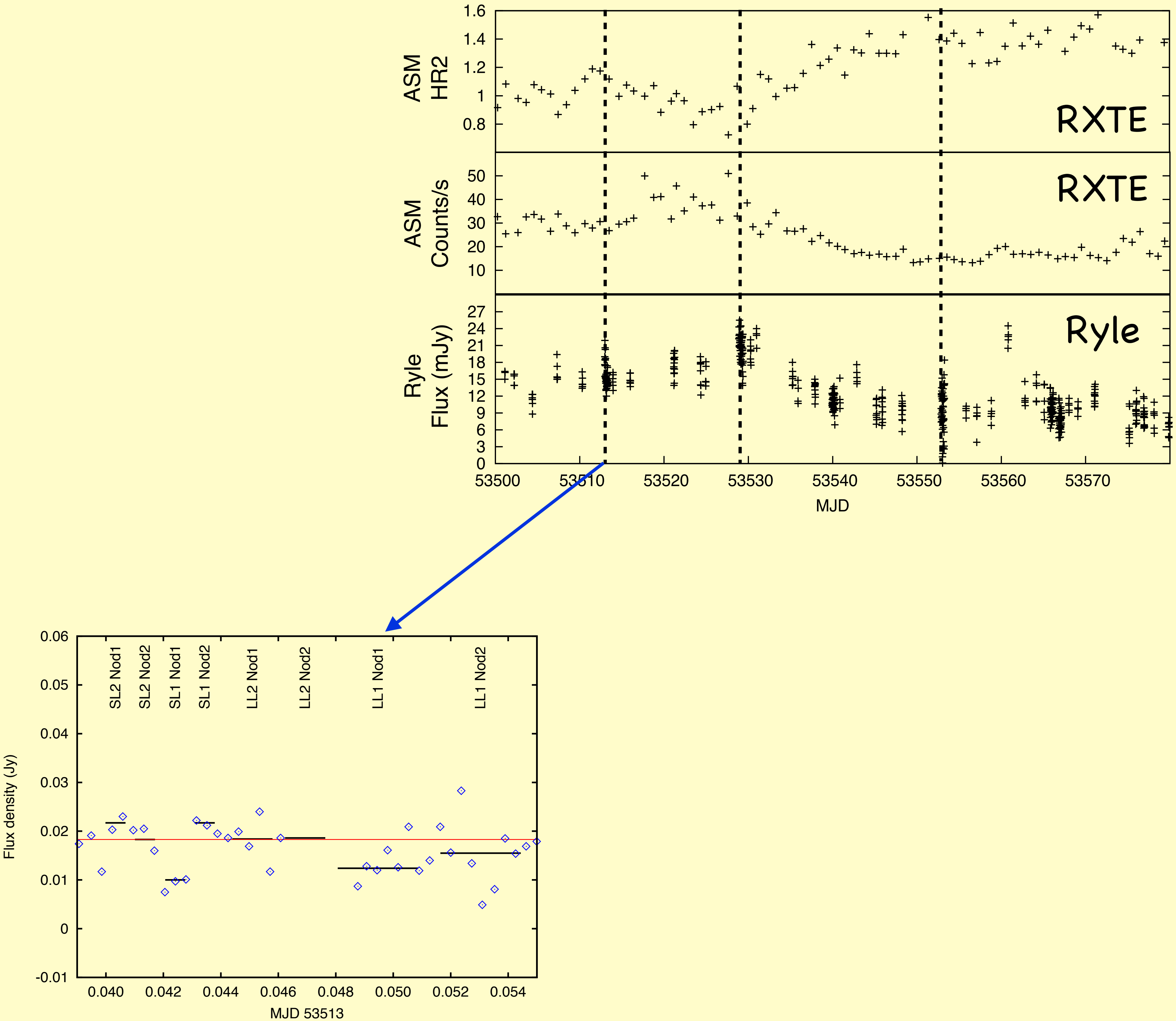

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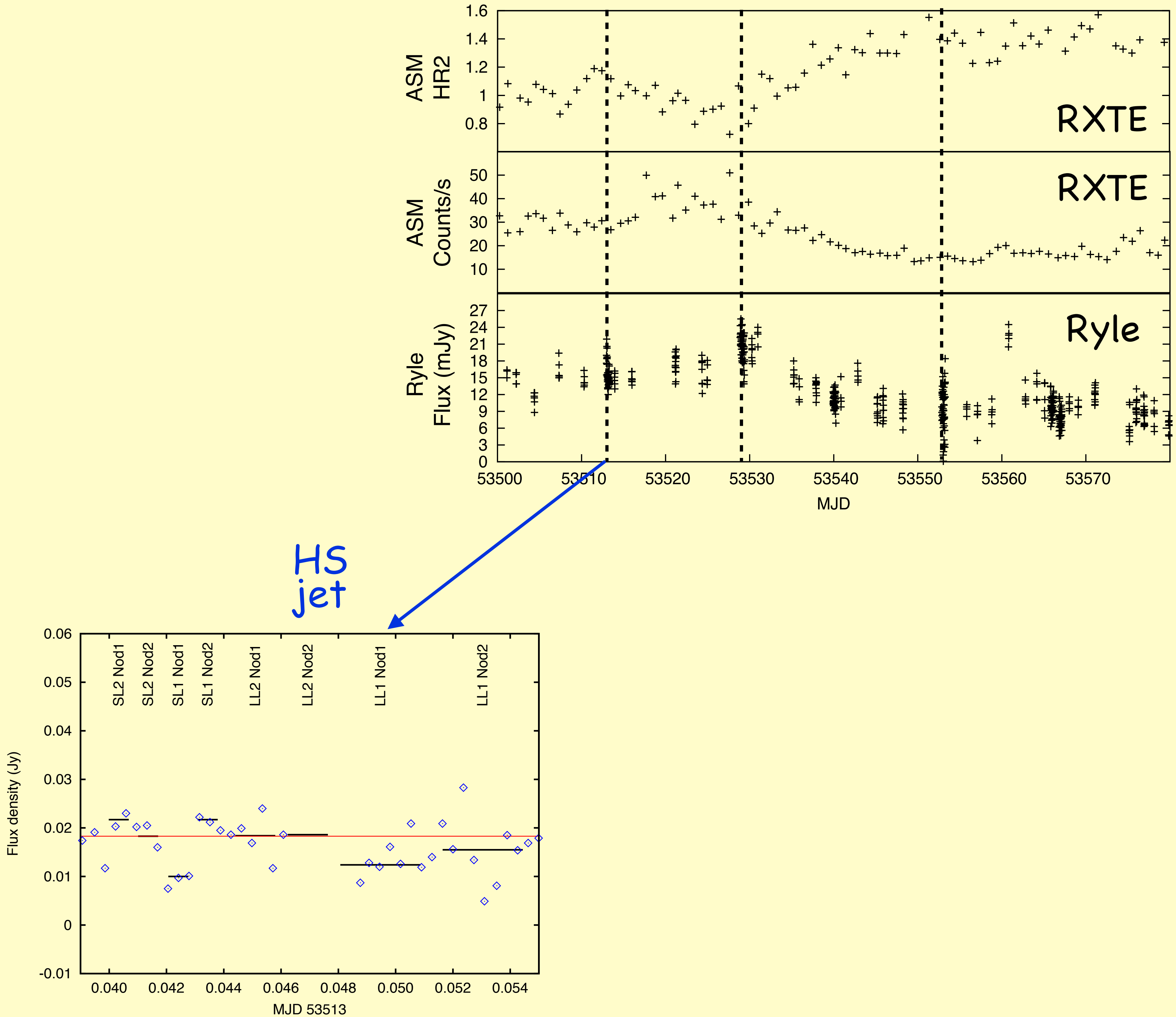

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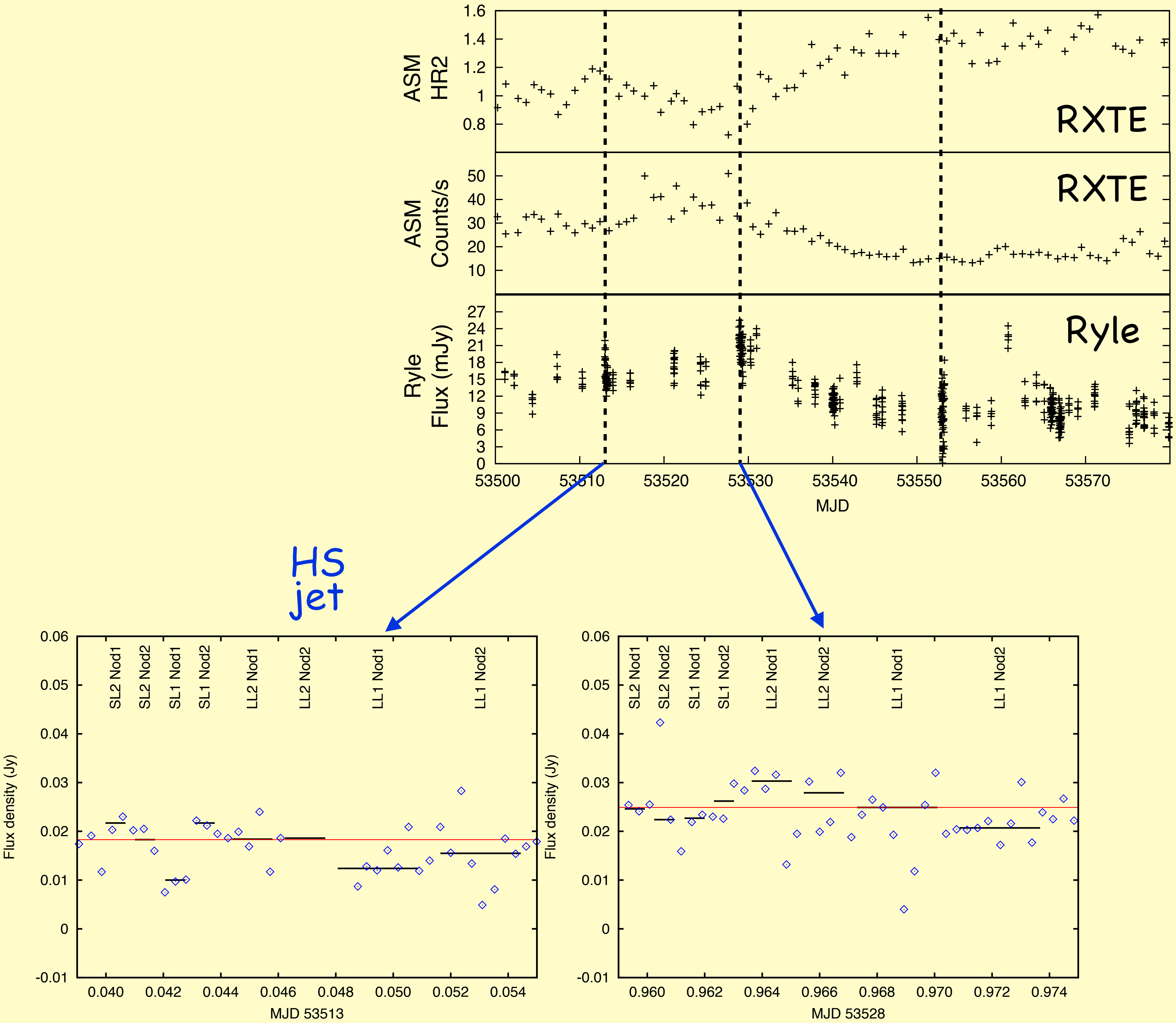

