The internal shock model applied to X-ray binaries

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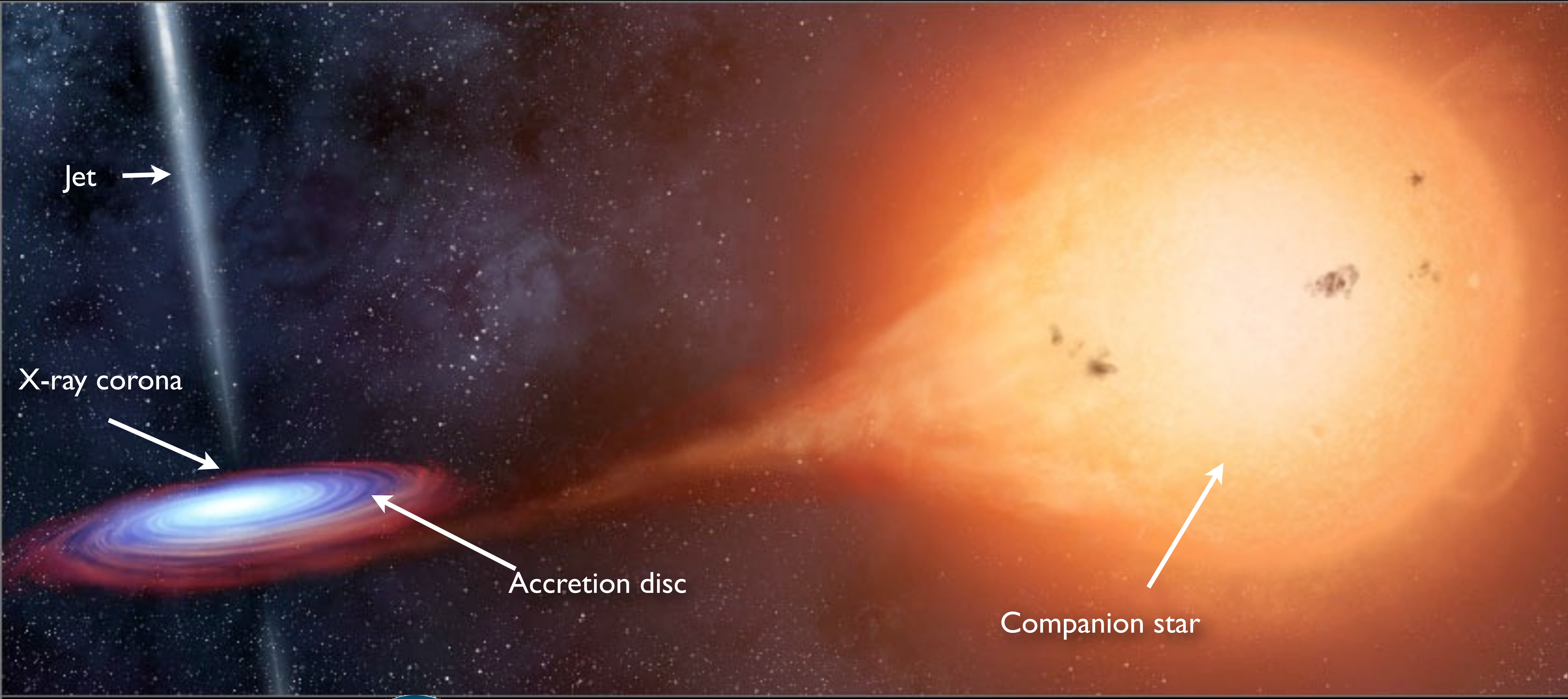

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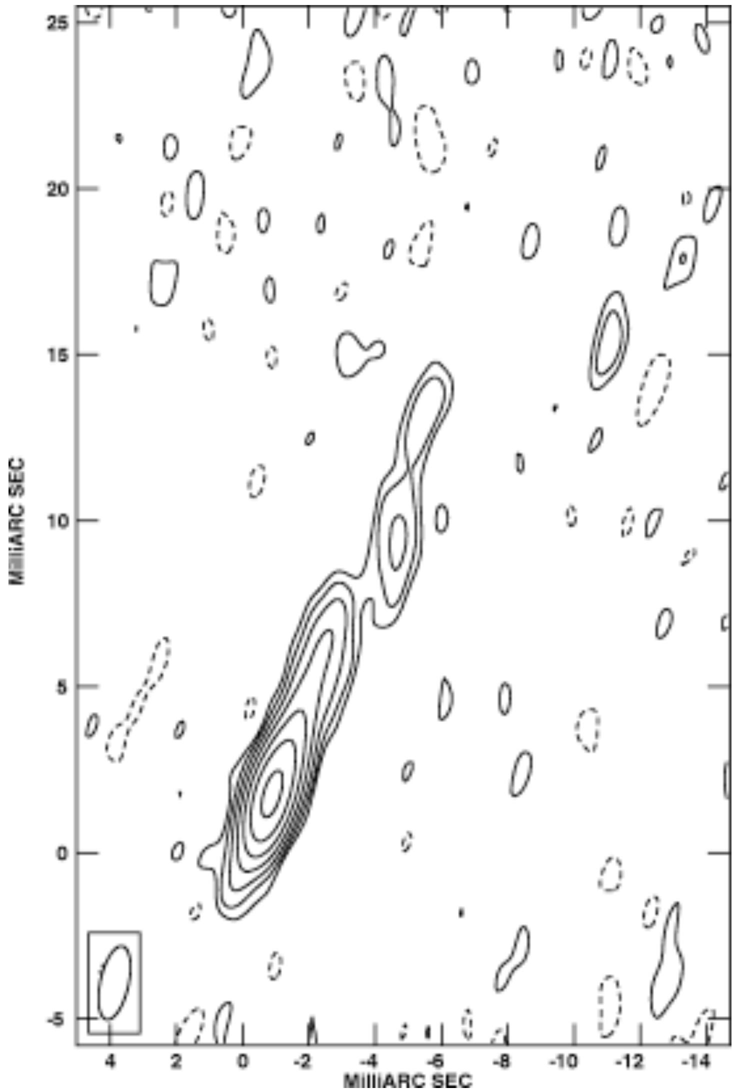
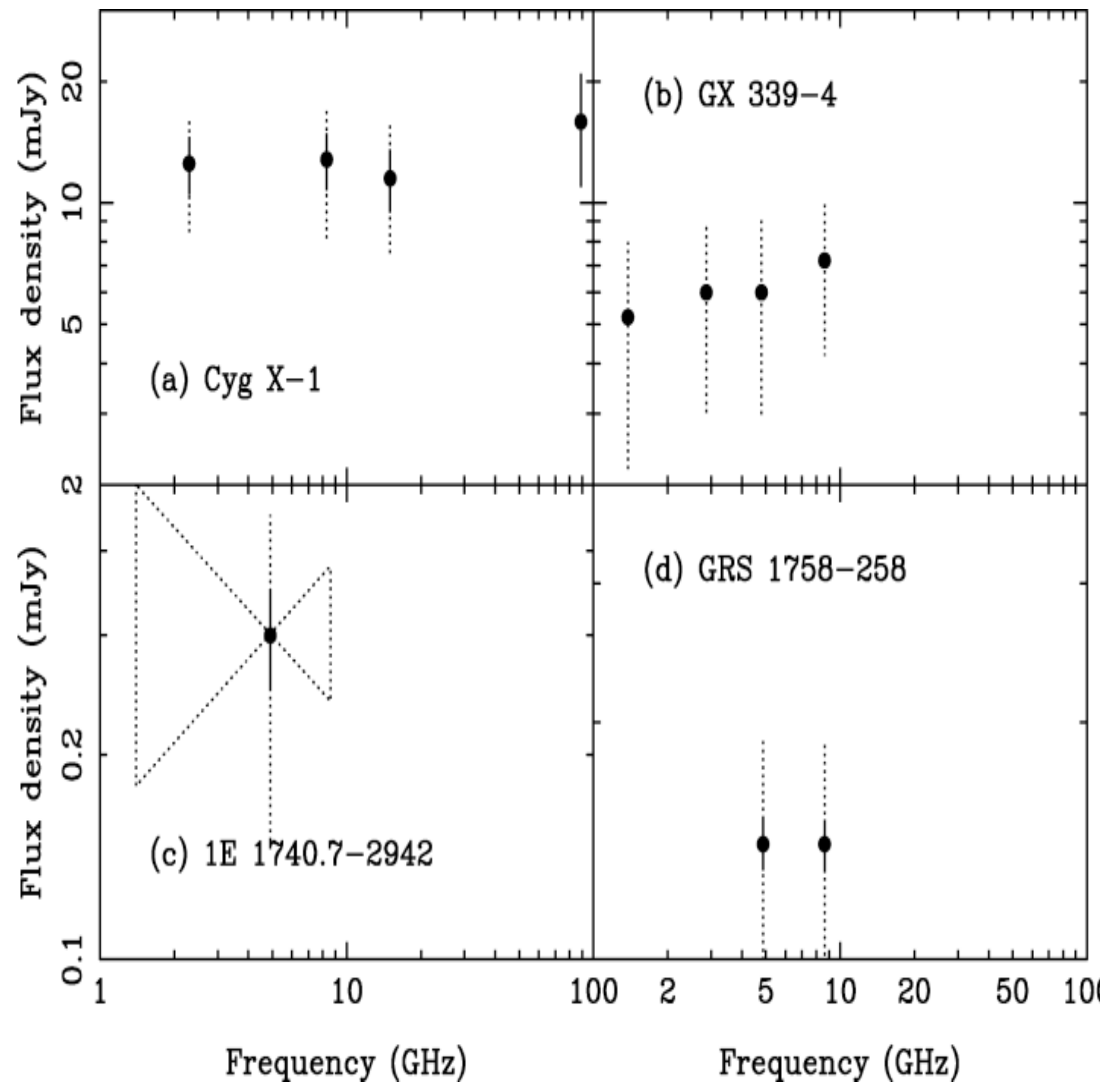
Evidence for compact radio jets in XRBs in the hard spectral state



Cygnus X-1

(Stirling et al. 2001)



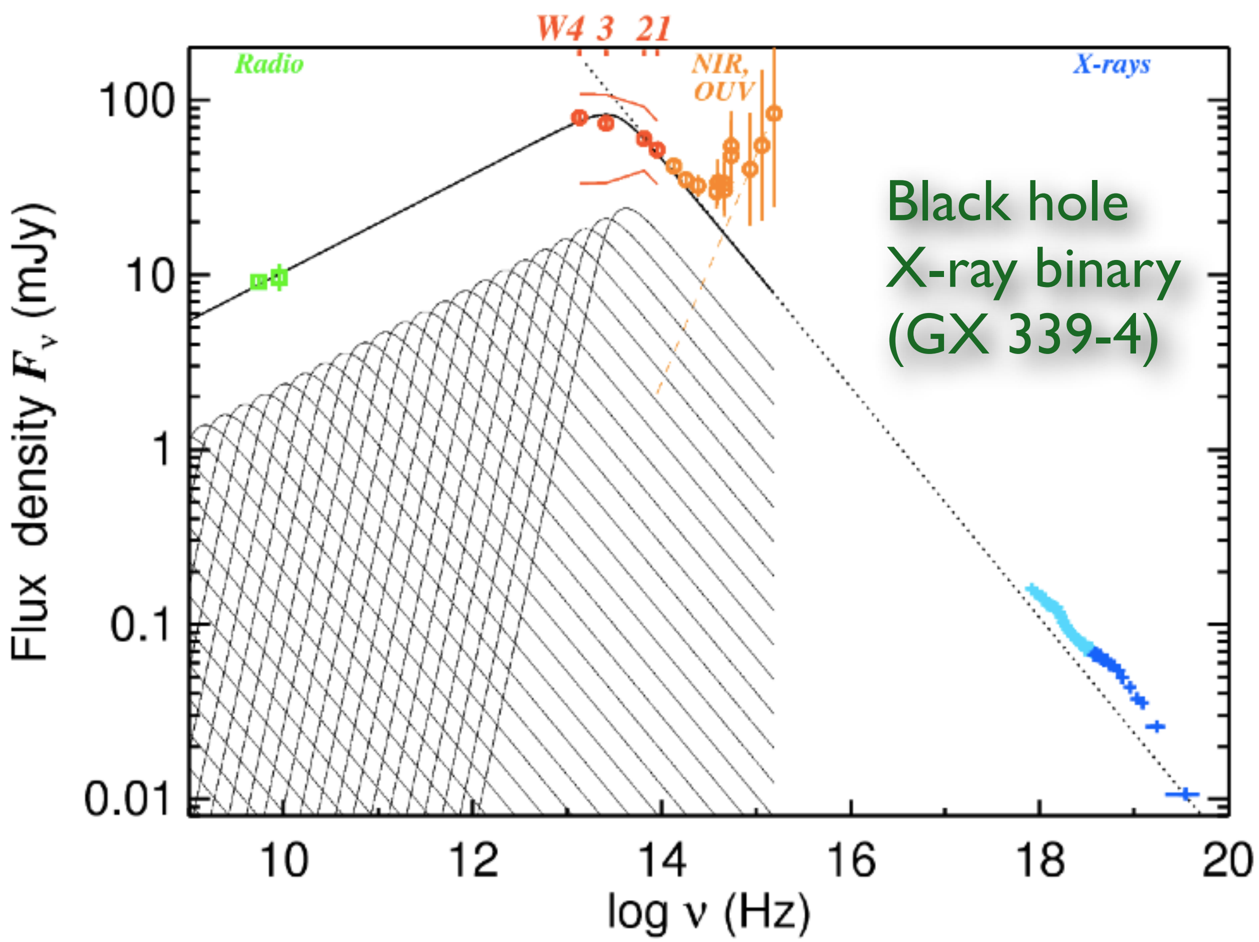
Flat/inverted radio spectra

(Fender 2001)

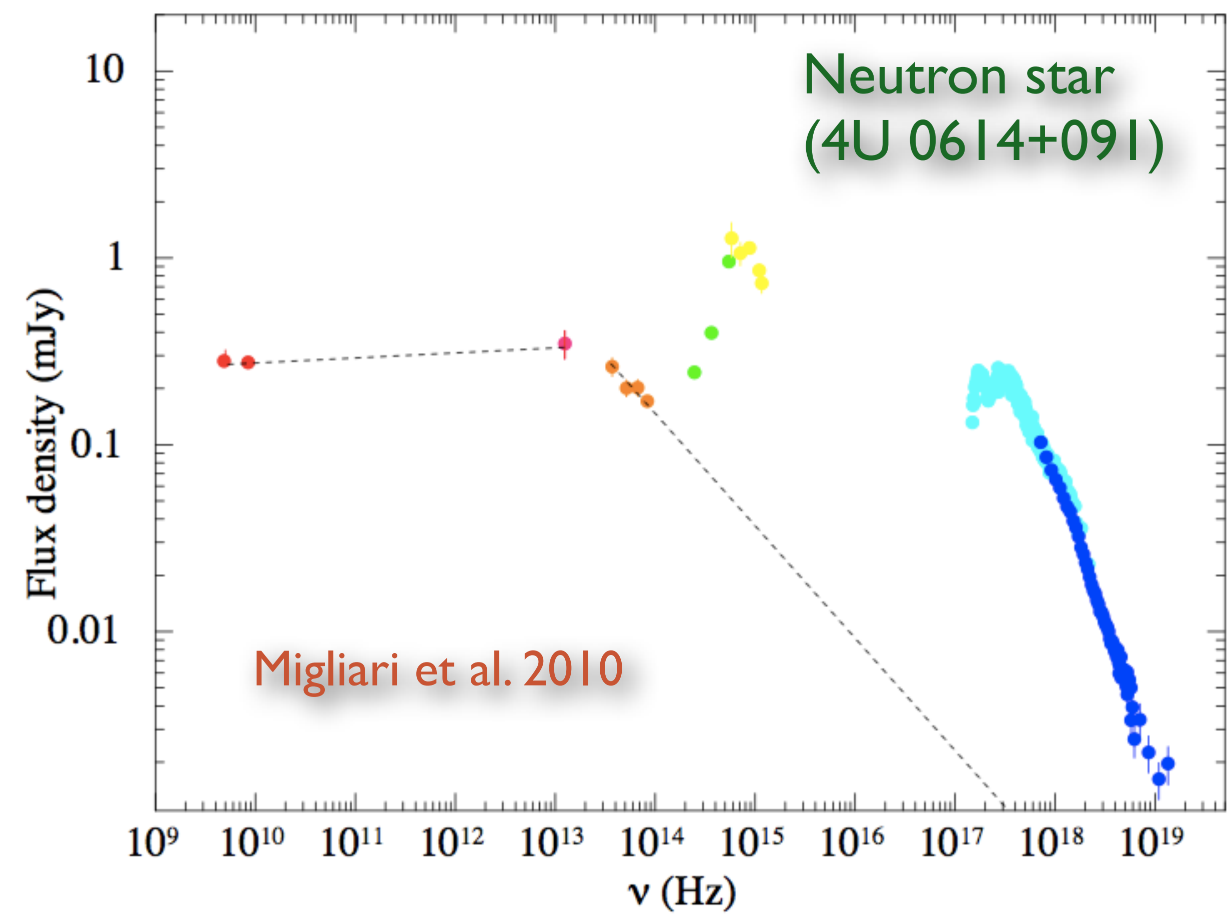
- Jet Lorentz factor $\Gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}} \sim 1.5 - 3$
- Jet kinetic power > X-ray luminosity
- Jet half-opening angle ~ a few degs
- Radio emission quenched in soft state