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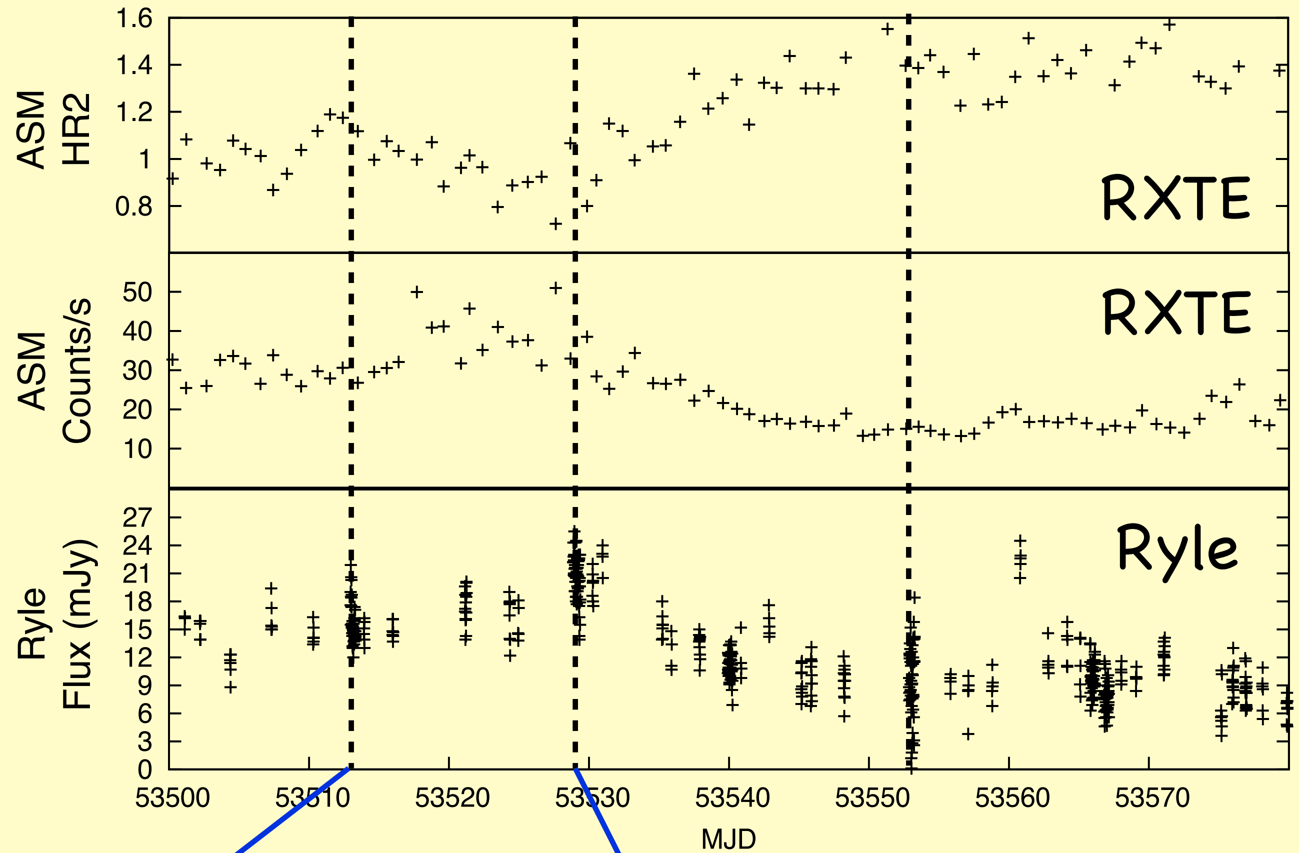

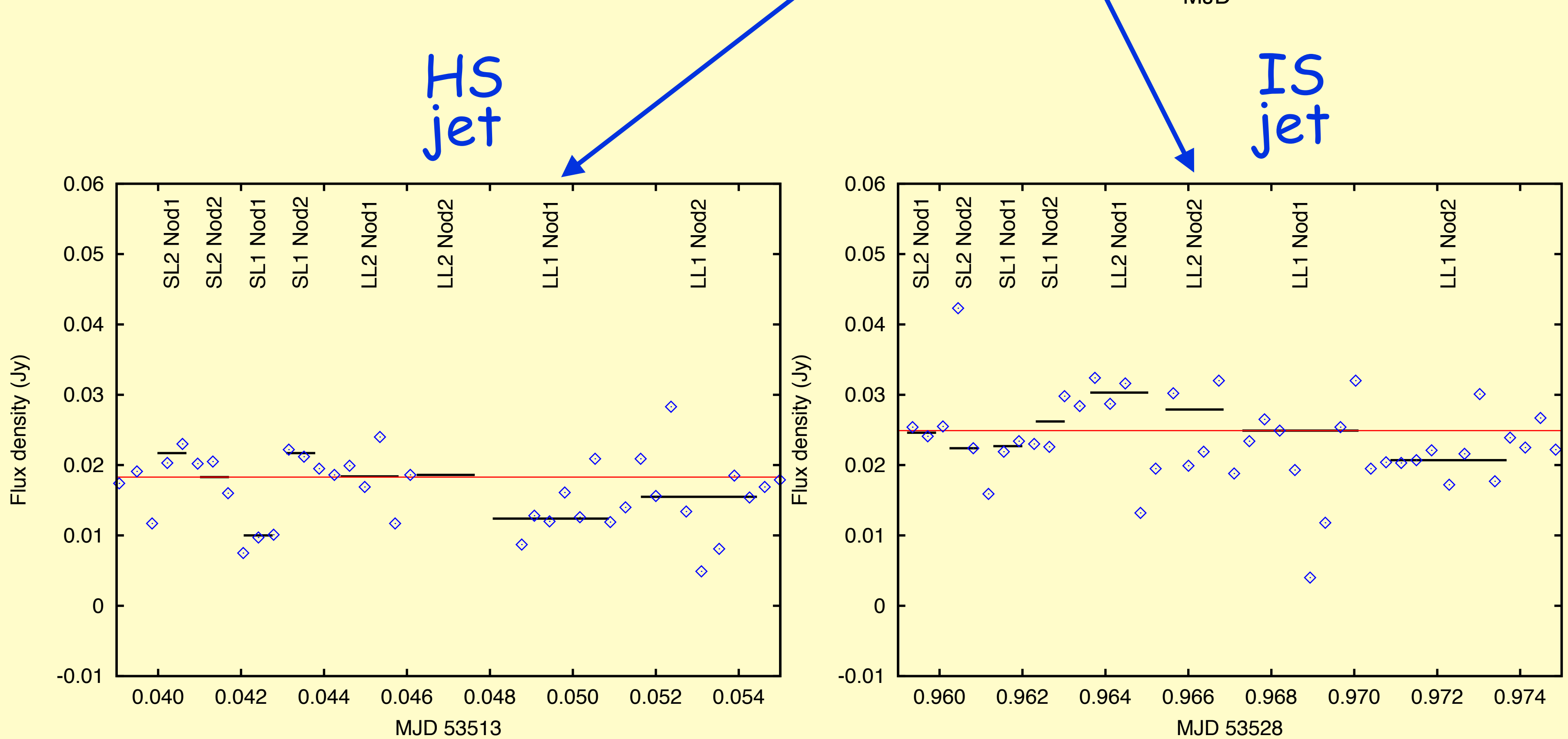

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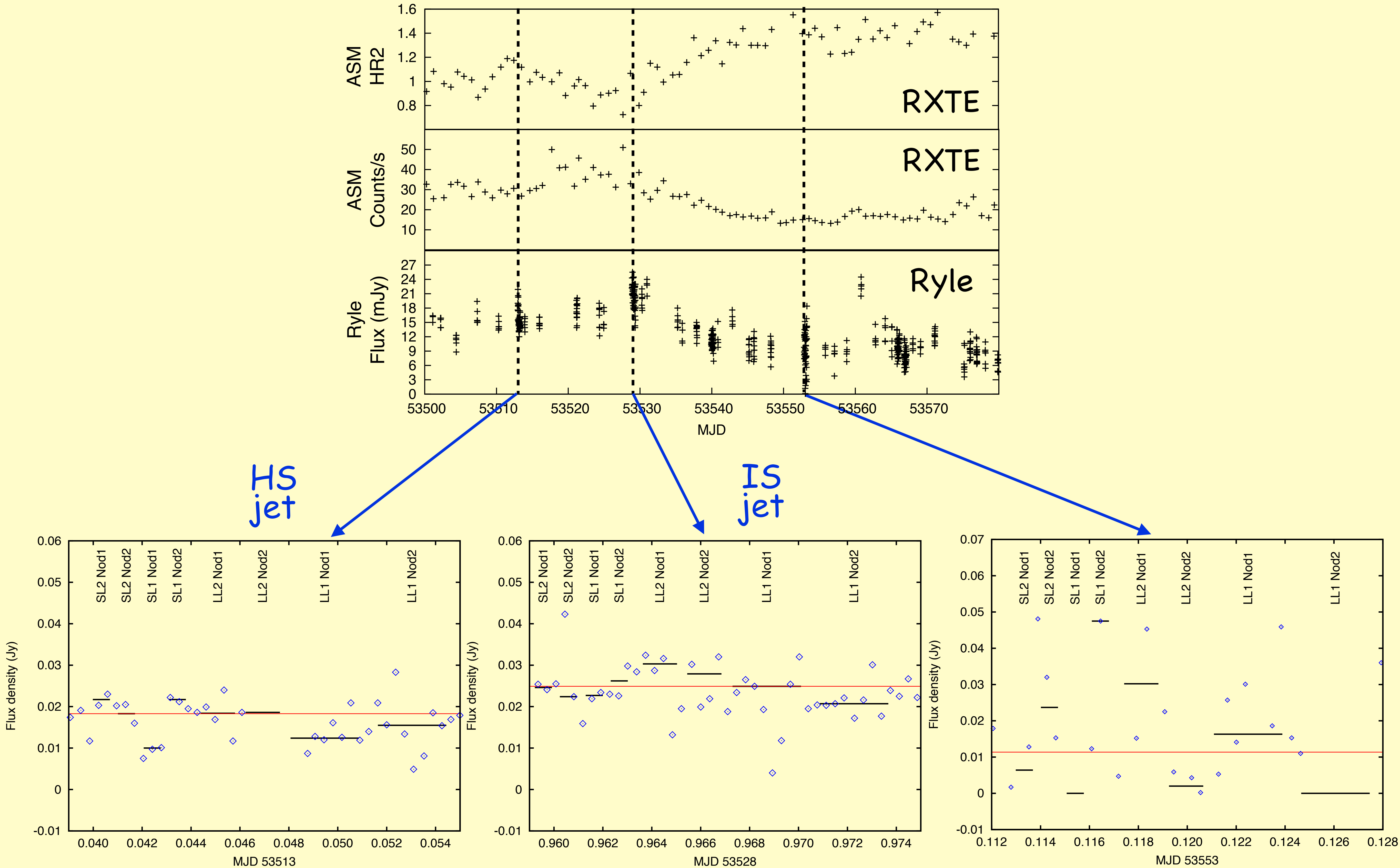