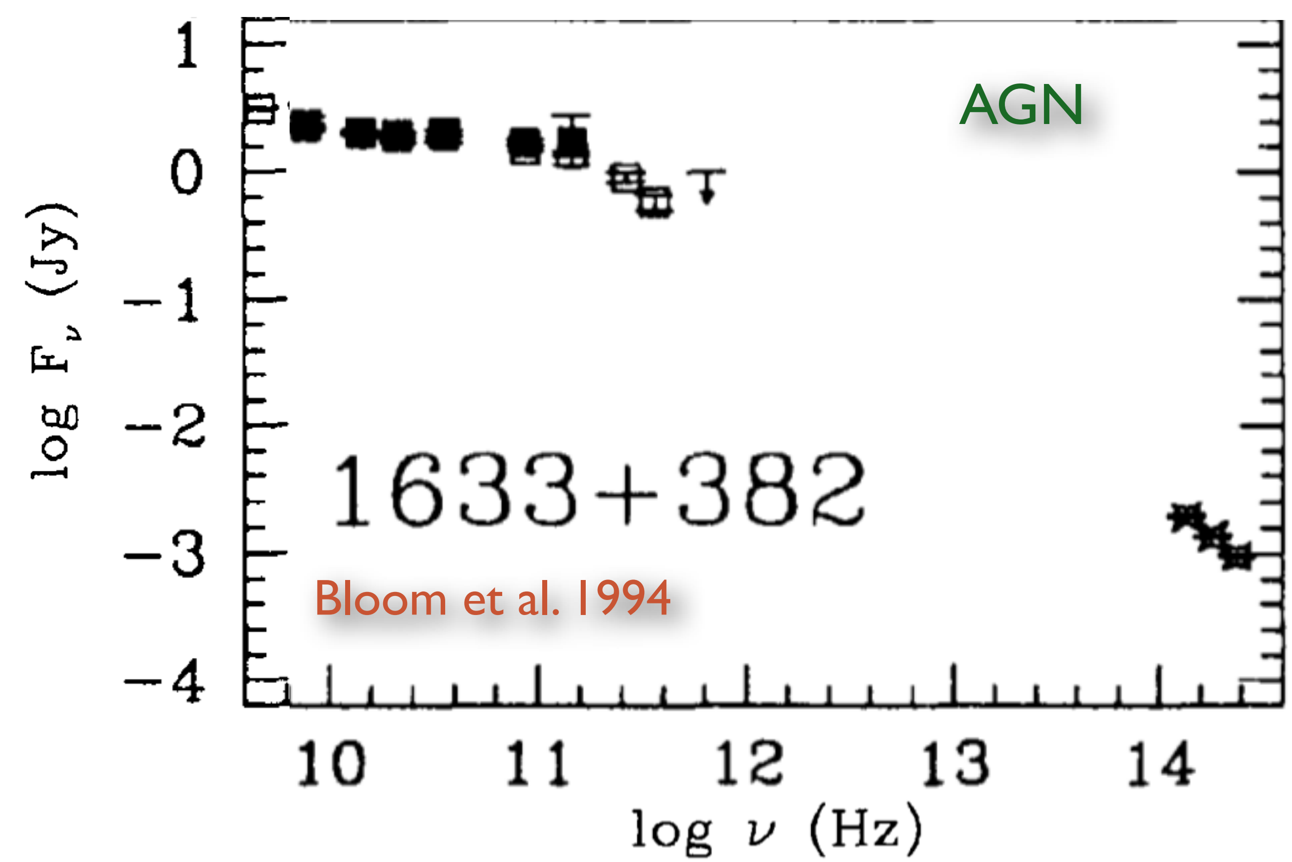
(Gallo et al. 2004)

Observed Spectral Energy Distribution of Compact Jets



Gandhi et al. 2011
see also Corbel & Fender 2002, Chaty et al. 2011; Rahoui et al 2012; Corbel et al. 2013; Russell et al. 2013...



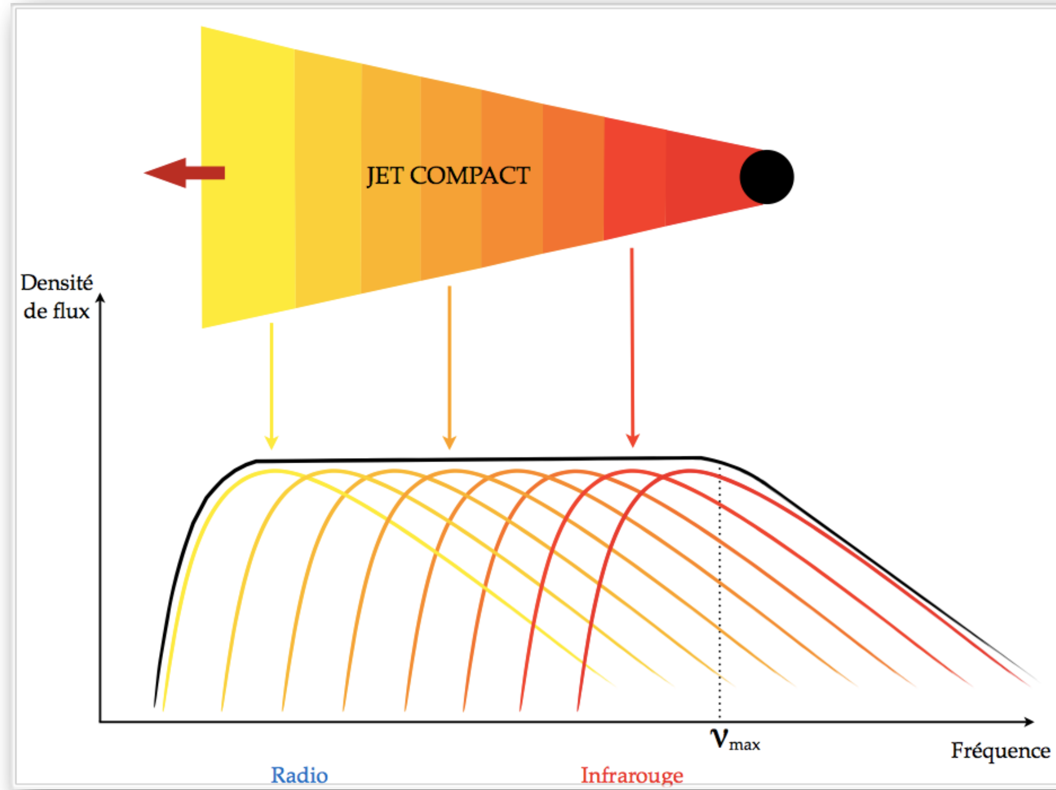


Standard conical jet emission model (Blandford & Koenigl 1979)

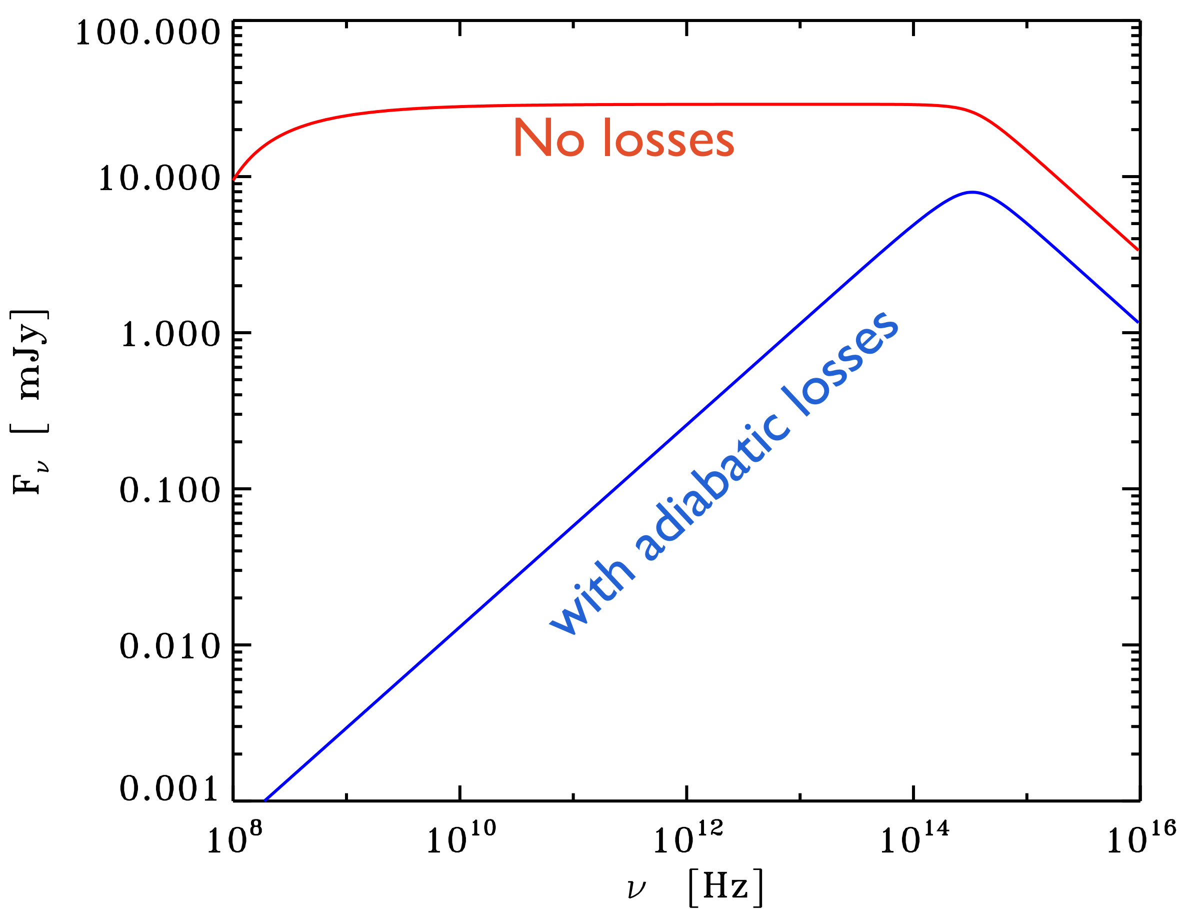
- Synchrotron radiation from a population of relativistic leptons travelling down the jet

$$n_e(\gamma_e) \propto \gamma_e^{-p}$$

- Energy losses neglected



(M. Coriat)



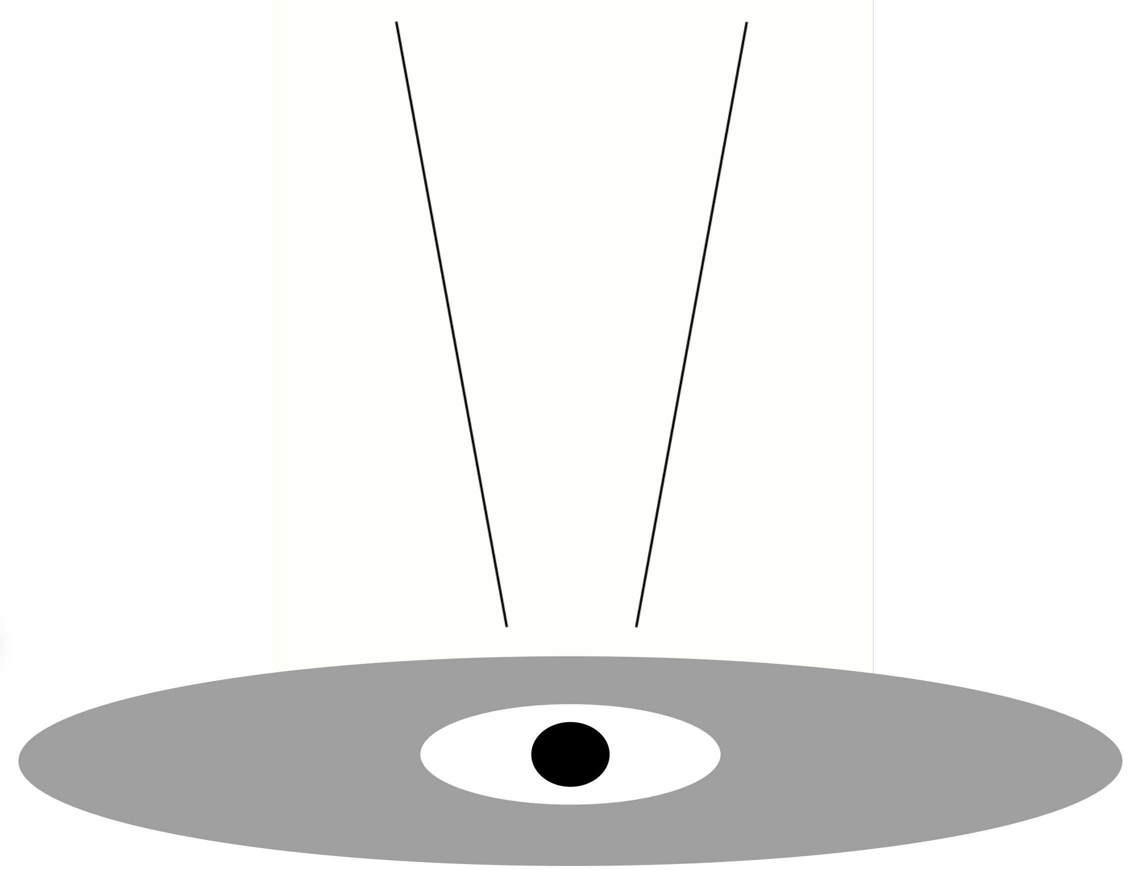
Adiabatic expansion energy losses:

➡ strongly inverted SED

➡ need to compensate for losses

Internal shock model

- Jet= 'shells' ejected a time intervals ~ t_{dyn} with randomly variable Lorentz factors
- Faster shells catch up will slower shells and collide
- Shocks, particle acceleration, and emission of synchrotron radiation
- Hierarchical merging process



Jamil et al. 2010; Malzac 2013

➡ ISHEM code: simulate SEDs and light curves

Malzac 2014

Shell collisions

Energy dissipated during collision:

$$E_{s,i} = (\gamma_1 m_1 + \gamma_2 m_2)c^2 - \gamma_c(m_1 + m_2)c^2.$$

$$\gamma_c = \frac{m_1\gamma_1 + m_2\gamma_2}{\sqrt{m_1^2 + m_2^2 + 2m_1 m_2 \gamma_1 \gamma_2 (1 - \beta_1\beta_2)}}$$

Reverse and forward shock front velocities estimated from jump conditions of Blandford & Mc Kee (1978)