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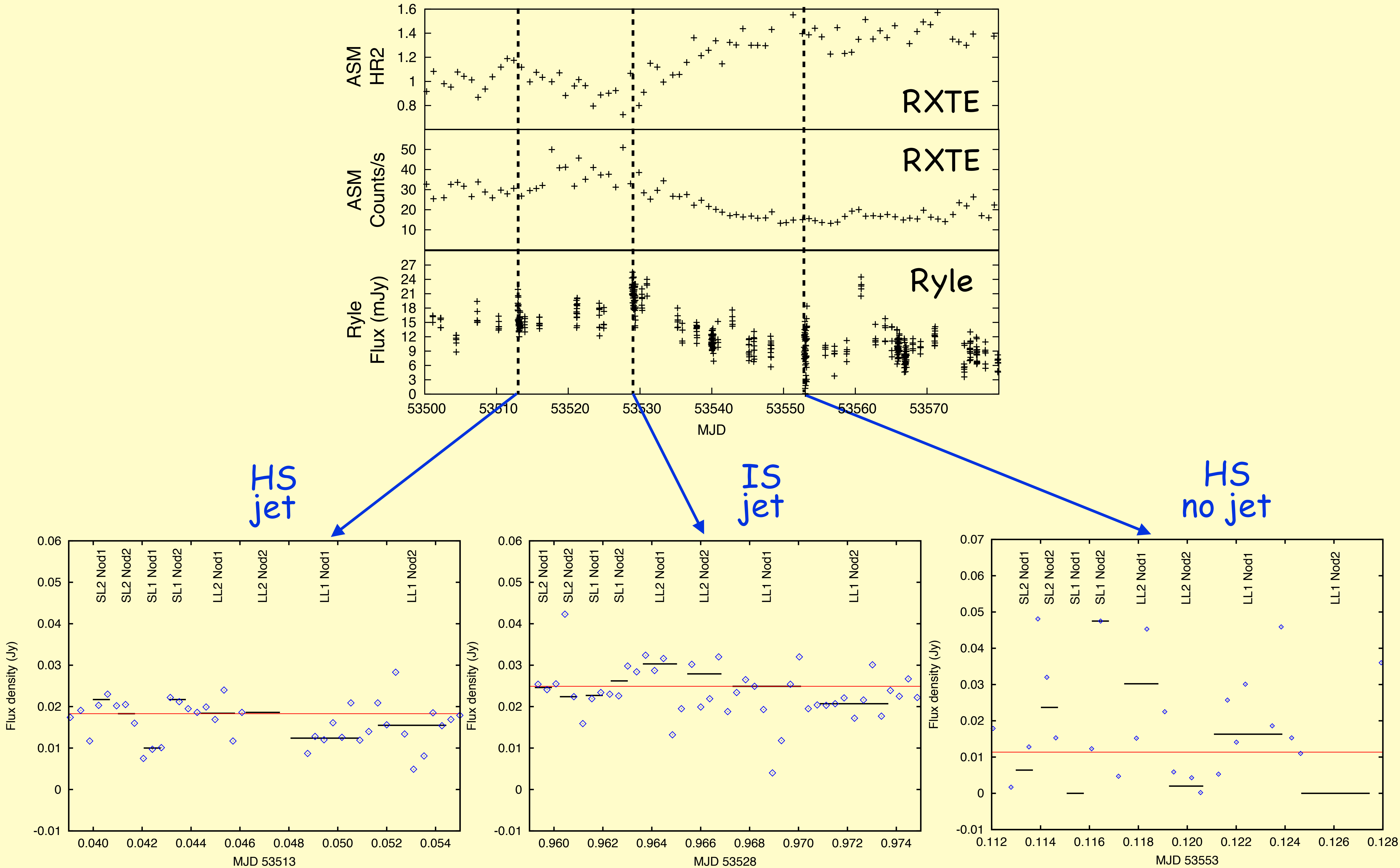
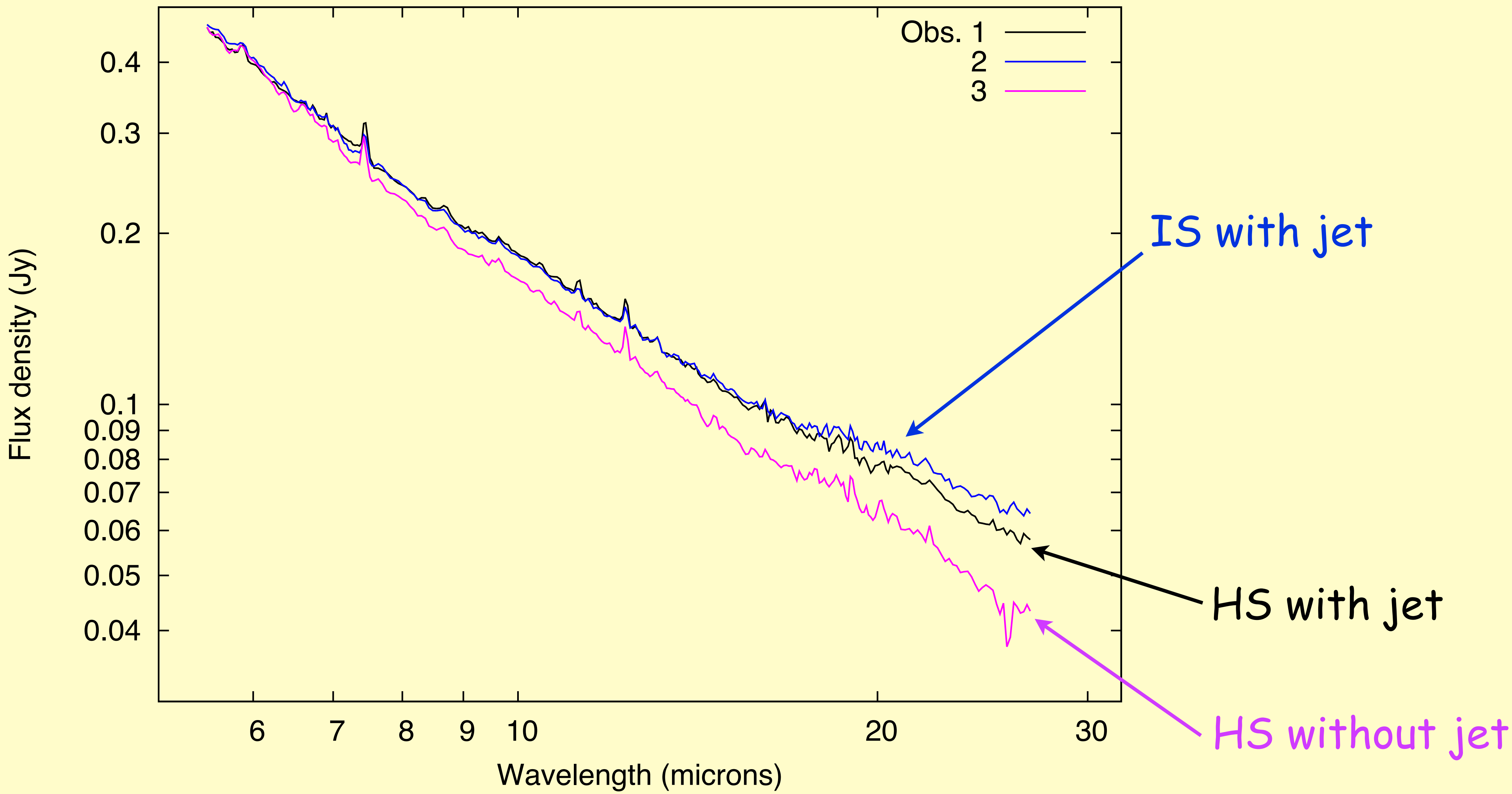