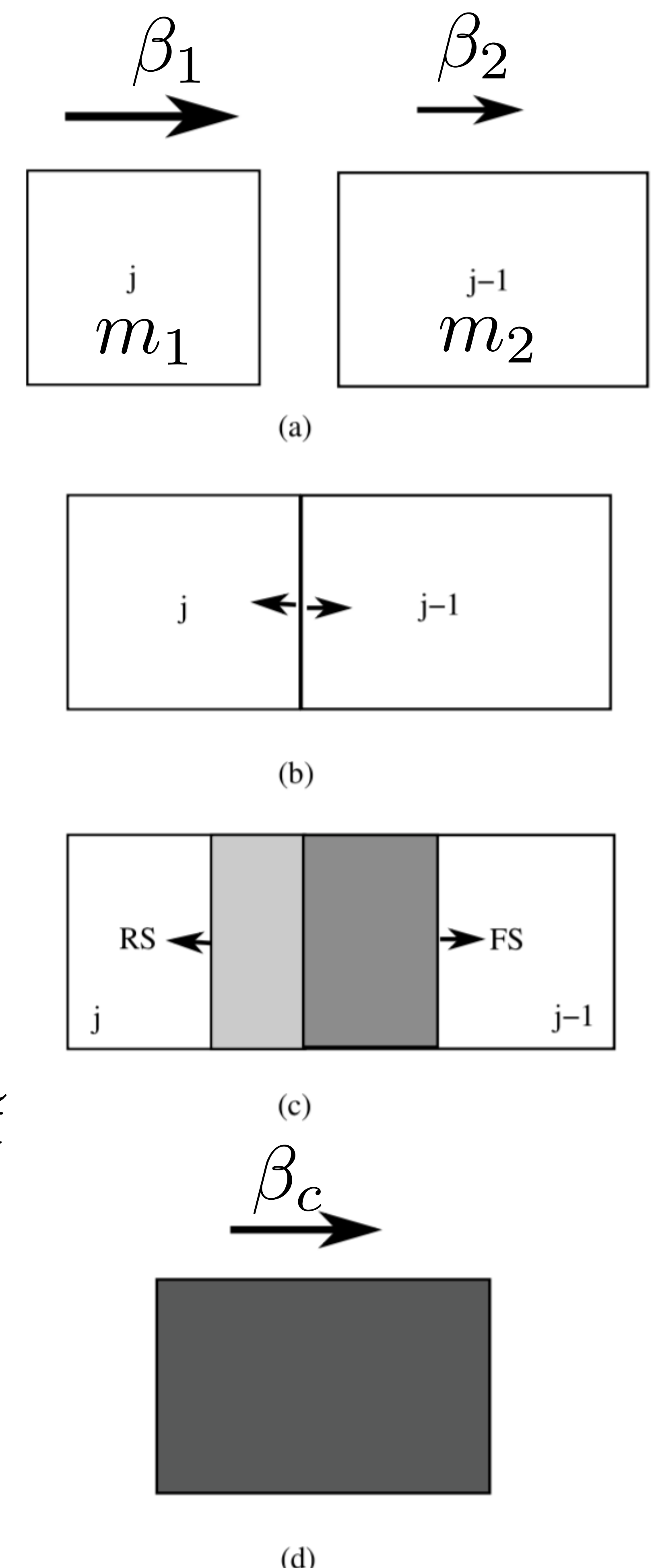
Shock crossing times —> dissipation time t_{dis}

During this duration, we assume dissipation occurs at a constant rate: $P_T = E_{s,i}/t_{dis}$

The (comoving) specific internal energy per unit mass $\tilde{\epsilon}$ increases at a rate $\dot{\epsilon} = P_T/(m_1 + m2)$

After t_{dis} dissipation stops.

In practice, other collisions with other shells may happen during t_{dis}



Shell geometry

Homogeneous expanding cylinder:

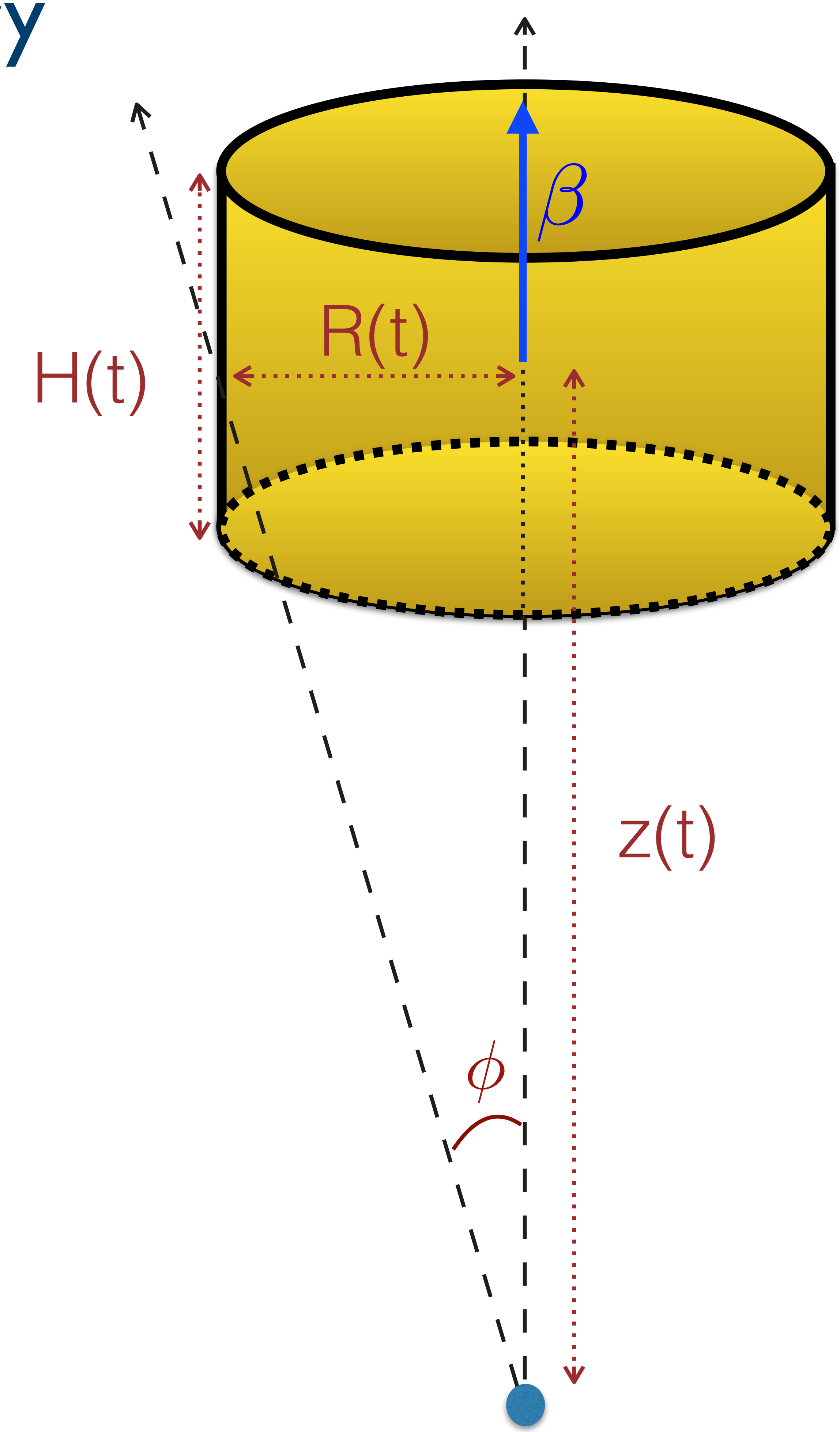
$$z = z_0 + \gamma\beta c\tilde{t},$$

$$R = R_0 + \gamma\beta c\tilde{t}\tan\phi,$$

$$\tilde{H} = \tilde{H}_0 + 2\tilde{\beta}c\tilde{t},$$

Longitudinal expansion/compression velocity

$$\tilde{V} = \pi R^2 \tilde{H}$$



Time evolution of specific internal energy of a shell:

$$\frac{d\tilde{\epsilon}}{d\tilde{t}} = \dot{\epsilon} - \underbrace{\tilde{\epsilon}(\gamma_a - 1)\frac{2}{R}\frac{dR}{d\tilde{t}}}.$$

Pressure work against external medium as shell expands:

$$d\tilde{W} = Pd\tilde{V} = (\gamma_a - 1)\frac{m\tilde{\epsilon}}{\tilde{V}}d\tilde{V} \simeq (\gamma_a - 1)m\tilde{\epsilon}\frac{2dR}{R}$$

(longitudinal expansion losses neglected)

Solution:

$$\tilde{\epsilon} = \left[\dot{\epsilon}\tau_d \frac{x^{2\gamma_a - 1} - 1}{2\gamma_a - 1} + \tilde{\epsilon_0}\right] x^{2-2\gamma_a},$$

$$x = \frac{R}{R_0} = \frac{z}{z_0} = 1 + \frac{\tilde{t}}{\tau_d}. \qquad \tau_d = \frac{z_0}{\gamma\beta c}$$

Internal energy budget

Total internal energy density:

$$\tilde{u} = \frac{m}{\tilde{V}}\tilde{\epsilon} = \frac{m x^{-2\gamma_a}}{\pi R_0 \tilde{H}_0} \left[\dot{\epsilon}\tau_d \frac{x^{2\gamma_a - 1} - 1}{2\gamma_a - 1} + \tilde{\epsilon_0}\right] \left[1 + 2\frac{\tilde{\beta} c}{\tilde{H}_0}\tau_d (x-1)\right]^{-1}$$

Assume constant equipartition factors ξ_e, ξ_p

Magnetic energy density: $$\frac{B^2}{8\pi} = \frac{\tilde{u}}{1 + \xi_e + \xi_p}$$

Non-thermal leptons:

$$\tilde{u}_e = \frac{\xi_e \tilde{u}}{1 + \xi_e + \xi_p}$$

Thermal energy (protons+leptons):

$$\tilde{u}_p = \frac{\xi_p \tilde{u}}{1 + \xi_e + \xi_p}$$

Non-thermal leptons energy distribution

$$n(\gamma_e) = K_0 \gamma_e^{-s} \quad \text{for} \quad \gamma_{\max} > \gamma_e > \gamma_{\min}$$

$$K_0 = \frac{\tilde{u}_e}{m_e c^2} \frac{2-s}{\gamma_{\min}^{2-s} - \gamma_{\max}^{2-s}} \qquad 2 < s < 3$$

$\gamma_{\min}, \gamma_{\max}$ and s are fixed parameters.

=> effects of cooling/heating only through normalization !

Synchrotron emission

Uniform comoving specific intensity at the cylinder surface:

$$\tilde{I}_{\tilde{\nu}} = \frac{\tilde{j}_{\tilde{\nu}}}{\tilde{\alpha}_{\tilde{\nu}}} \left(1 - e^{-\tilde{\alpha}_{\tilde{\nu}} \langle \tilde{l} \rangle}\right)$$

Use of standard analytical formulae for $j_{\tilde{\nu}}$ and $\alpha_{\tilde{\nu}}$

for electrons with a power-law energy distribution.

Instantaneous flux emitted by the cylinder (in observer's frame):

$$F_{\nu} = \frac{A_{\perp}}{D^2} \delta^3 \tilde{I}_{\tilde{\nu}}$$

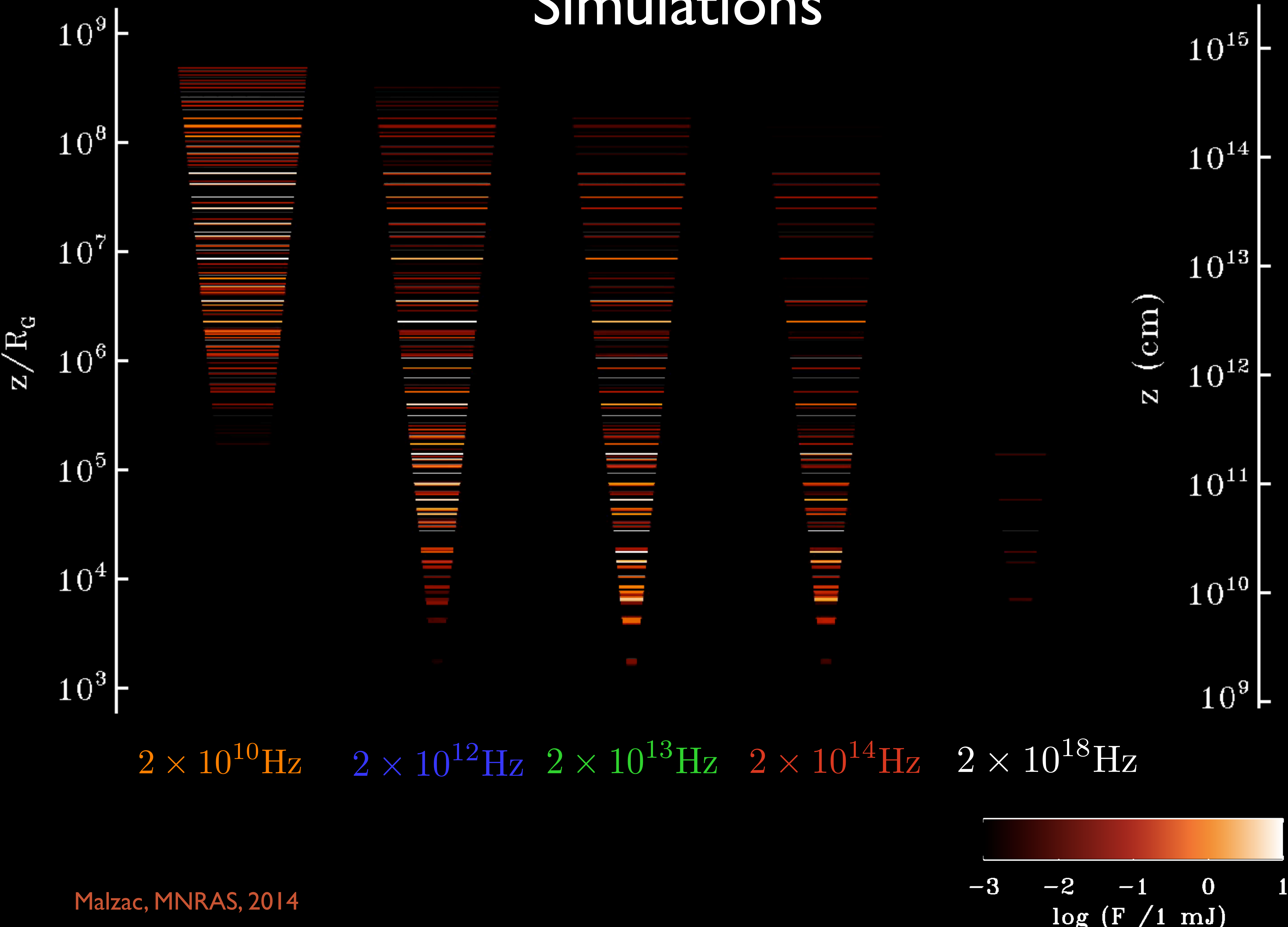
Instantaneous flux received from the shell:

$$F_{s\nu}(t_r) = \int_{t_0}^{t_1} F_{\nu}(t') g_l(t', t_r) dt'.$$

The code provides an average of the flux over specified exposure times $\Delta_r = t_f - t_i,$

$$\bar{F}_{\nu} = \int_{t_i}^{t_f} \frac{F_{s\nu}}{\Delta_r} dt_r$$

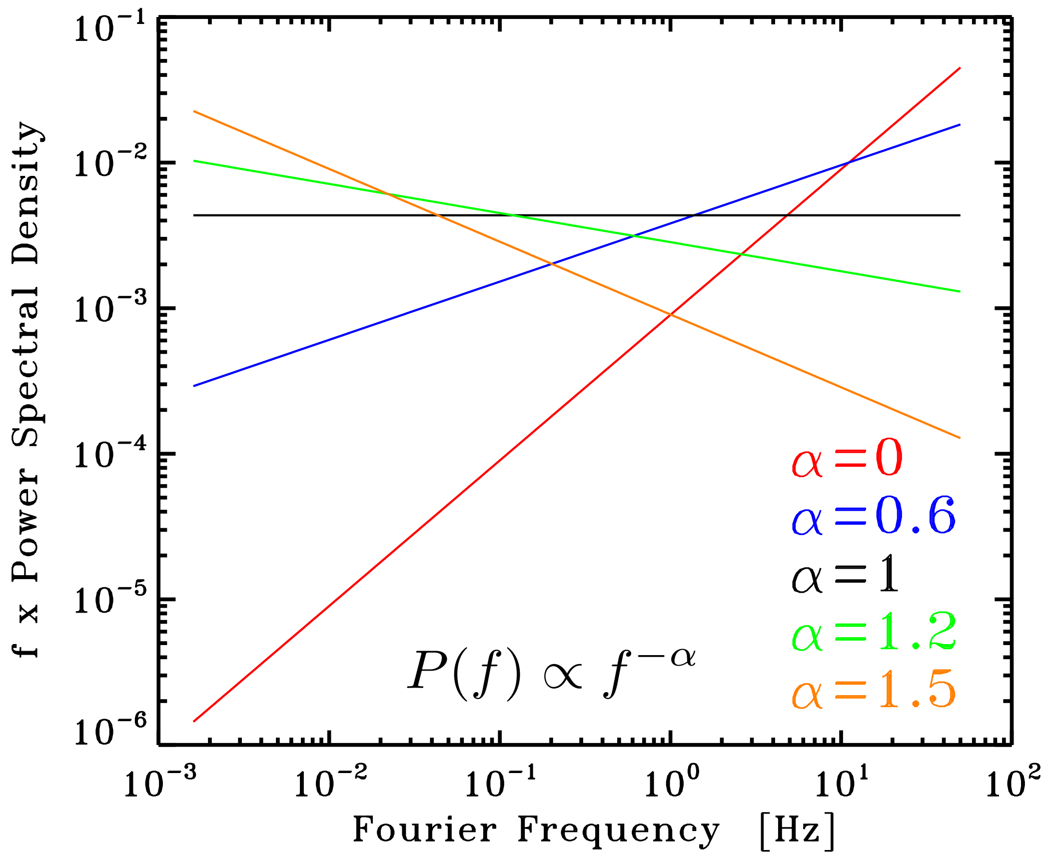
Simulations



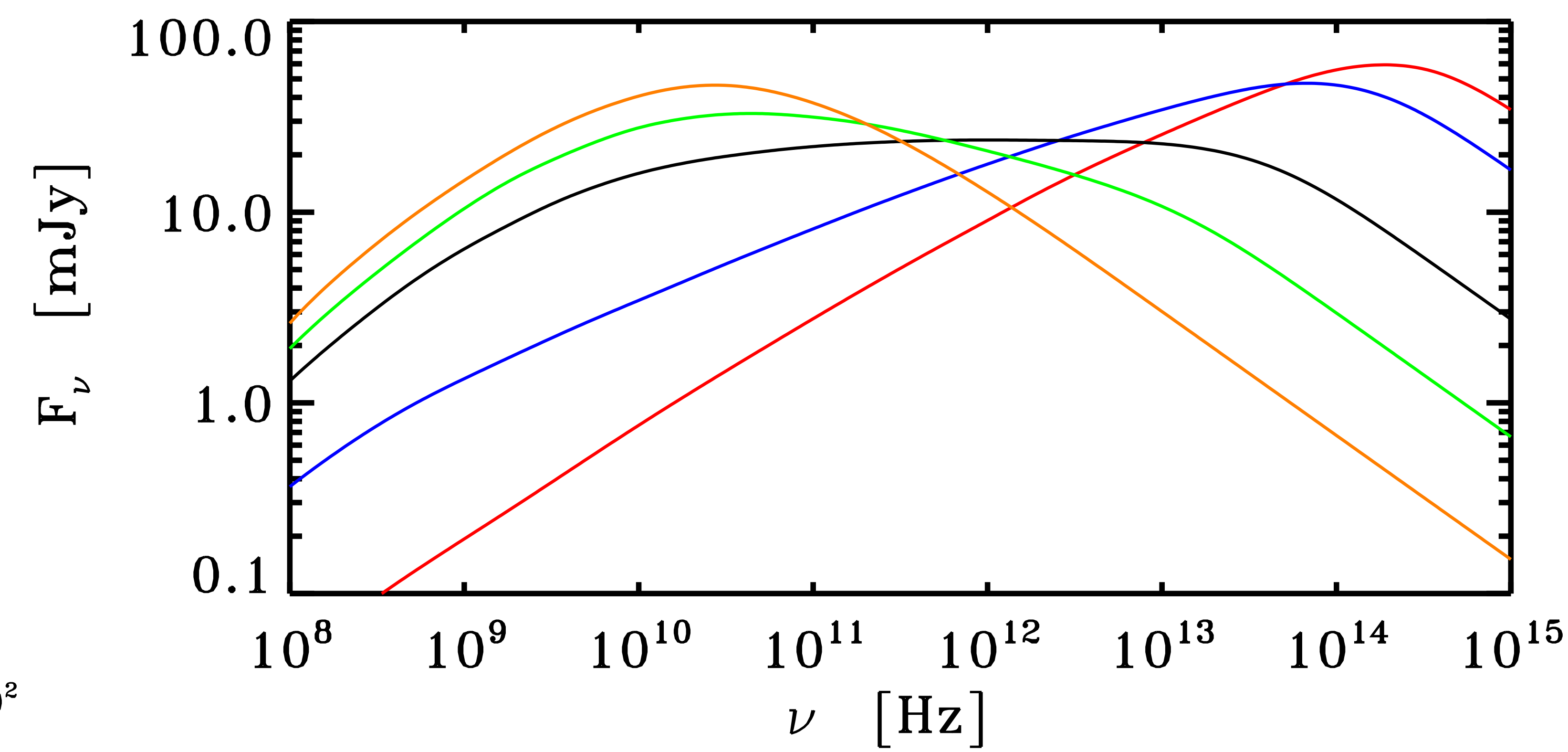
Malzac, MNRAS, 2014

Can shock dissipation balance energy losses ?

- Dissipation profile and SED sensitive to Fourier PSD of input Lorentz factor fluctuations



PSD of Lorentz factor fluctuations



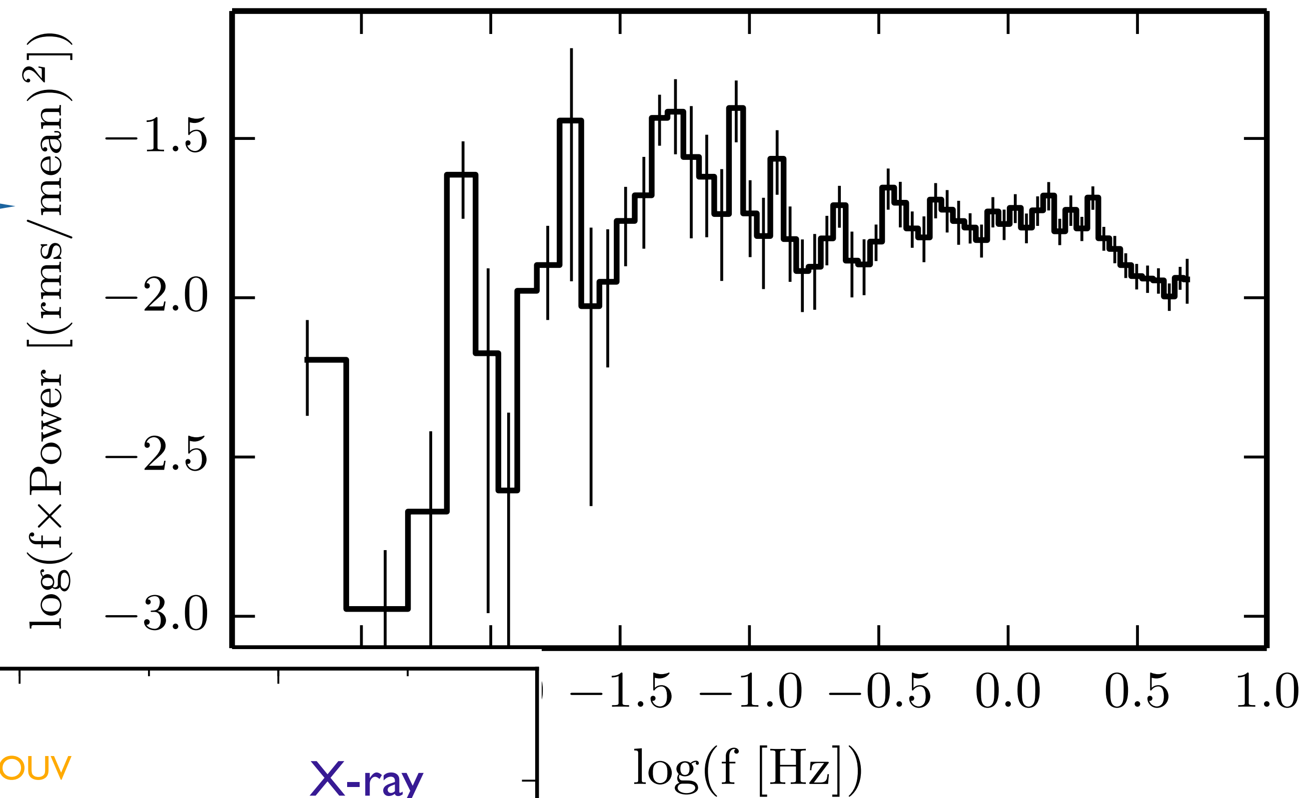
Spectral energy distribution

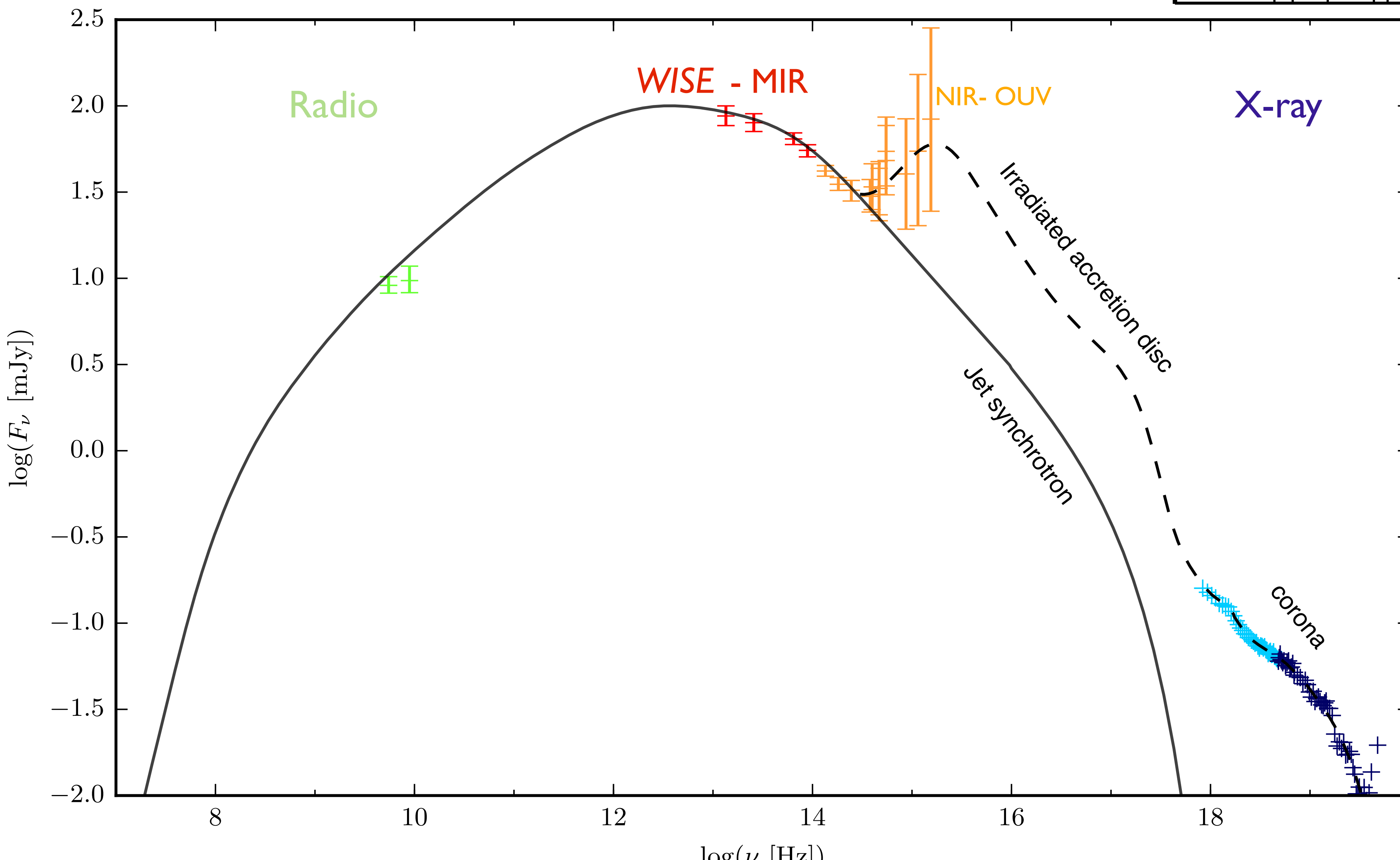
➡Flat radio-IR spectra produced for flicker noise Lorentz factor fluctuations

Malzac, MNRAS, 2013

- Jet Lorentz factor fluctuations driven by accretion flow variability which is best traced by X-ray light curves