Dereddened mid-IR Spectra



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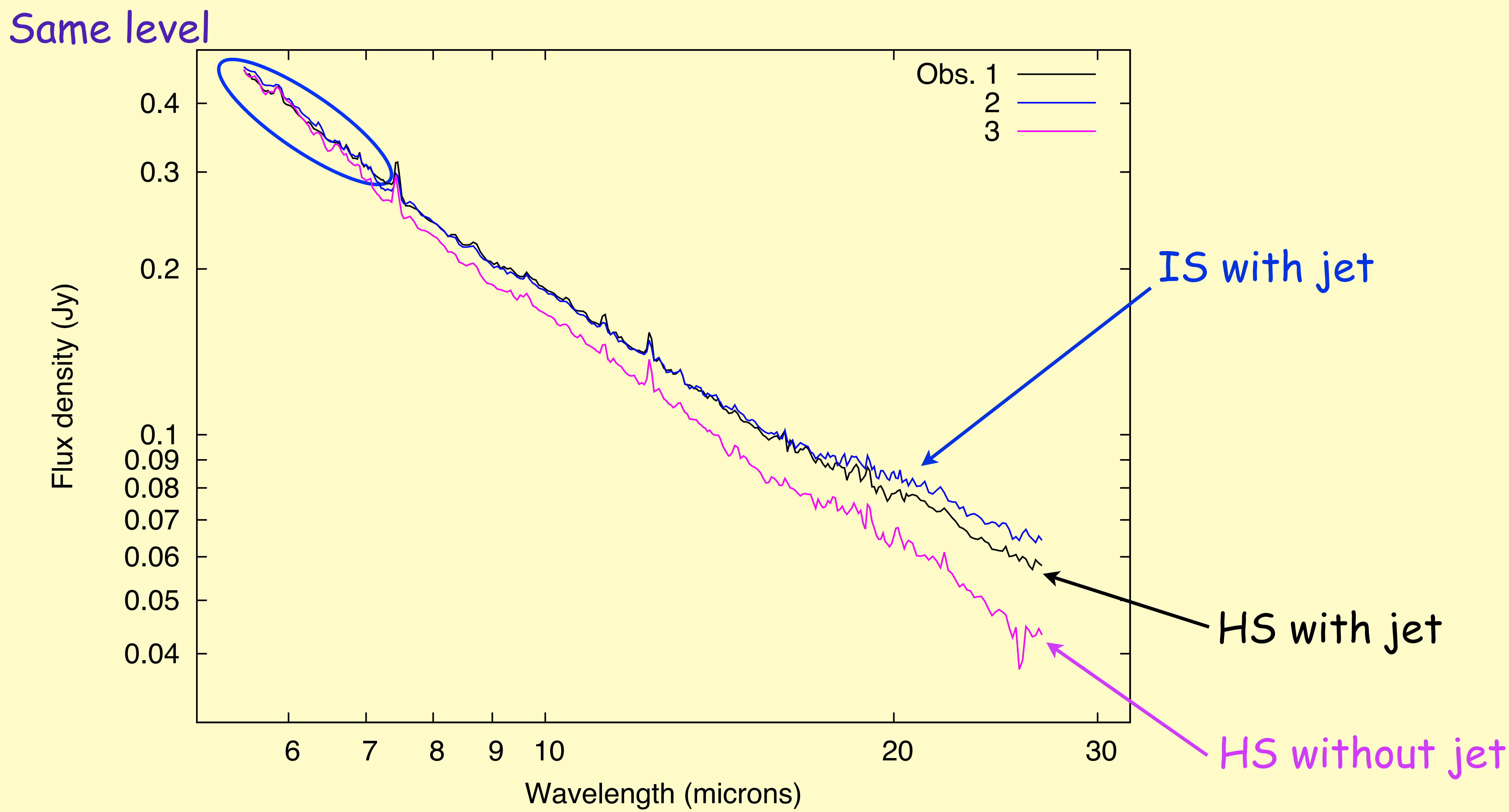

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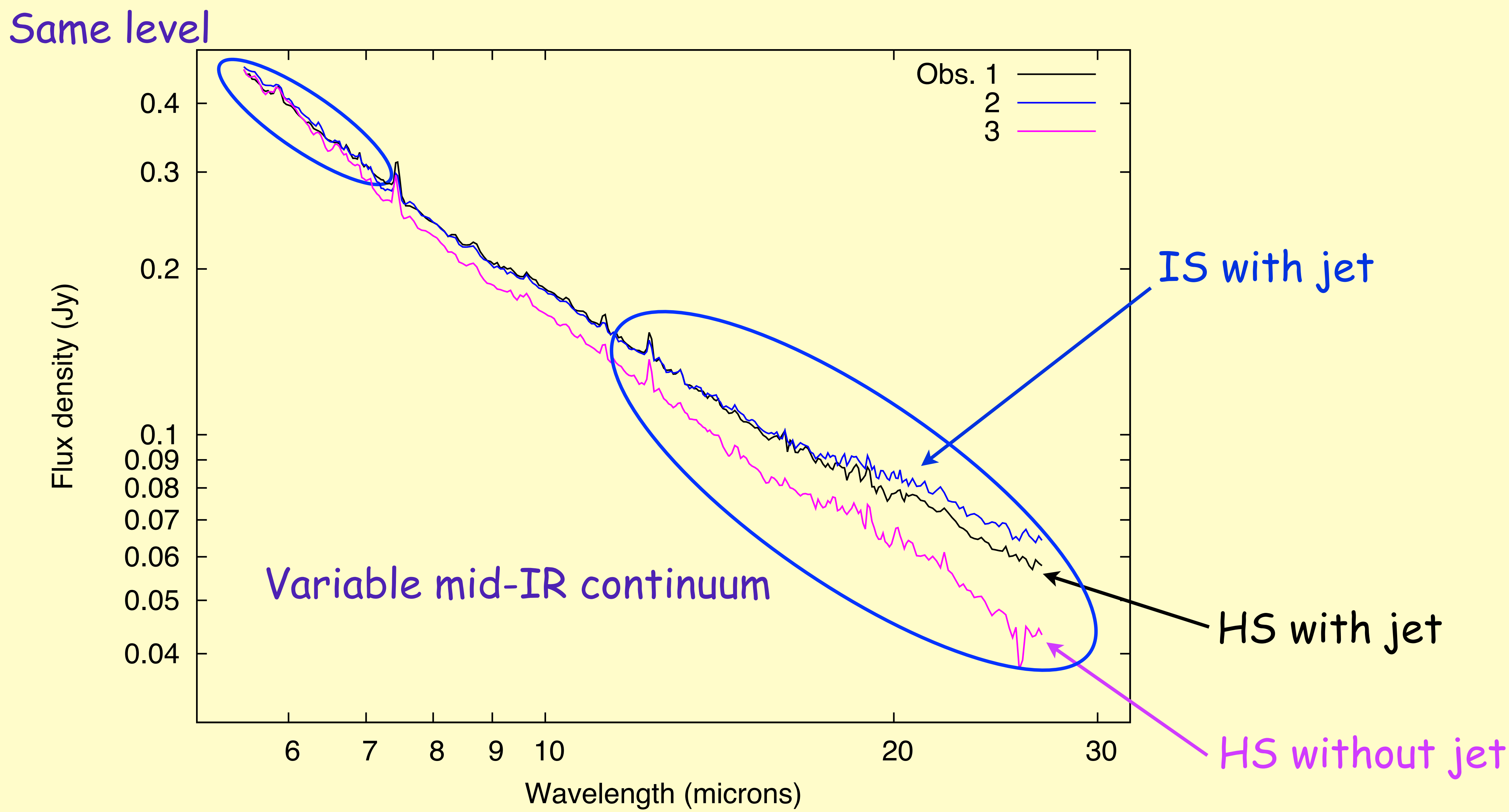

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- Variations at longer mid-IR wavelengths may be due to:
  - Synchrotron emission from compact jets
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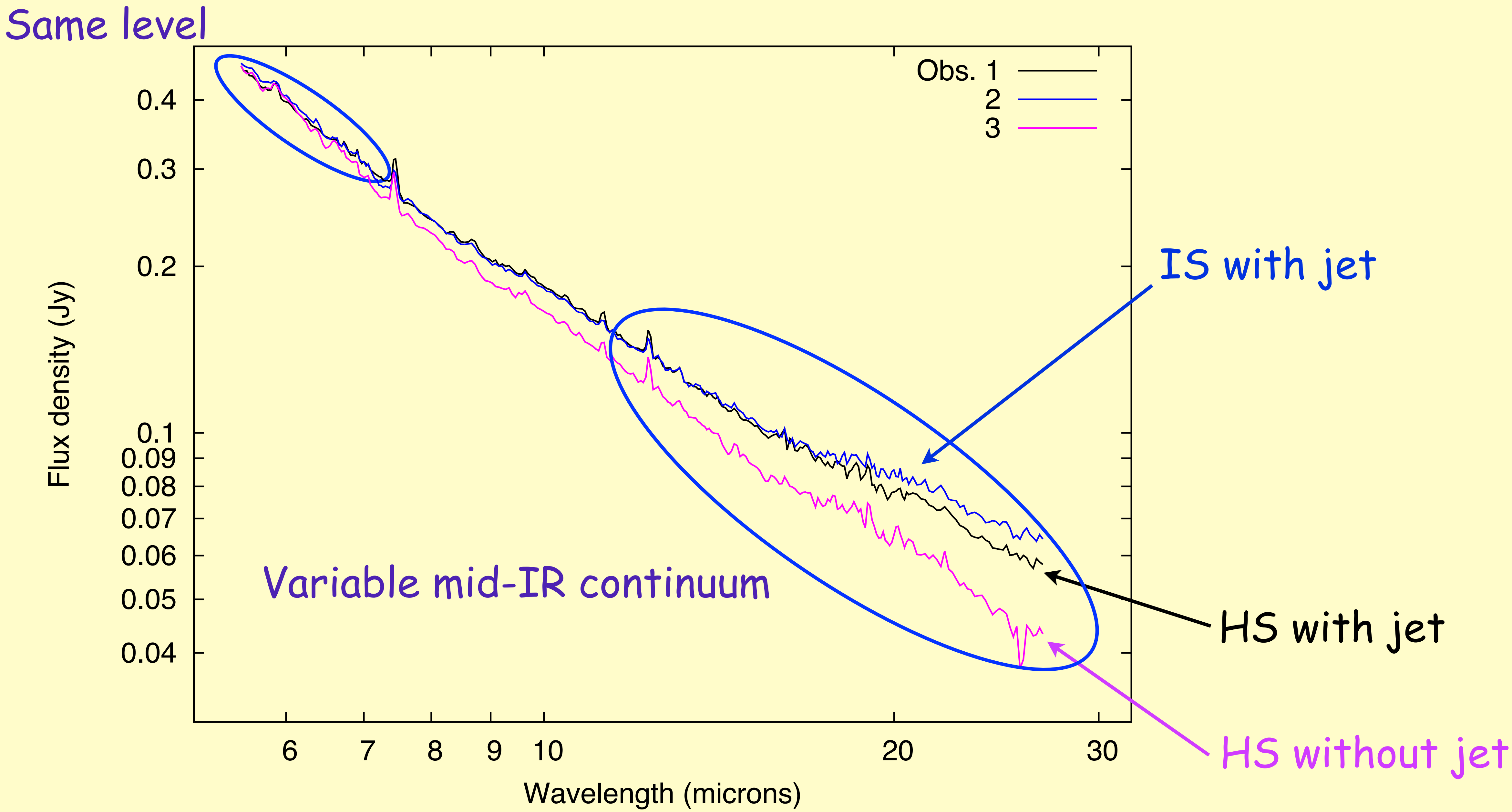

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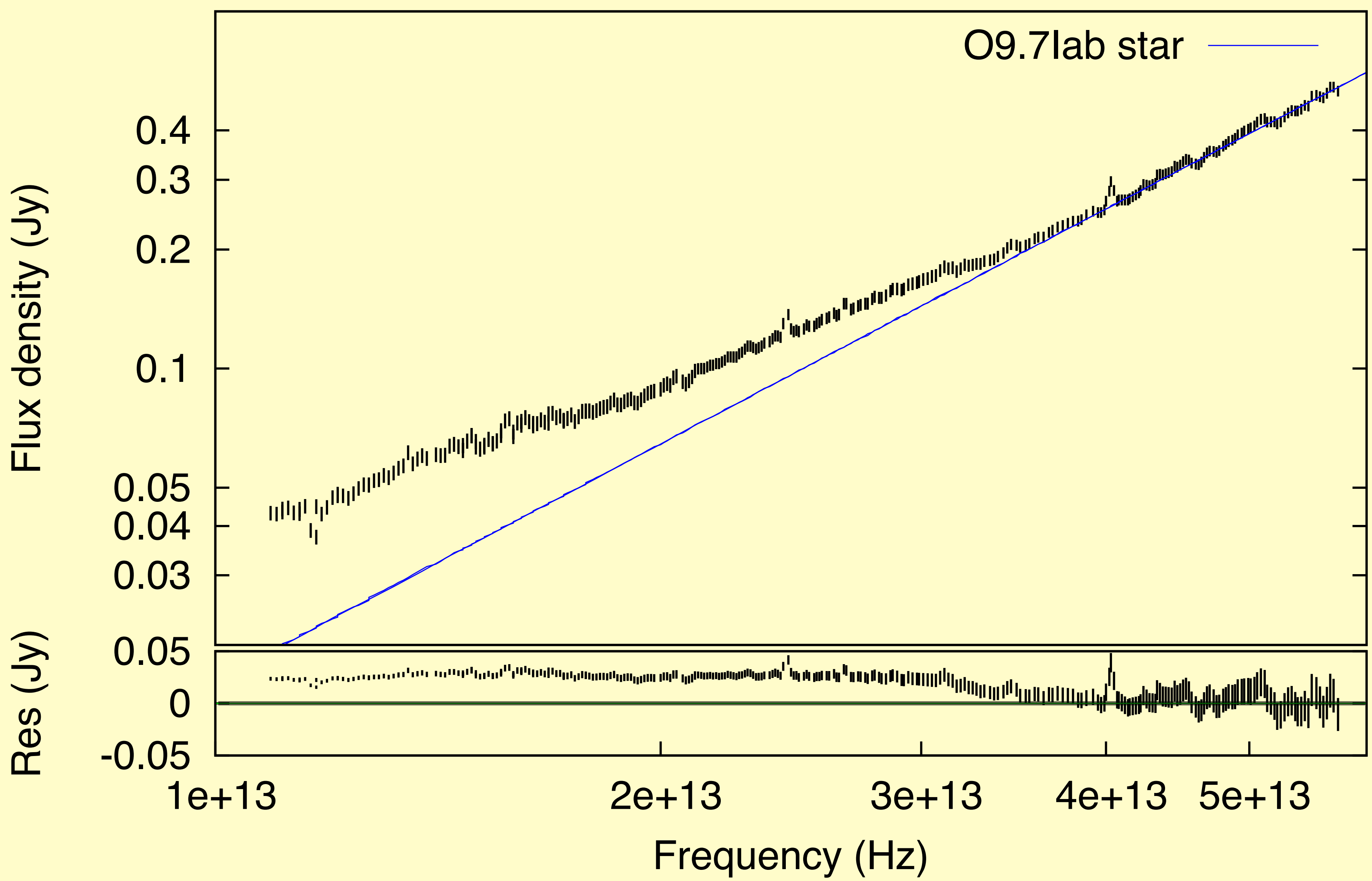
~~HEATED DUST~~

J.C. Lee et al, in prep

HS without Jet(s)



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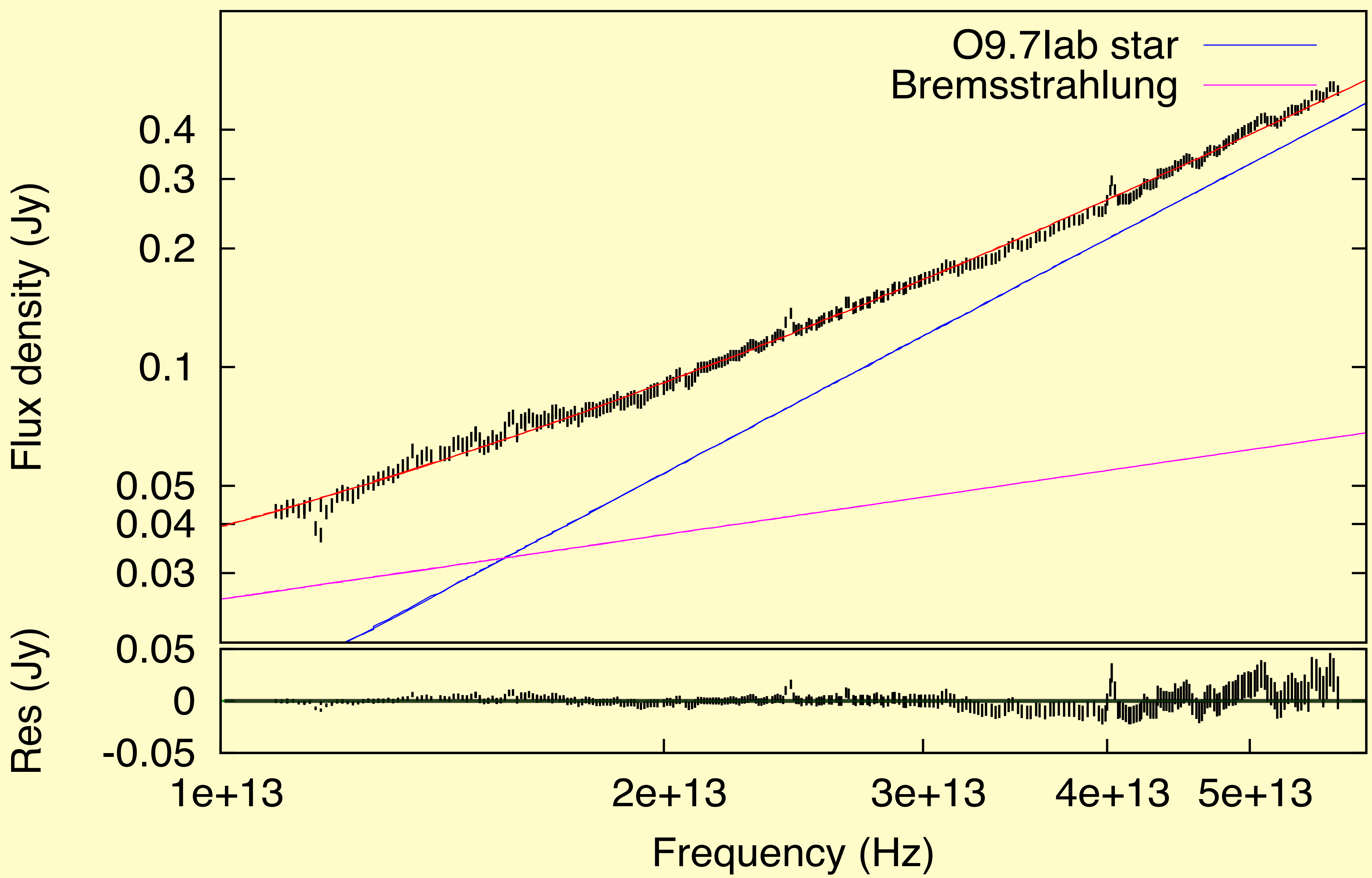

1/ O9.7Iab photosphere with BB, T=28000 K and R/D free, but excess

2/ Add $S_\nu \propto \nu^\beta$ and $\beta=0.55\pm0.07\approx0.6$, value for bremsstrahlung from a spherically expanding stellar wind (Wright&Barlow 1975, Panagia&Felli 1975)

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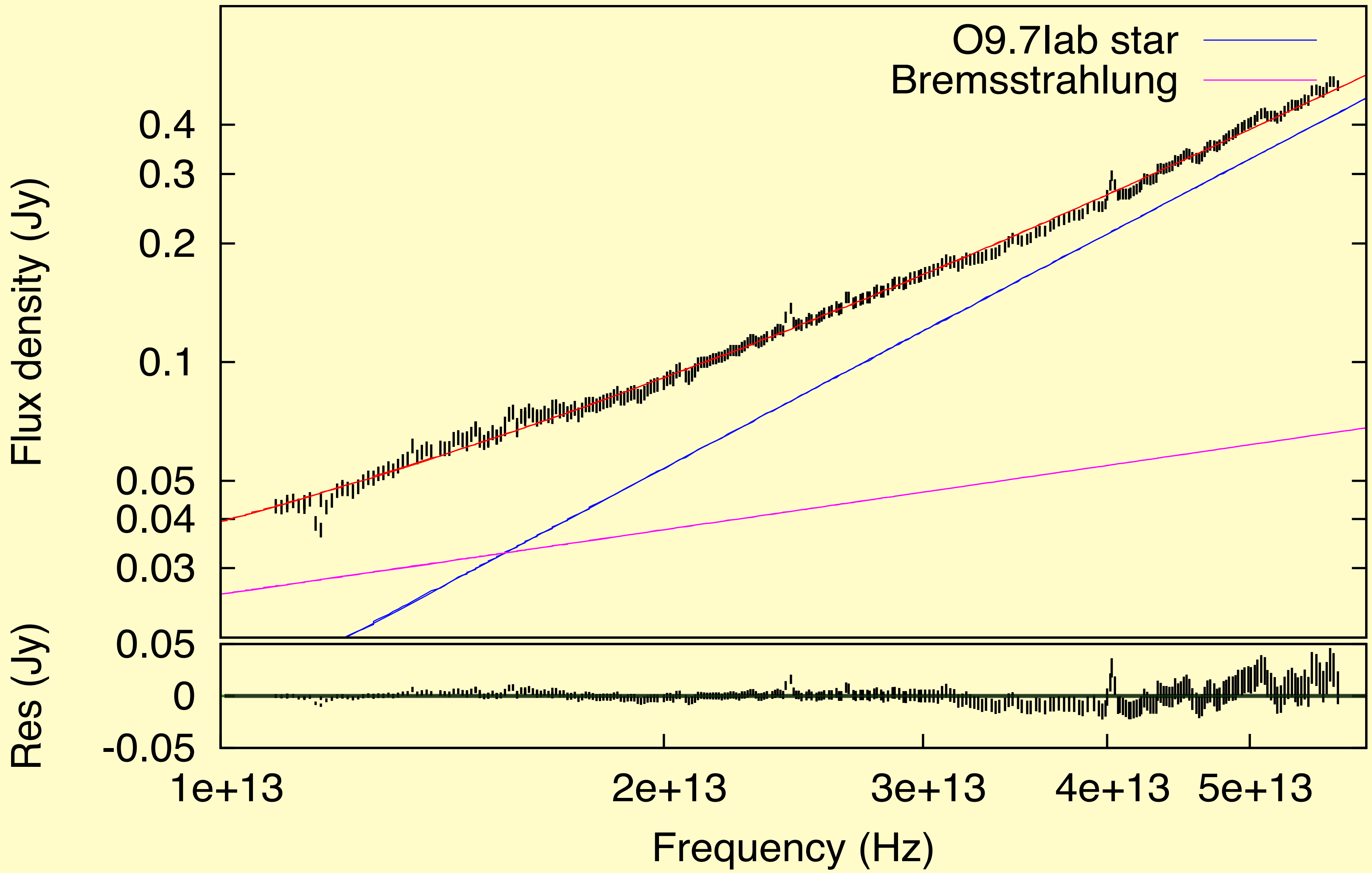