Fourier PDS of X-ray light curve
=
Power spectrum of Lorentz factor fluctuations

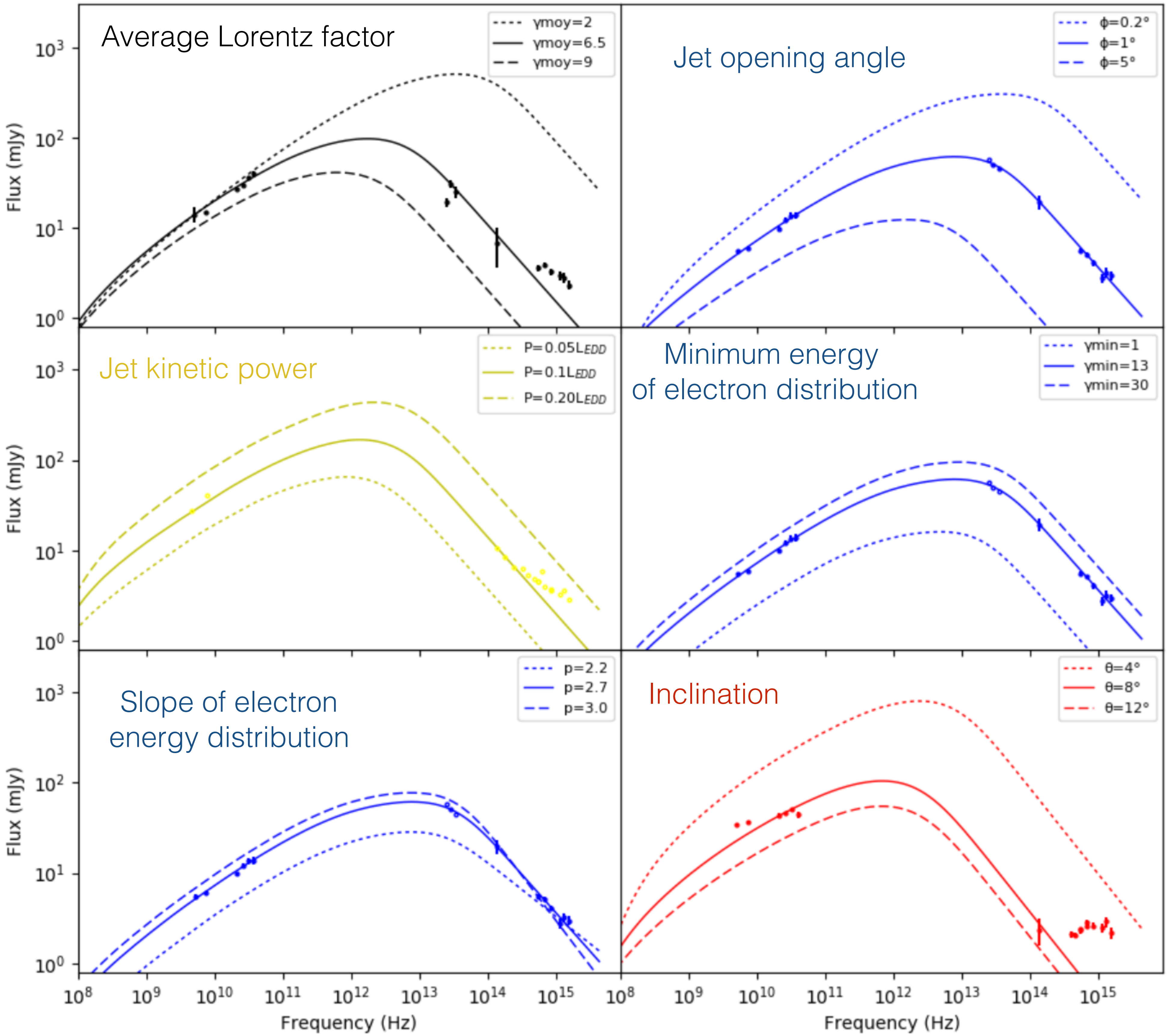




Jet SED

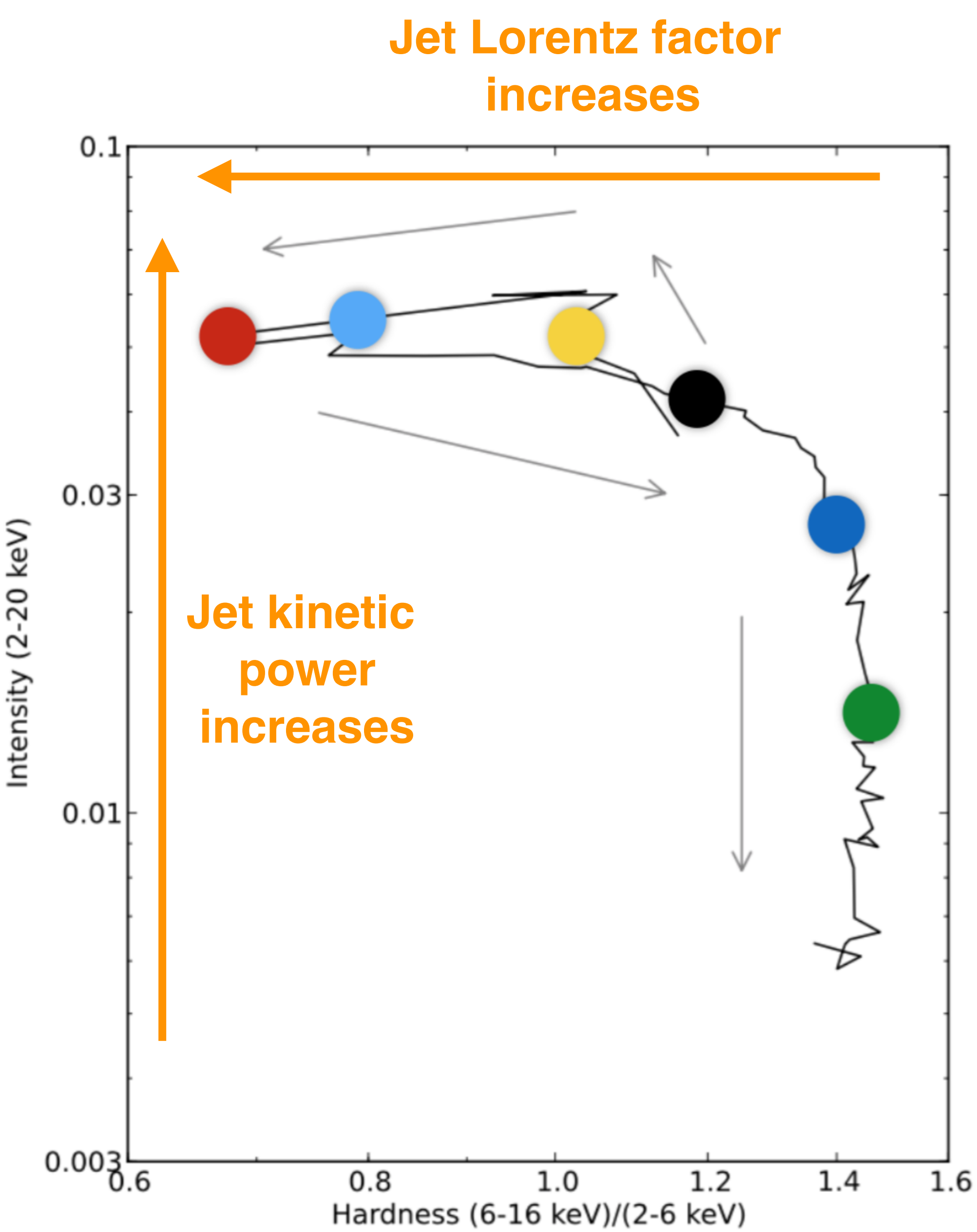
Drappeau, et al. MNRAS, 2015

Effects of parameters on SED

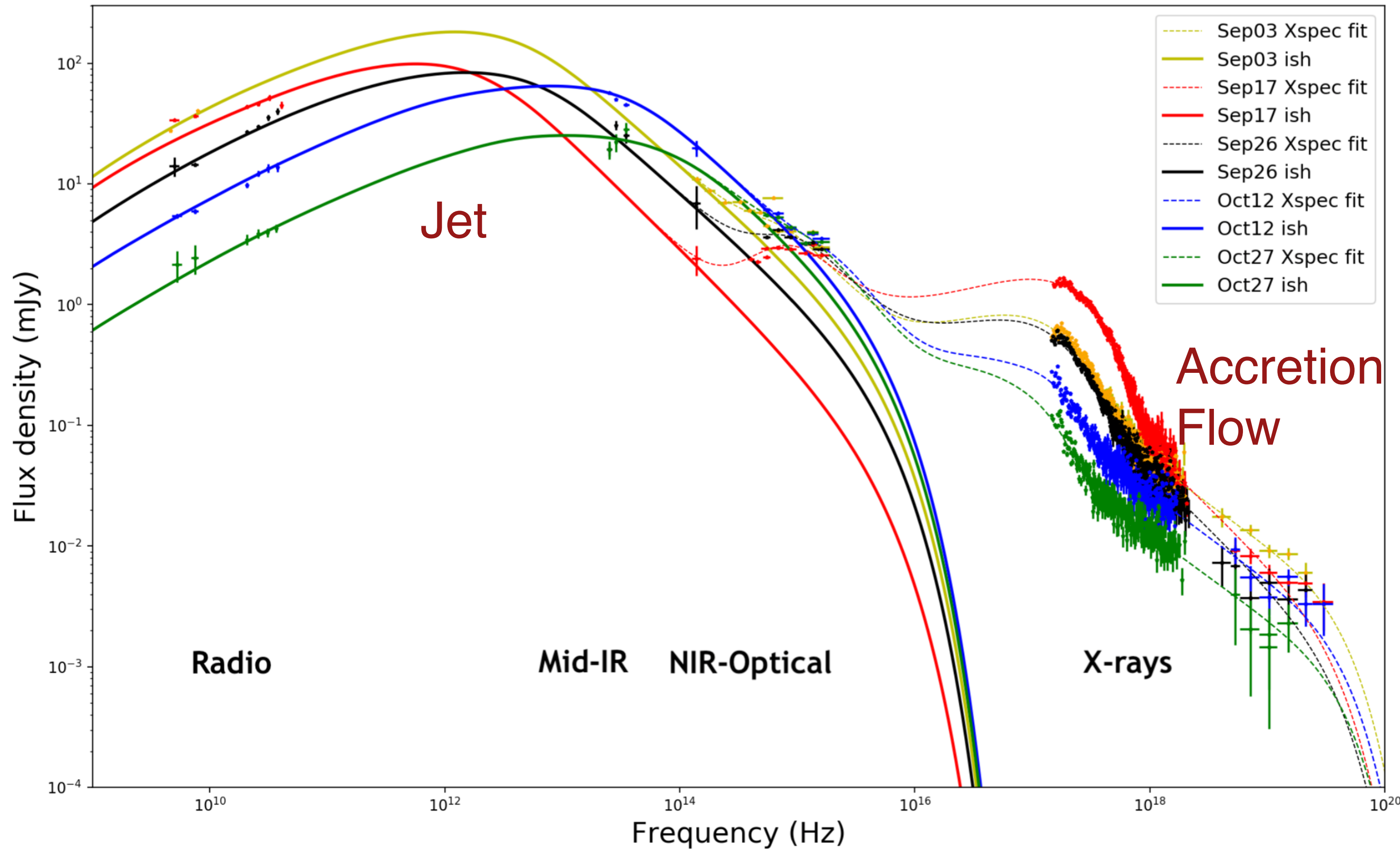


➡ Large parameter degeneracy

Modeling the jet SEDs of MAXI J1836-194



2011 Outburst

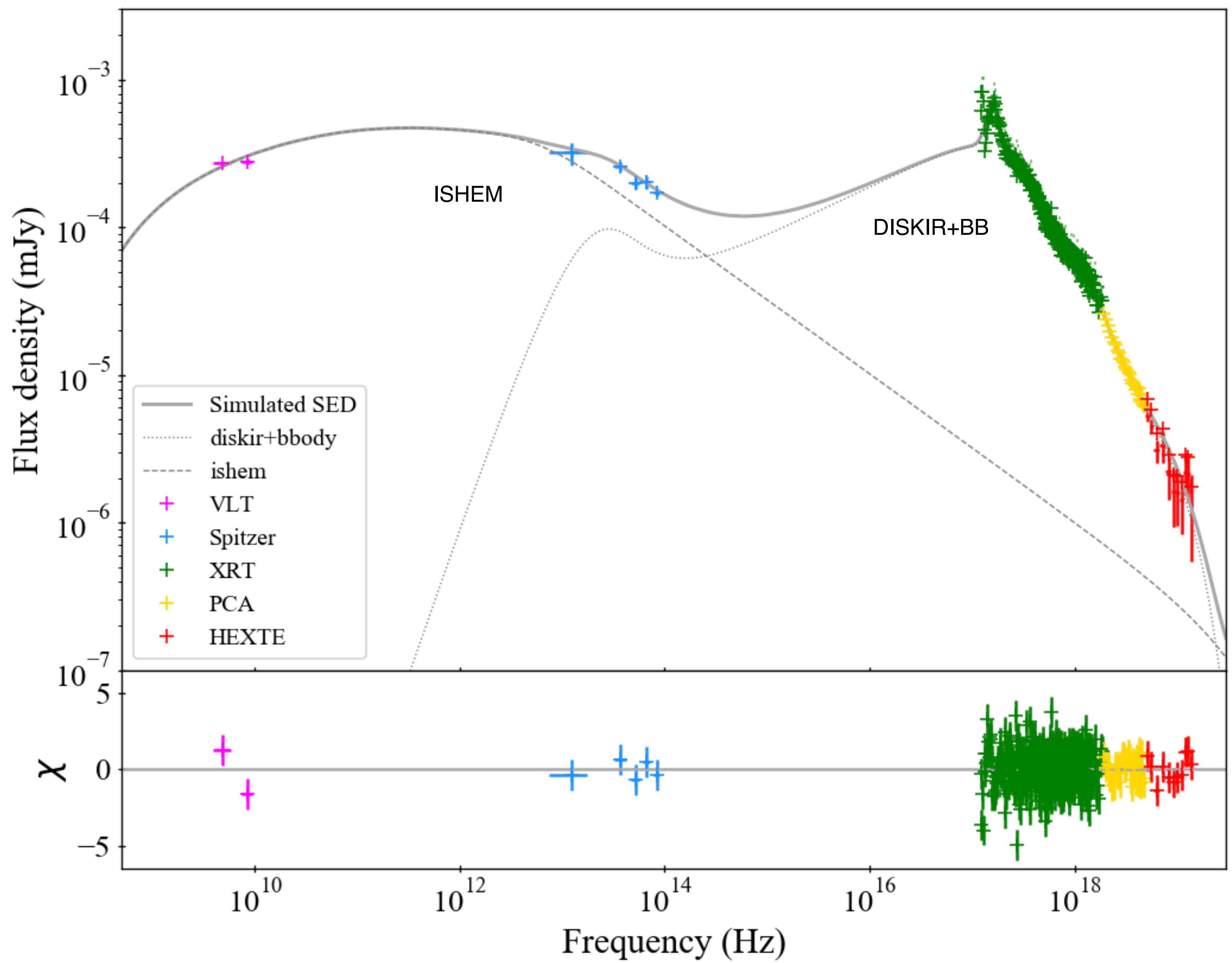


Data from Russell. et al (2013)
'fitted' with ISHEM
using the observed X-ray fluctuations as input

Péault et al. MNRAS 2018

Neutron star sources: the case of 4U 0614+091 (preliminary)

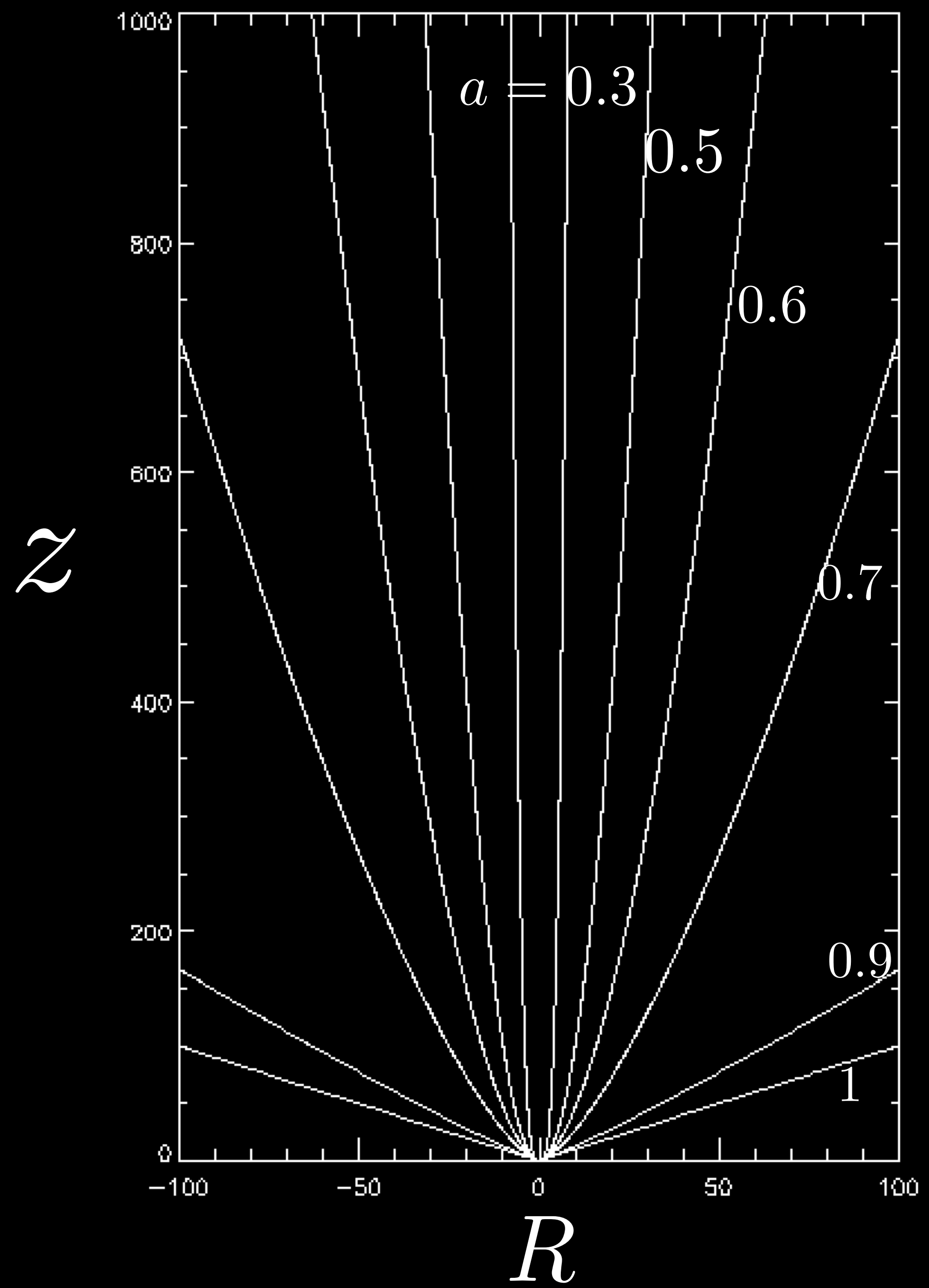
- System in persistent hard state with radio emission attributed to radio jet. (Migliari et al. 2010)