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No jet => mid-IR continuum due to photosphere and stellar winds

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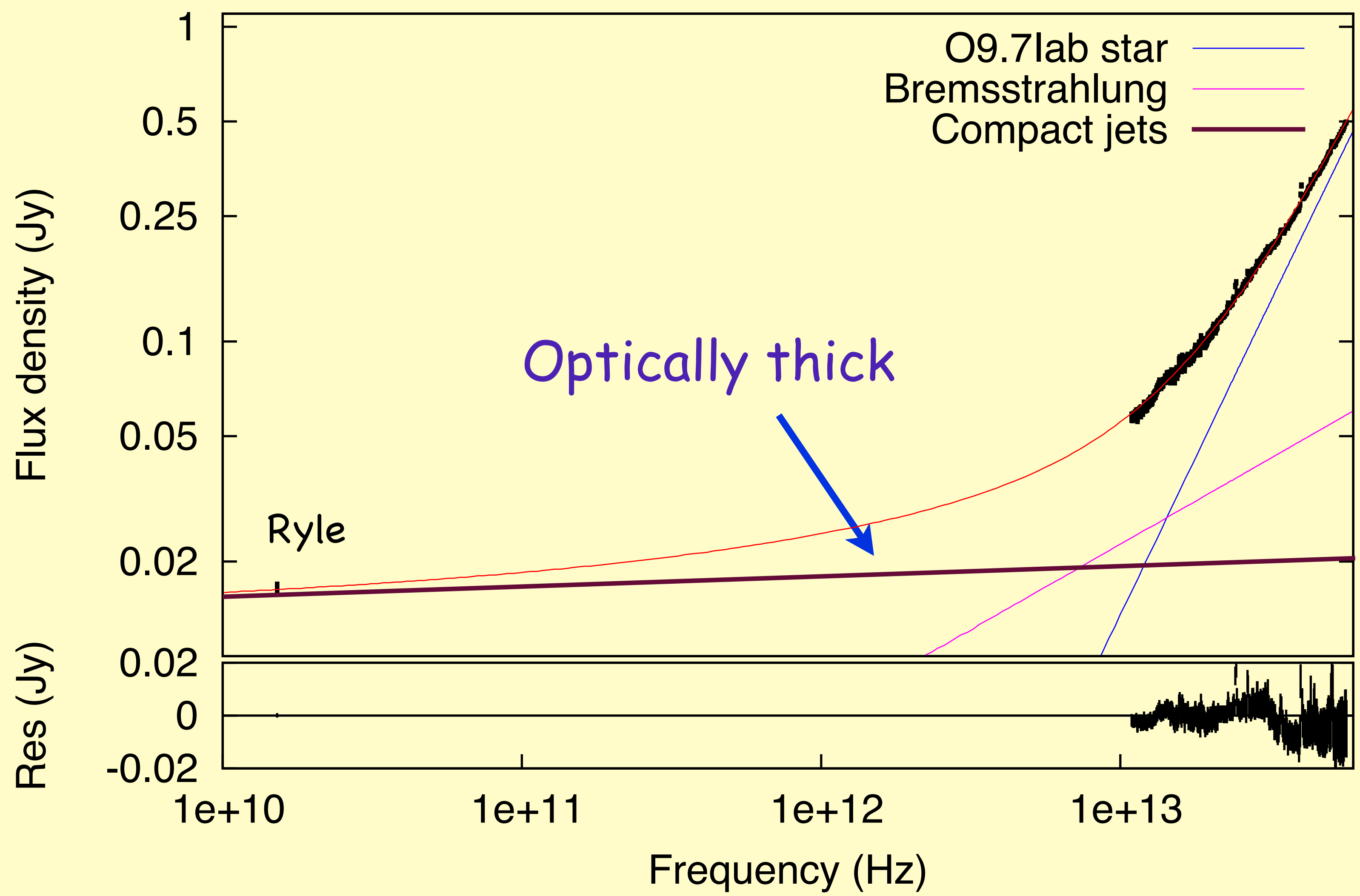

1/ Photosphere parameters (T, R/D) and bremsstrahlung index (ß) fixed
2/ Add PL to mimic synchrotron emission of compact jet

=> similar bremsstrahlung as HS w/o jet

=> flat PL consistent with optically thick synchrotron from jet

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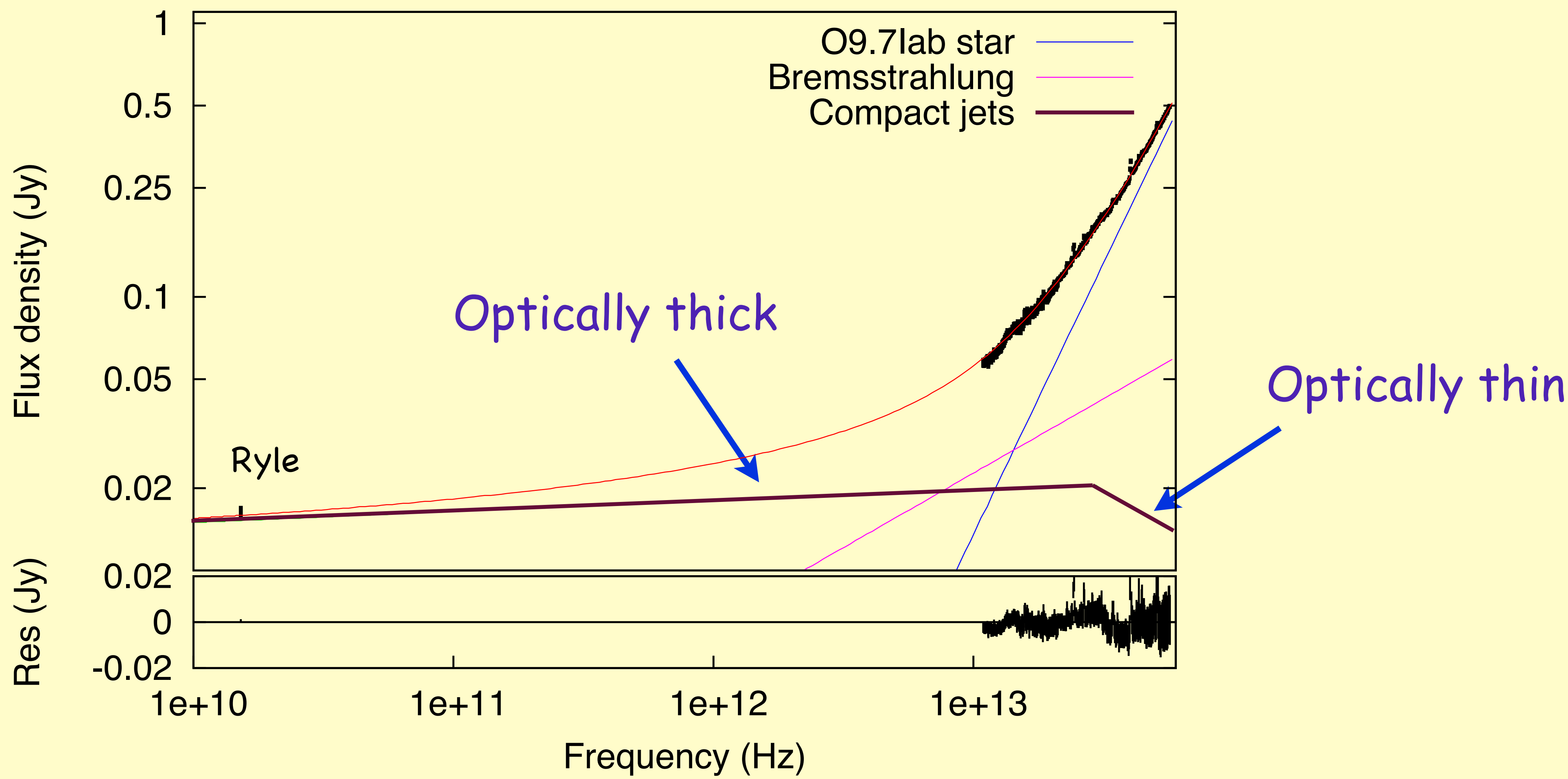
HS with Jet(s)



1/ Photosphere parameters (T, R/D) and bremsstrahlung index (ß) fixed
3/ Add broken PL to mimic compact jet optically thick-to-thin synchrotron emission (Blandford&Königl 1979)

- Bremsstrahlung normalization fixed to Obs 3 and broken PL free
- Bremsstrahlung normalization fixed to value for simple PL and broken PL free
- Bremsstrahlung normalization free to and optically-thin index fixed to -0.6