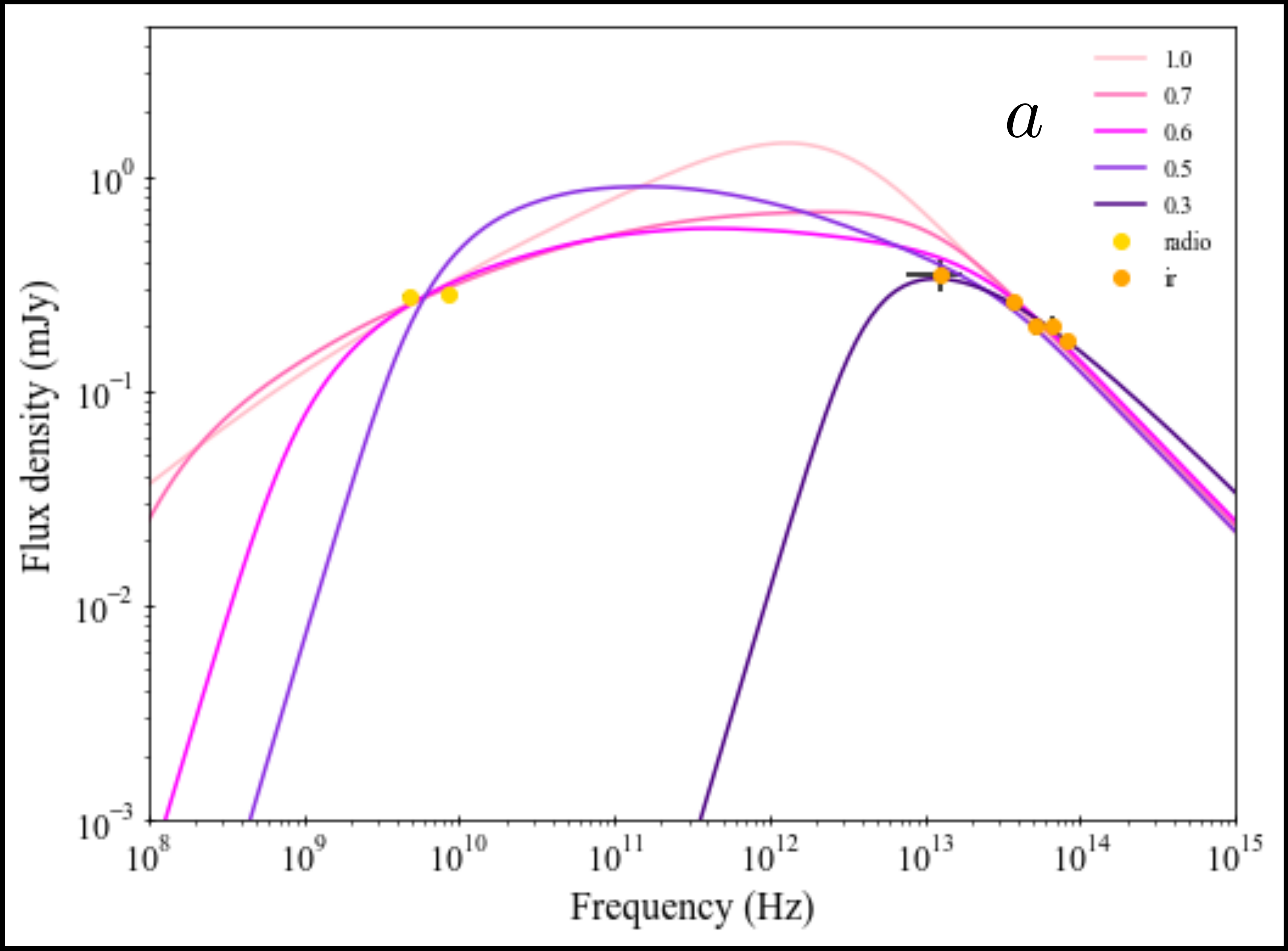


- Fitting the SED requires departure from conical jet geometry (Marino et al. in prep.)

Effects of jet geometry on jet SED

$$R \propto z^a$$

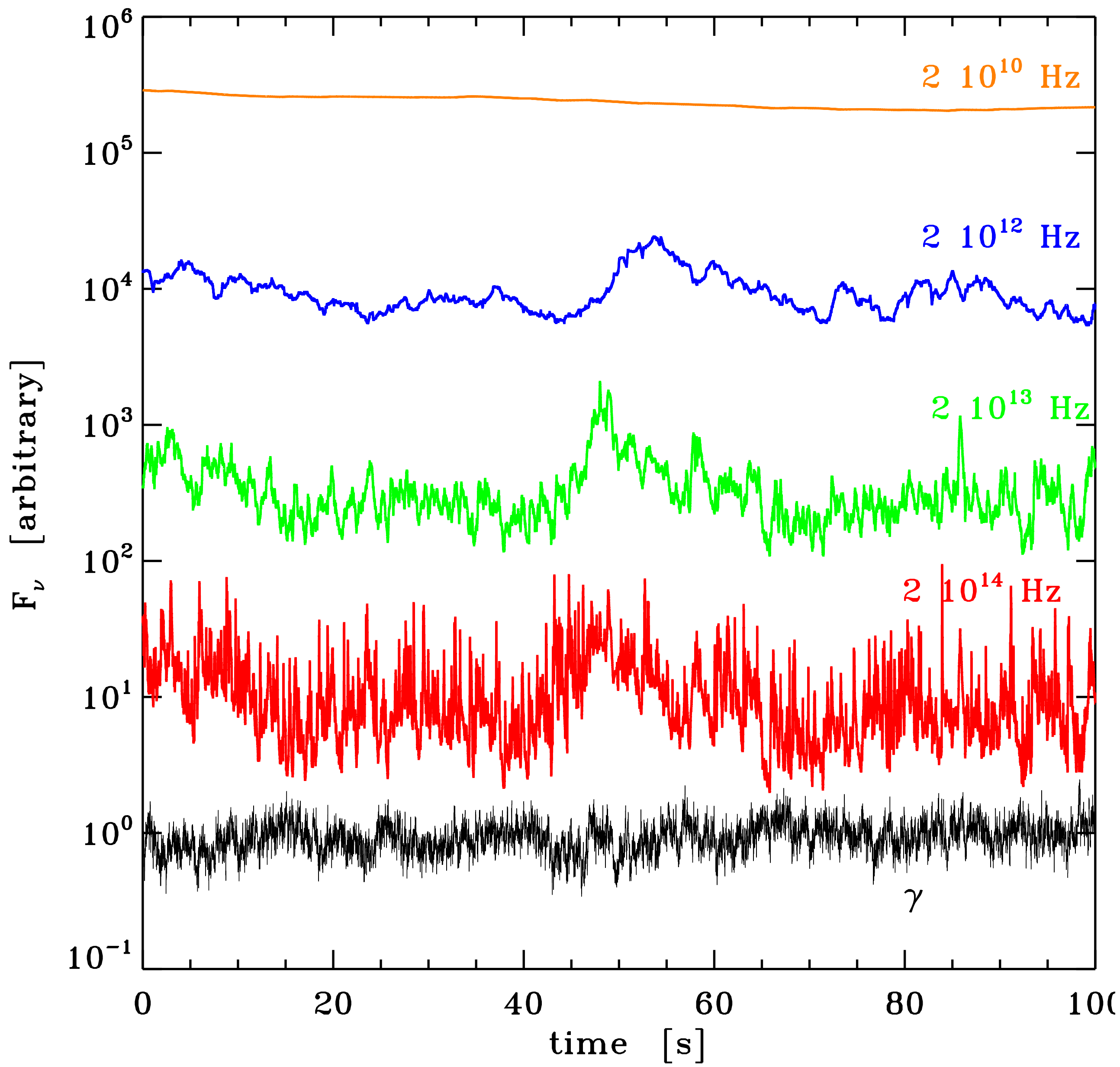




- **More collimated jet geometry in neutron stars ??**

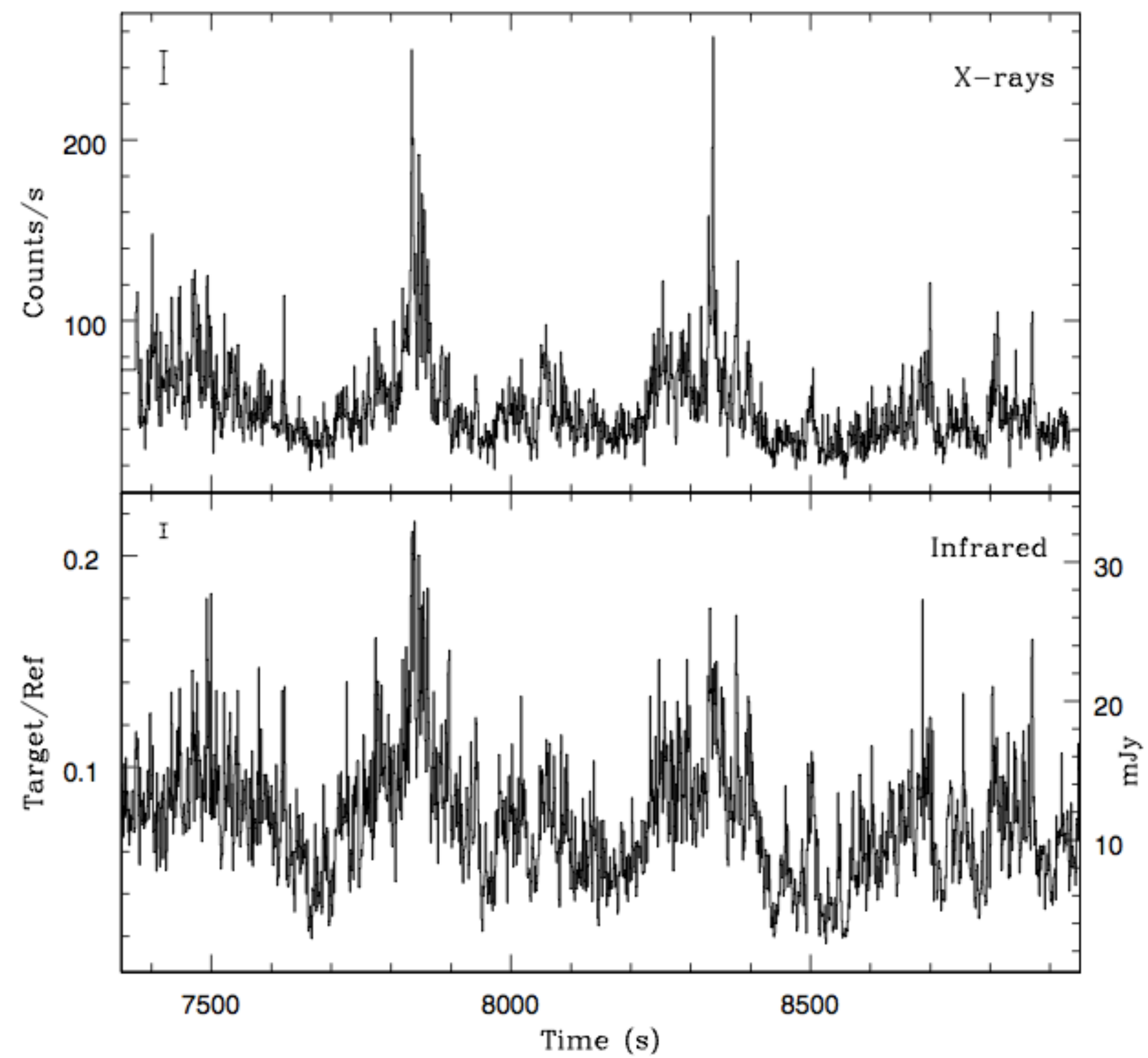
Fast variability from jets

Simulation



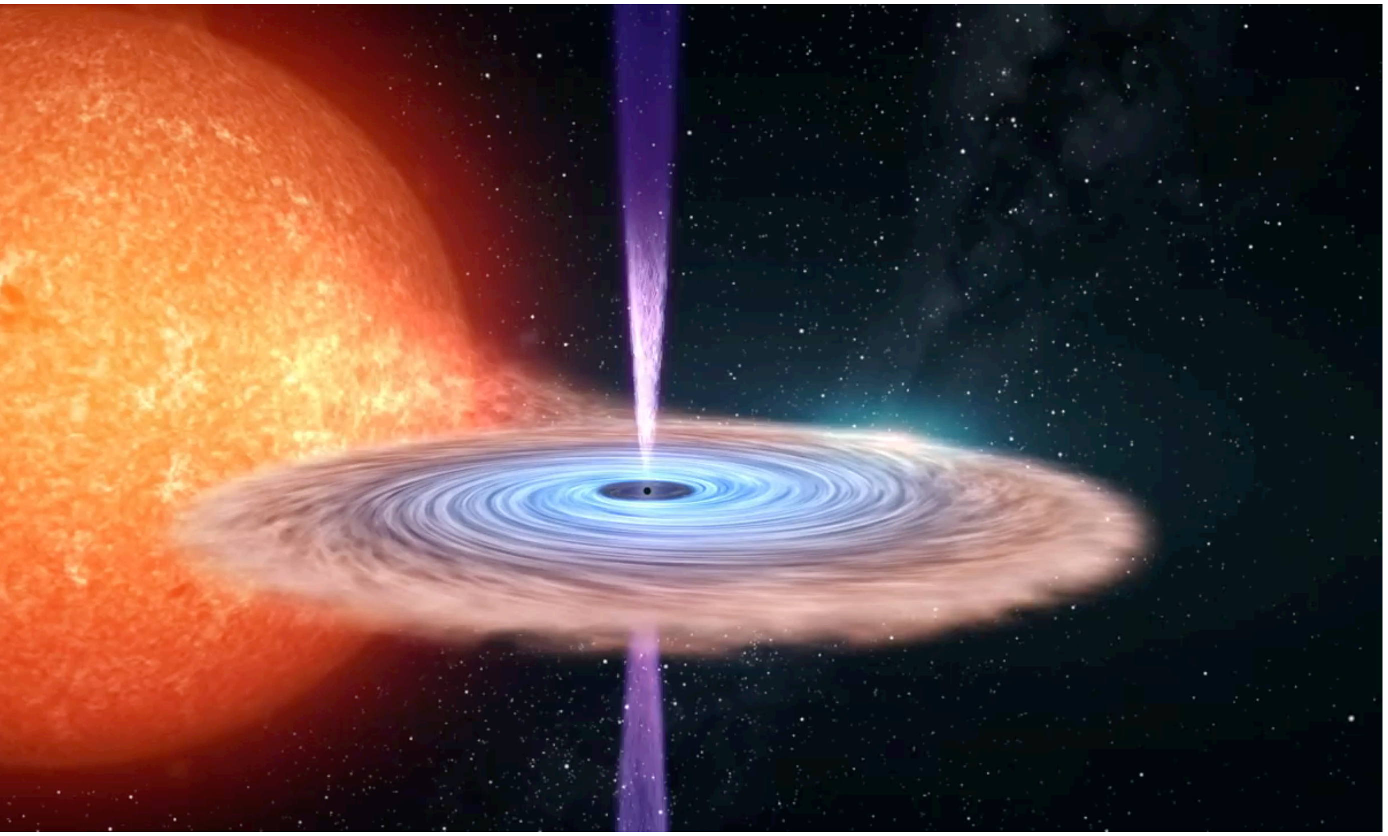
Malzac, MNRAS, 2014

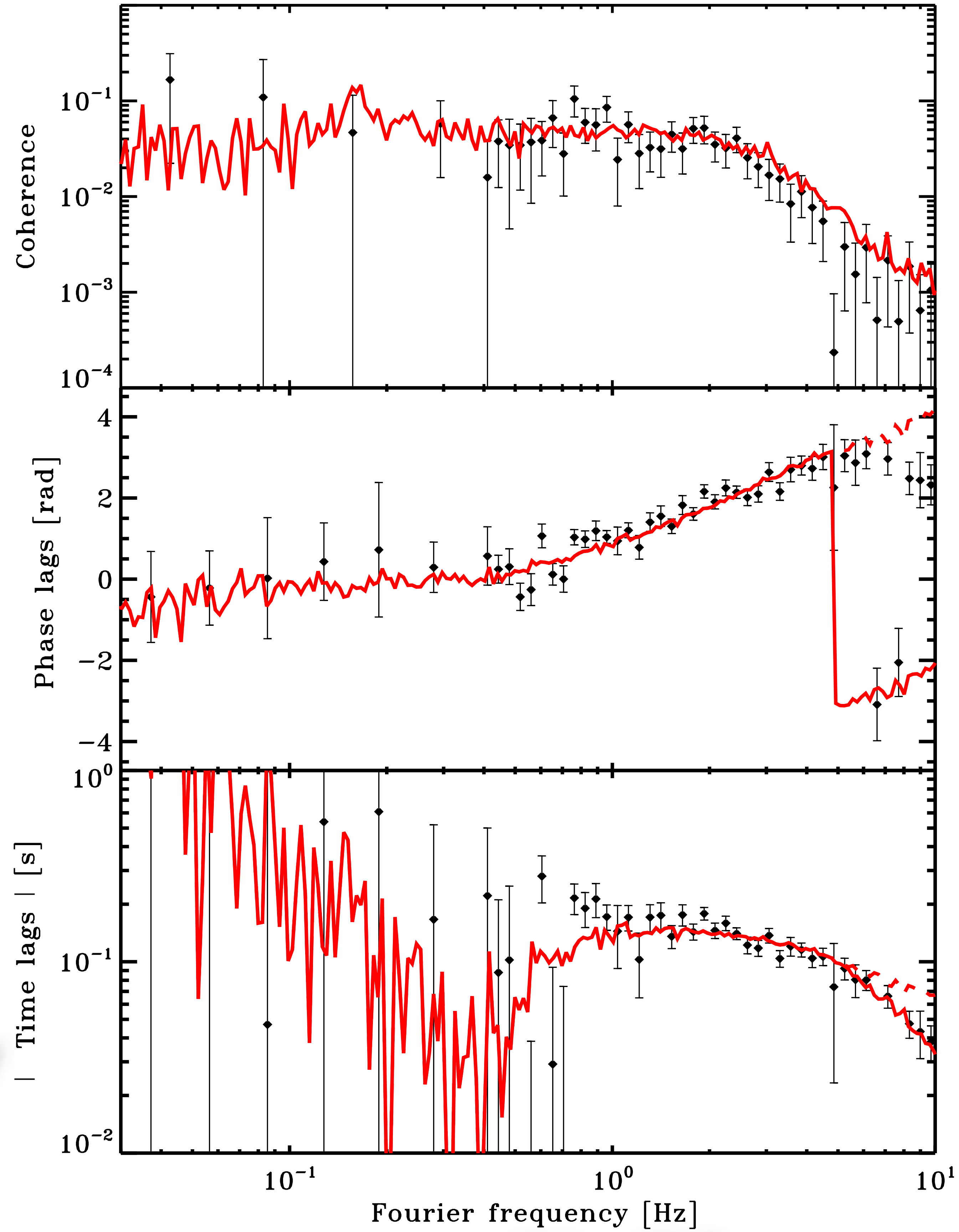
Observation



Casella et al. 2010

Fast IR /X-ray correlations in GX339-4





Malzac+2018

- IR vs X-ray Fourier coherence, and lags from Kalamkar et al. (2016) data

- Model:

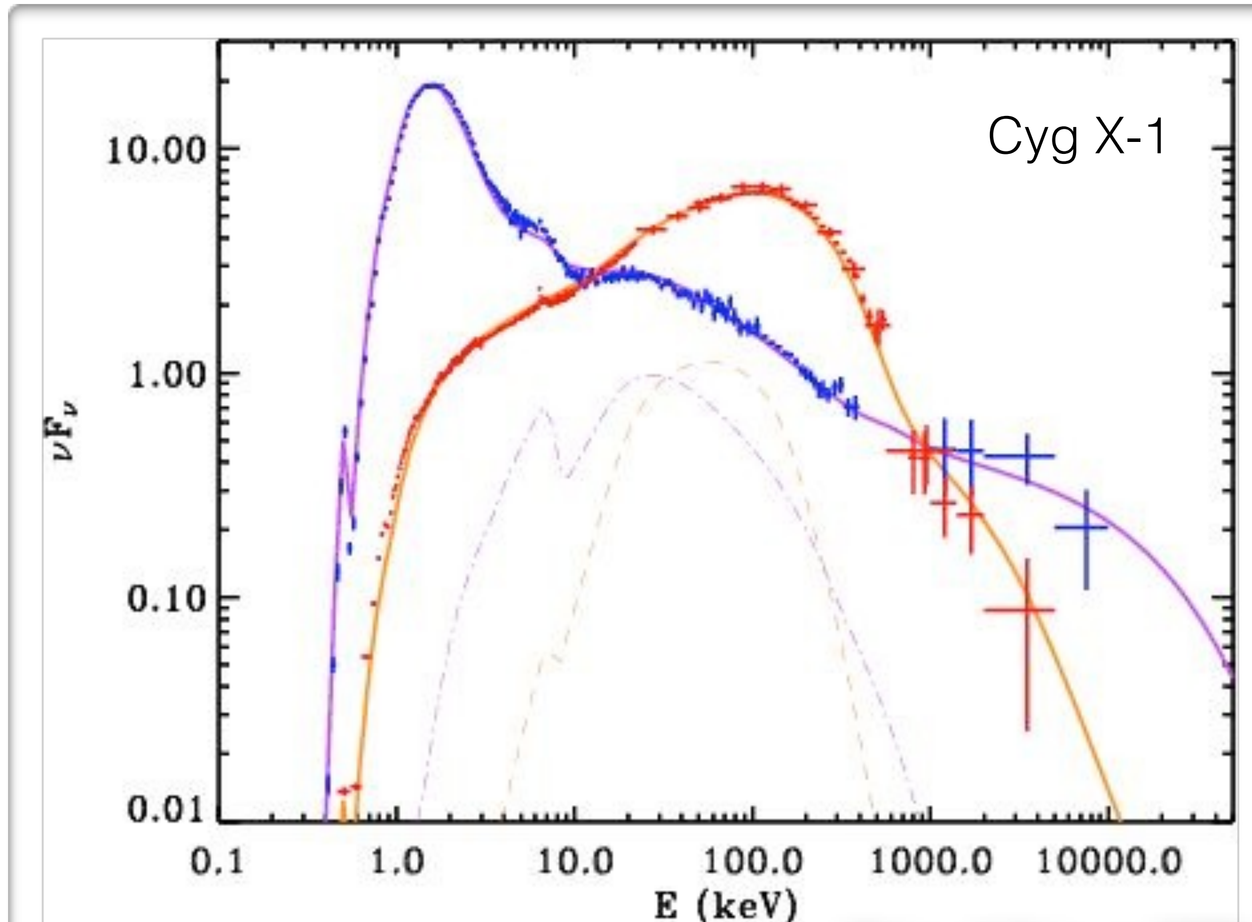
- IR light curve from same model used for SED and IR PSD.

- X-ray light curve: $L_X(t) \propto \Gamma(t) - 1$

Contribution of jets at high energies

- Emission in excess of thermal comptonization detected in several sources in hard state.
(Mc Connell et 2002; Del Santo et al. 2008)

- IC emission from non-thermal electrons in the corona (hybrid thermal/ non thermal models)
(Coppi & Poutanen 1998)

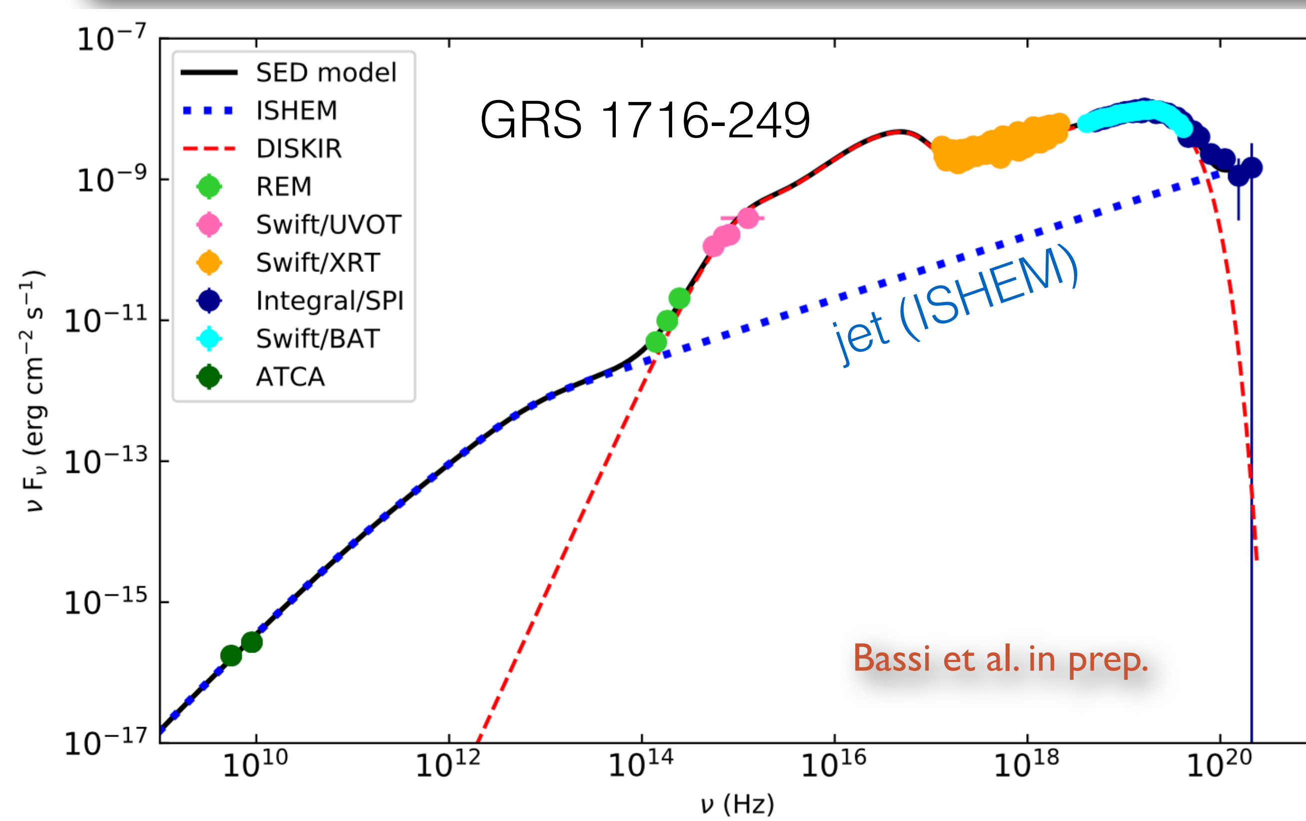


(Malzac & Belmont 2009)

- INTEGRAL polarization measurements in Cyg X-1 suggests excess is strongly polarized (PD: 76%+/-15% above 230 keV).

- Jet synchrotron emission ?

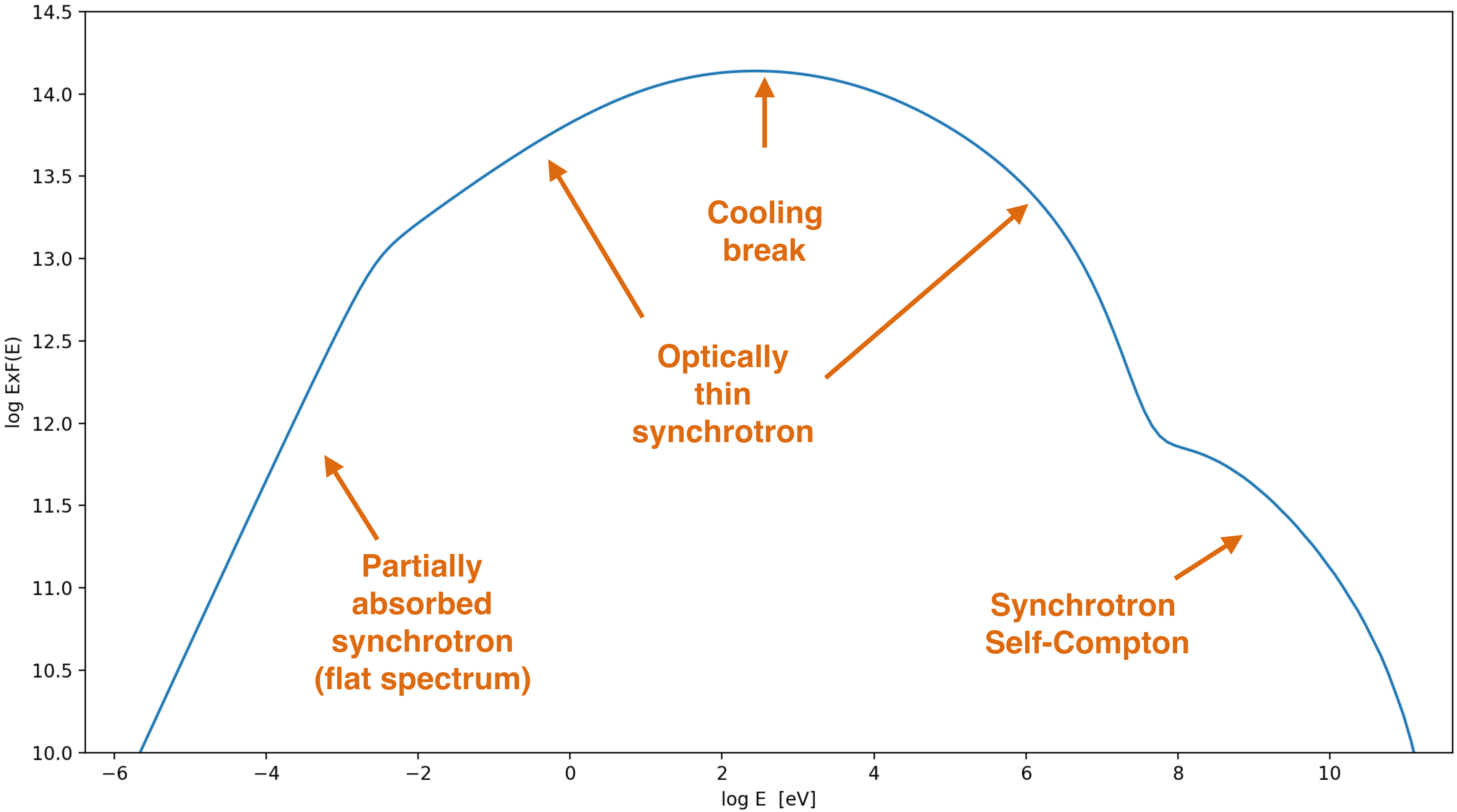
(Jourdain et al. 2012, Laurent et al 2012, but see Zdziarski et al. 2017)



Bassi et al. in prep.

Radiation cooling and inverse Compton (work in progress…)

- Resolution of kinetic equations to calculate evolution of particle and photon distribution during the propagation of the shocked shells



Summary

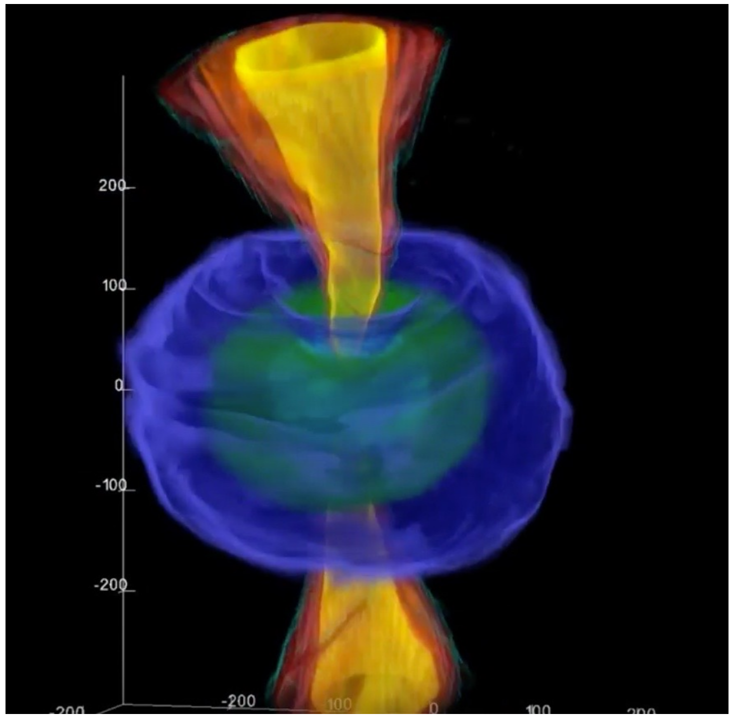
- Possible connection between X-ray power spectrum and jet SED: GX339-4 and MAXI J1836 consistent with internal shocks driven by fluctuations of the accretion flow. In NS system 4U 0614+091 a non-conical jet geometry is required to fit the SED.

- Internal shock model predicts strong variability and IR/X-ray correlations similar to that observed in GX339-4.