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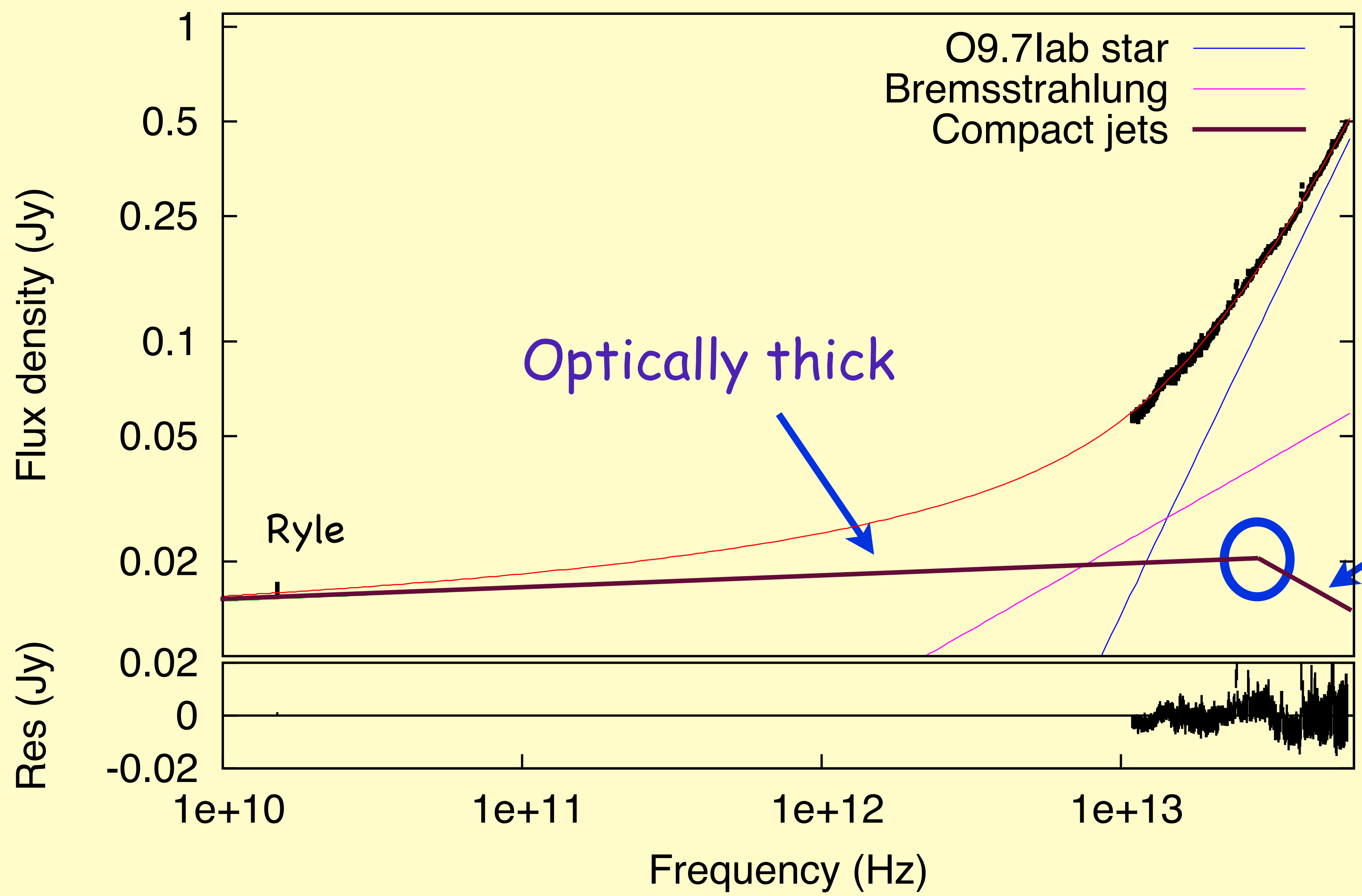

$\nu_b \approx 2.7 \times 10^{13}$ Hz

=> $B \approx 2 \times 10^4$ G

(model in Chaty et al. 2010)

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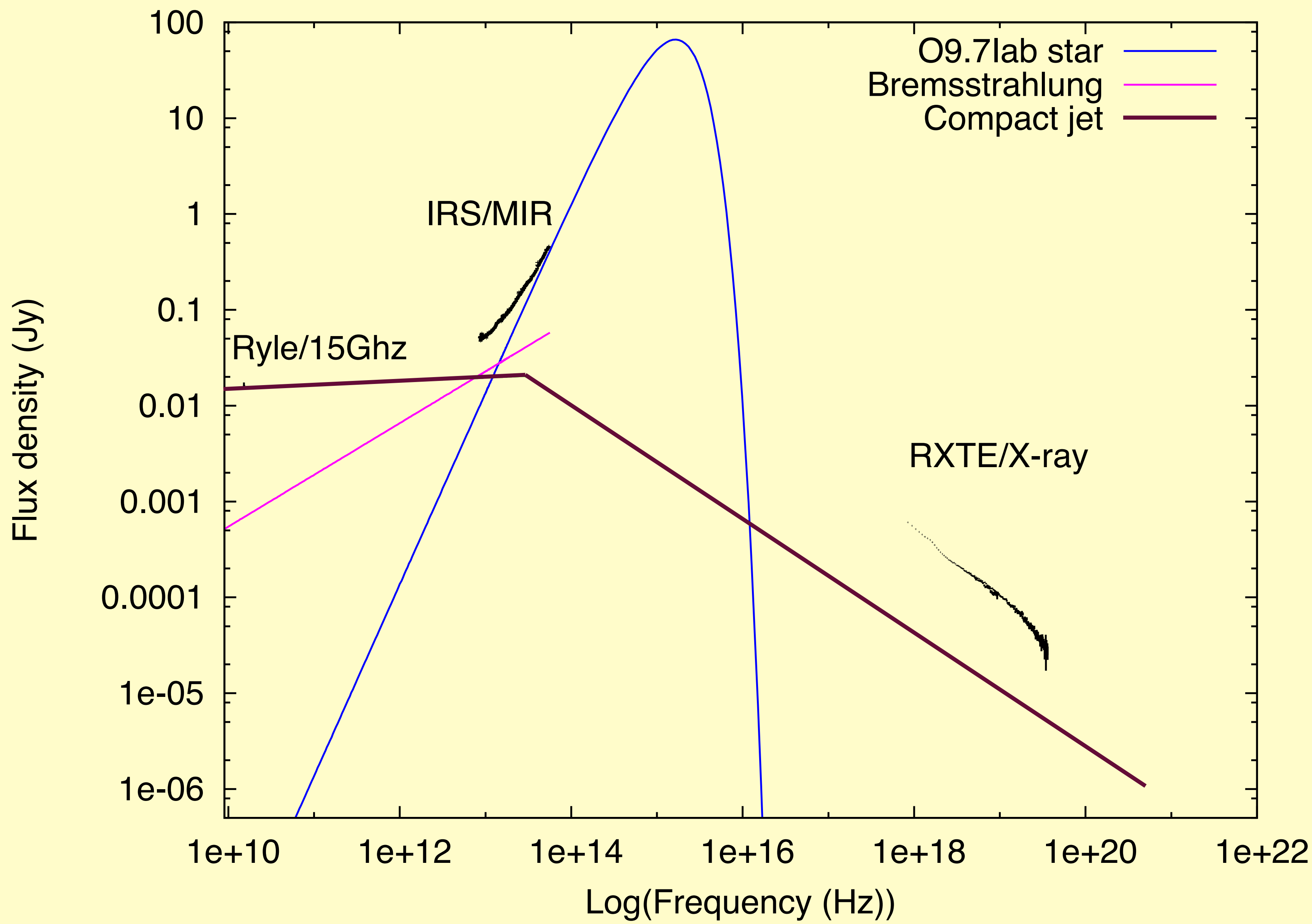
} Similar Results Improvement

Radio to X-ray SED during HS with Jet



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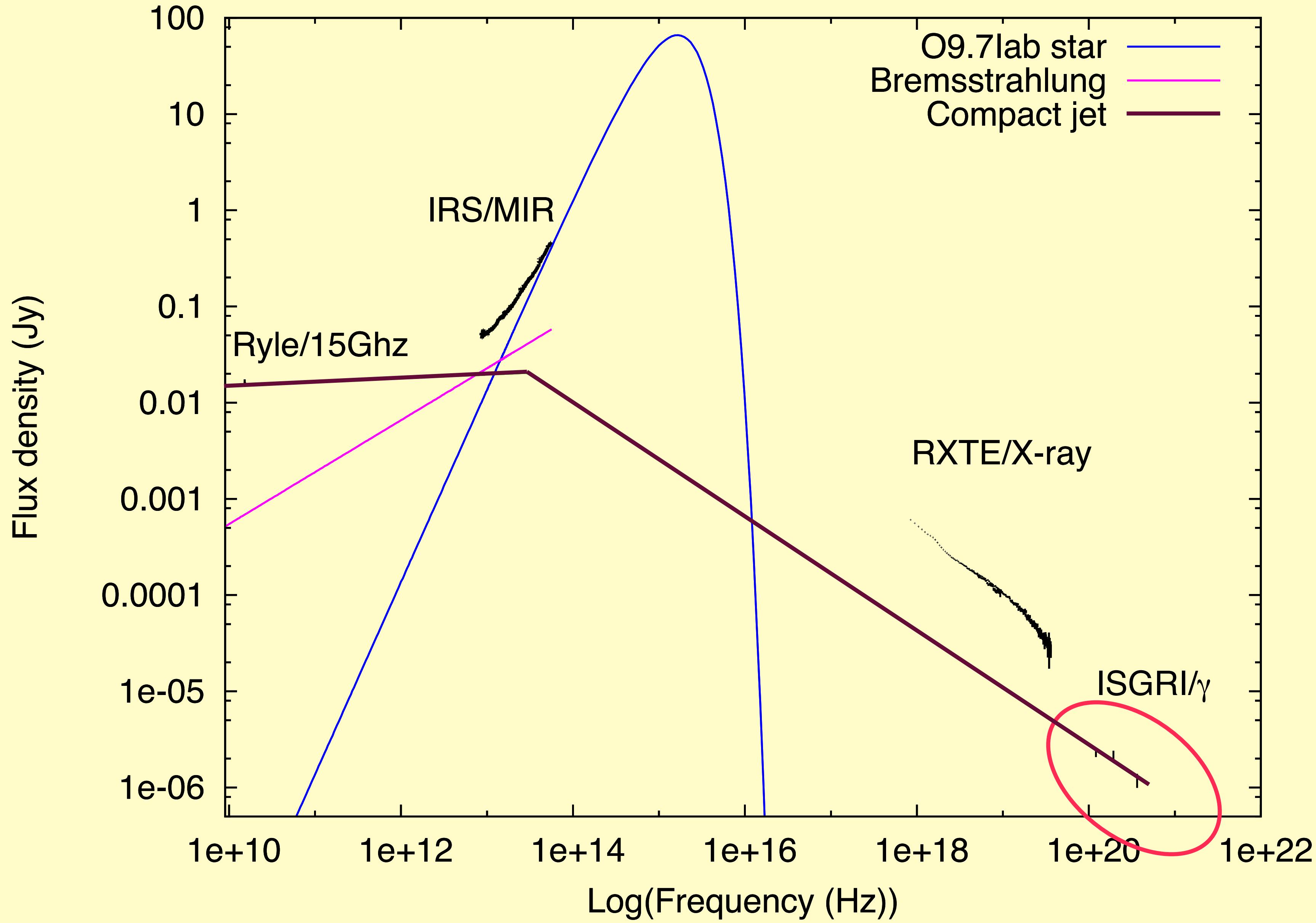

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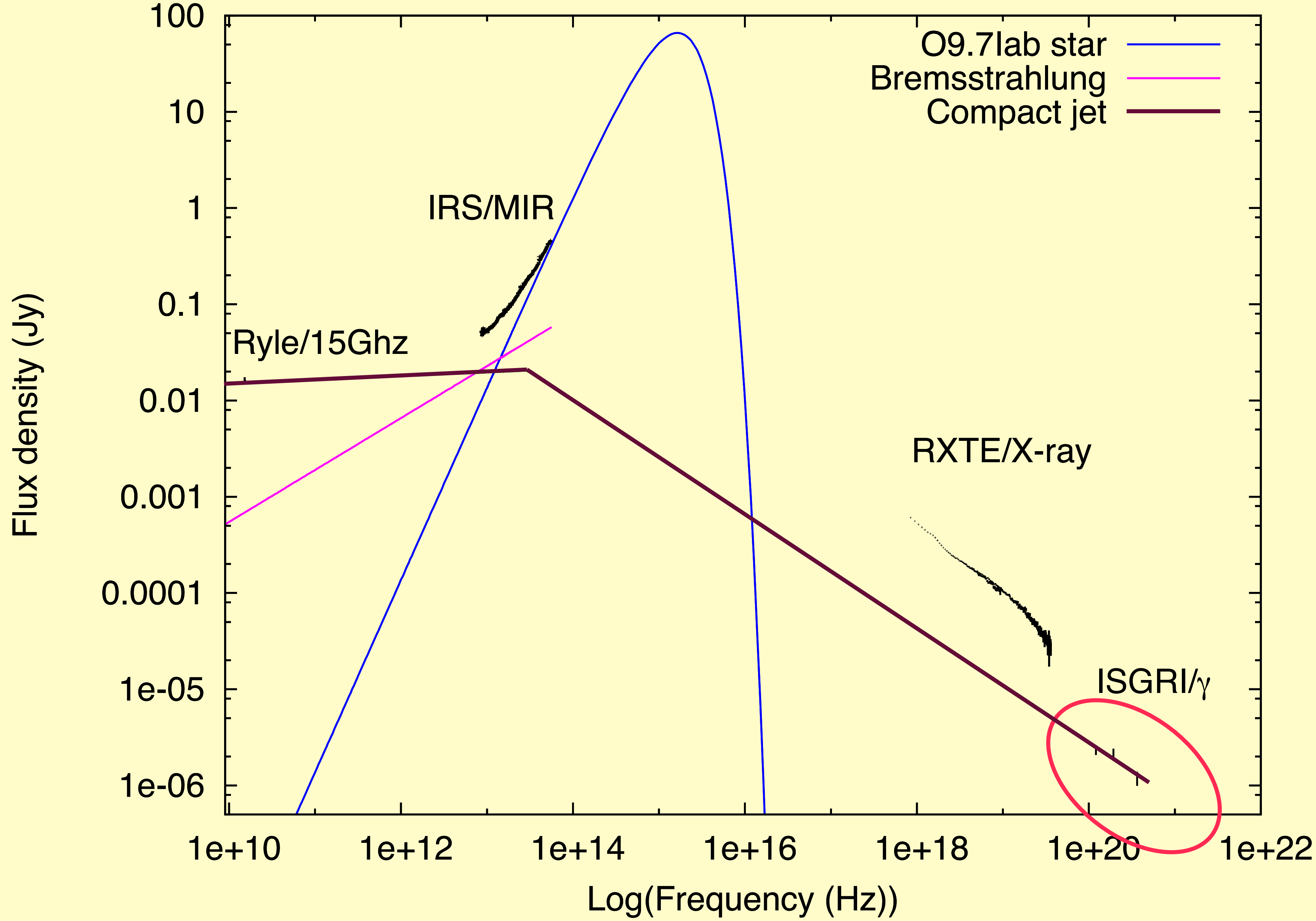
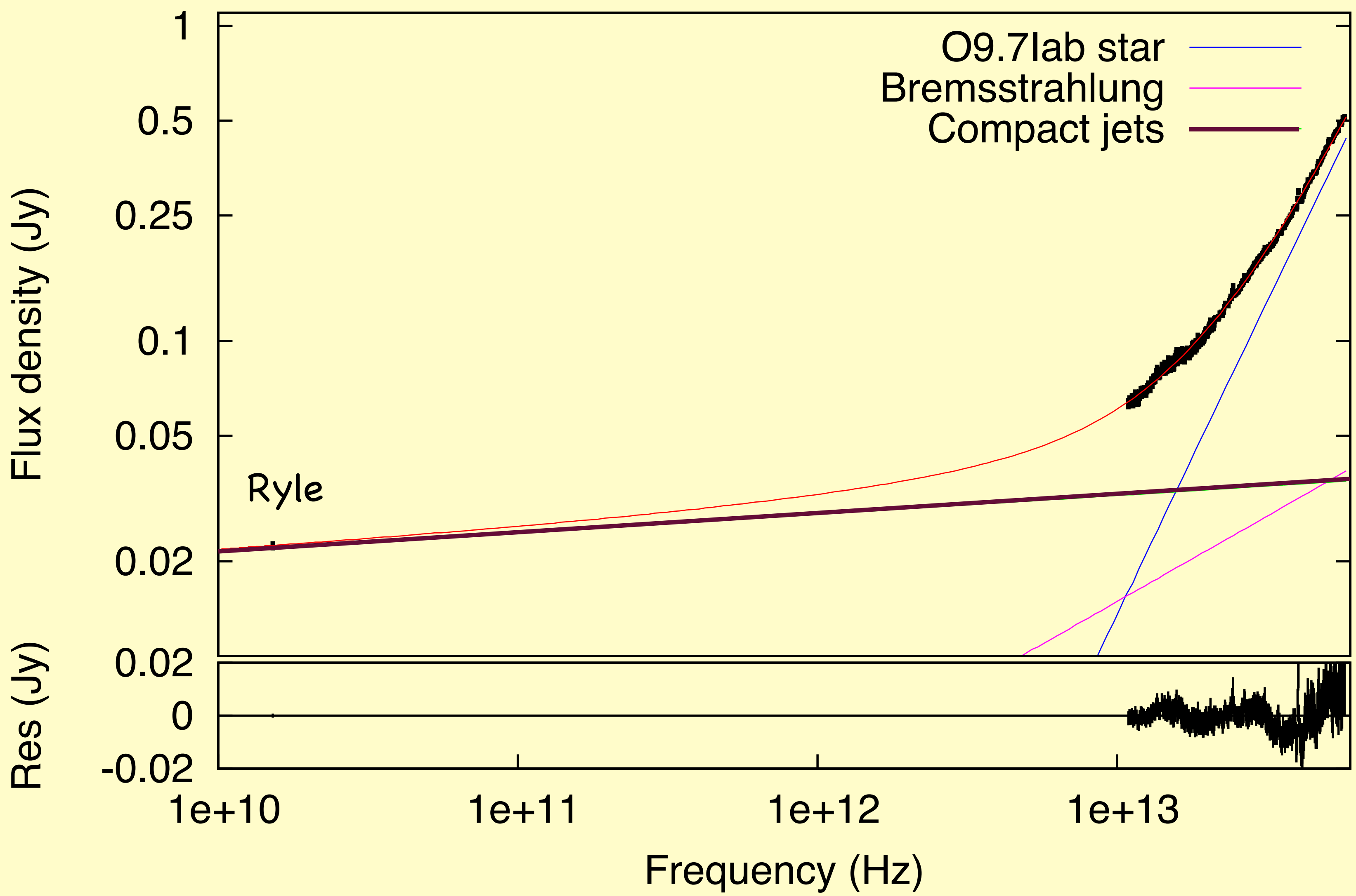


- IR slope consistent with INTEGRAL polarized emission in Laurent et al. (Science, 2011)
- IR slope underestimates RXTE => both the jet and corona contribute to X-rays but corona dominates below ≈200 keV

IS with Jet(s)



1/ Best-fit suggests break shifted to higher frequency, as expected

2/ Bremsstrahlung level 30-40% lower than HS (with and w/o jets):

=> lower mass-loss rate of stellar winds

=> consistent with anti-correlation mass-accretion/mass-loss rates (Gies et al. 2003, 2008)

Wind Clumpiness

Mass-loss rate including wind clumpiness (Lamers & Waters 1984)

$$\dot{M}_w = 2.26\ 10^{-7} \times \sqrt{f_\infty} \times \left[S_\nu \left(\frac{\nu}{10\ \mathrm{GHz}}\right)^{-0.6} \left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{-0.1} \left(\frac{D}{1\ \mathrm{kpc}}\right)^{2} \right]^{\frac{3}{4}} \left(\frac{\mu v_\infty}{100\ \mathrm{km\ s^{-1}}}\right)\ M_\odot\ \mathrm{yr}^{-1}$$

$$\text{If } \sqrt{f_\infty} = 1, \text{ then } \begin{cases} \dot{M}_w = 8.79\ 10^{-6}\ M_\odot\ \mathrm{yr}^{-1} \text{ in HS} \\ \dot{M}_w = 5.95\ 10^{-6}\ M_\odot\ \mathrm{yr}^{-1} \text{ in IS} \end{cases}$$

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3 to 4x higher than in Gies et al. (2003) => $f_\infty = 0.09\text{-}0.1$

Summary & Conclusion

- Significant contribution of compact jets to mid-IR spectrum

  - first **spectroscopic** measurement of the jet spectral break in a microquasar (Rahoui et al. 2011) but photometric breaks have been detected for GX 339-4 (Corbel & Fender 2002, Gandhi et al. 2011)

  - Cygnus X-1: $\boldsymbol{\nu_b}$=2.7 10^{13} Hz ≈ 11 μm => B≈2×10^4 G

- Jet consistent with polarized γ−ray detected by INTEGRAL but not with X-rays detected by RXTE

  - Presence of a corona-dominated X-ray emission

- Significant stellar wind bremsstrahlung

  - Mass-loss rate anticorrelated to mass-accretion rate

  - Stellar winds likely clumpy with f_∞ ≈ 0.1