- Opt/IR/X-ray correlations can unveil the dynamics of accretion and ejection physics. Need to combine accretion flow and jet models

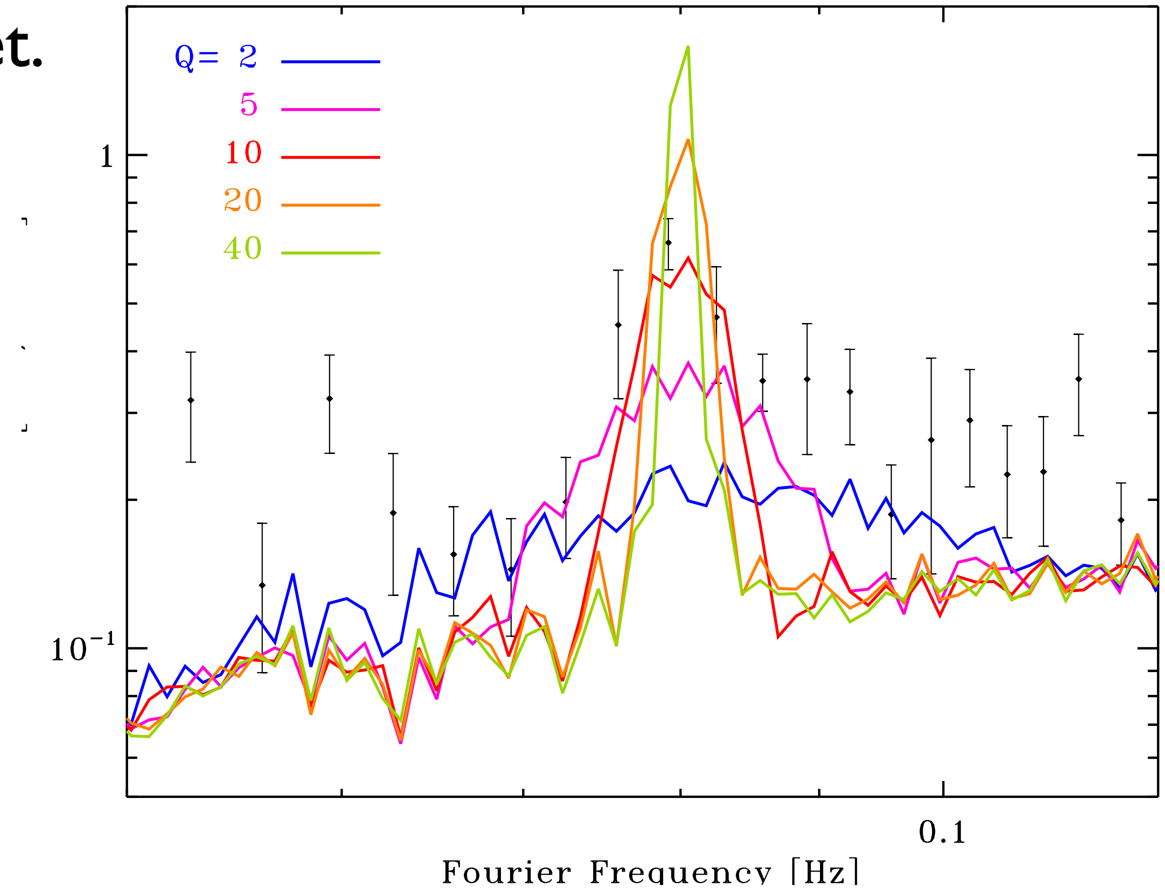
Nature of OIR QPOs

- Synchrotron emission from precessing jet.

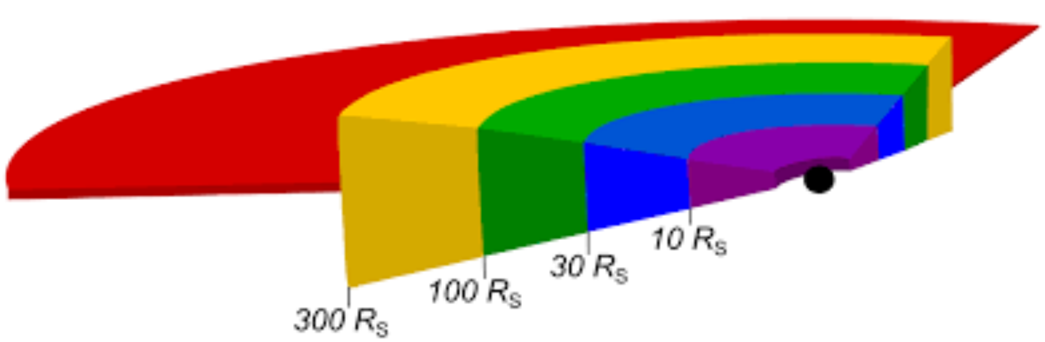


Liska et al. 2018

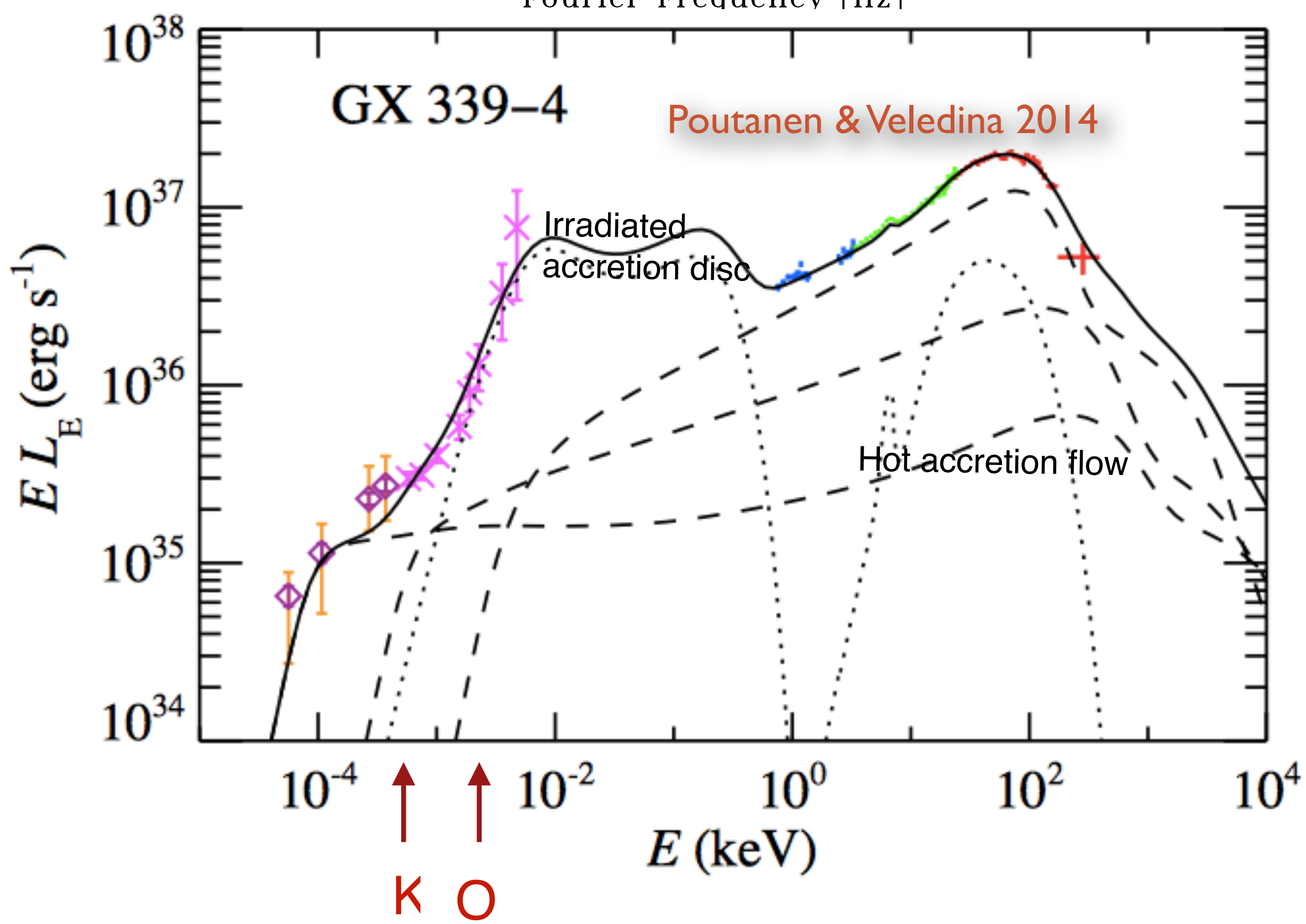
Kalamkar et al. 2016; Malzac et al. 2018



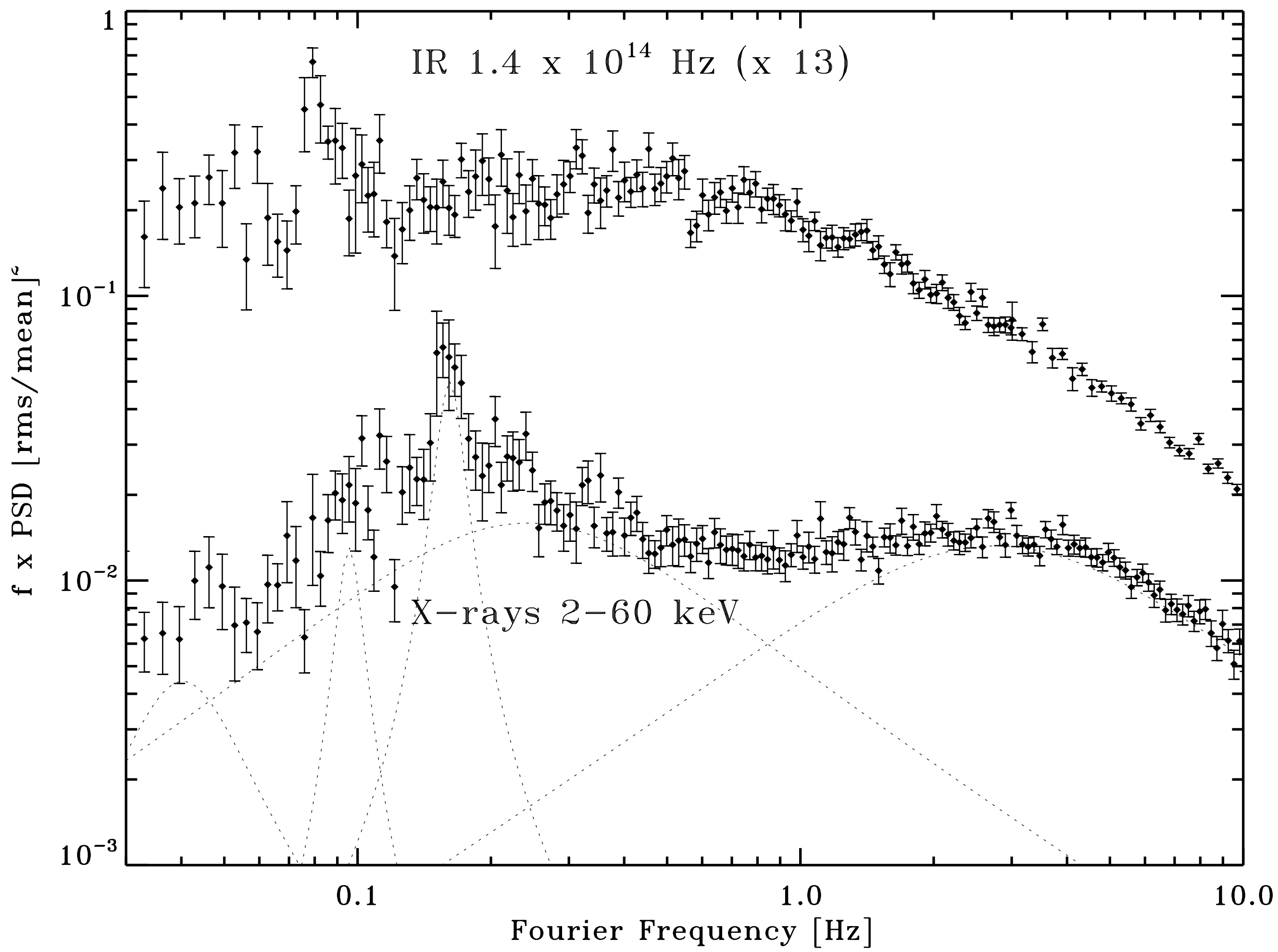
- Synchrotron from non-thermal particles in the same precessing hot flow that produces the X-ray QPO.



Veledina et al. 2013



The case of the simultaneous X-ray and IR QPO of GX 339-4

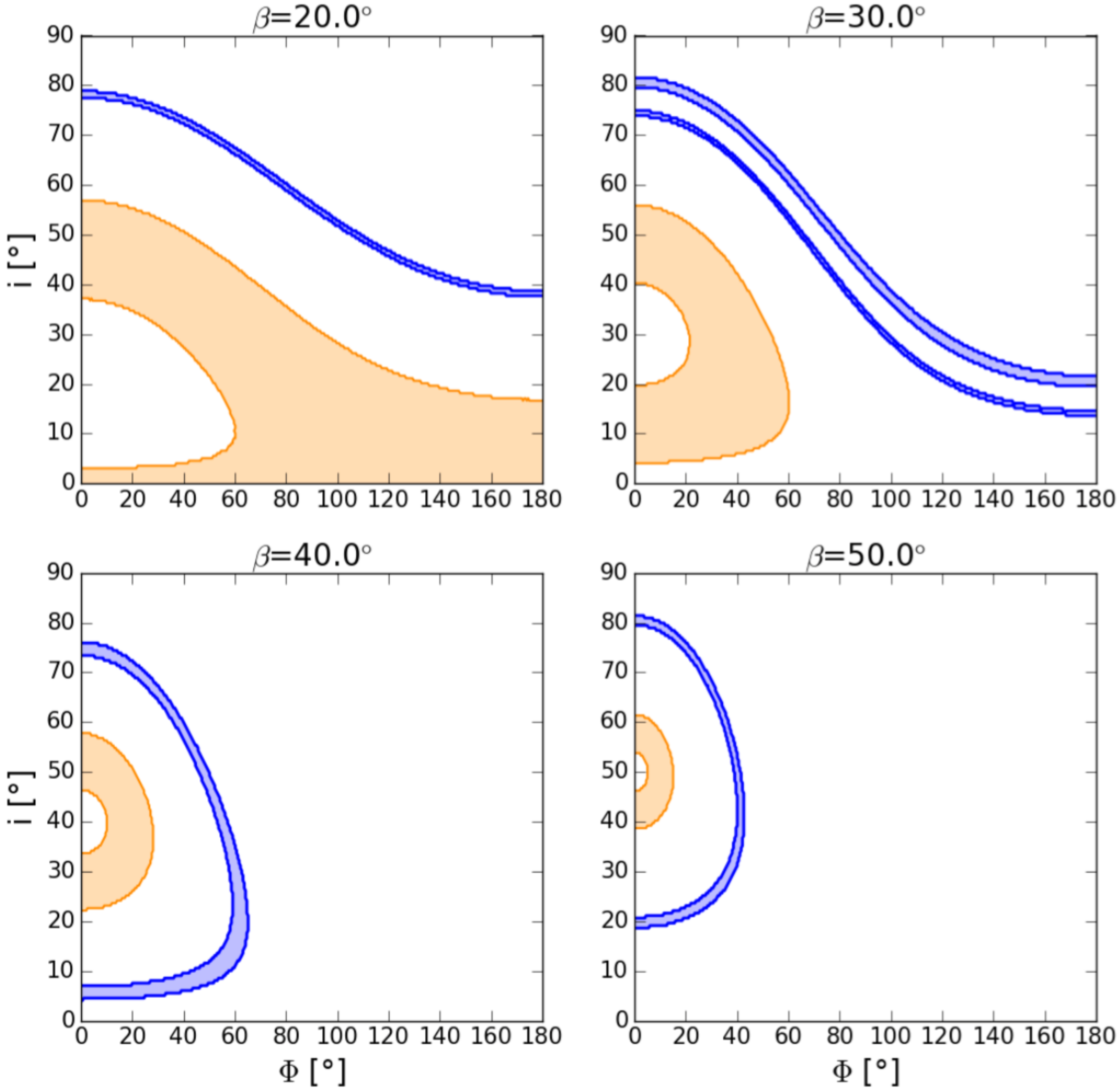


➡ **Main X-ray QPO and IR QPO frequencies are different but in harmonic**

- Precession model: Depending on hot flow geometry, orbital inclination and precession angle, X-ray QPO can be dominated by second harmonic.

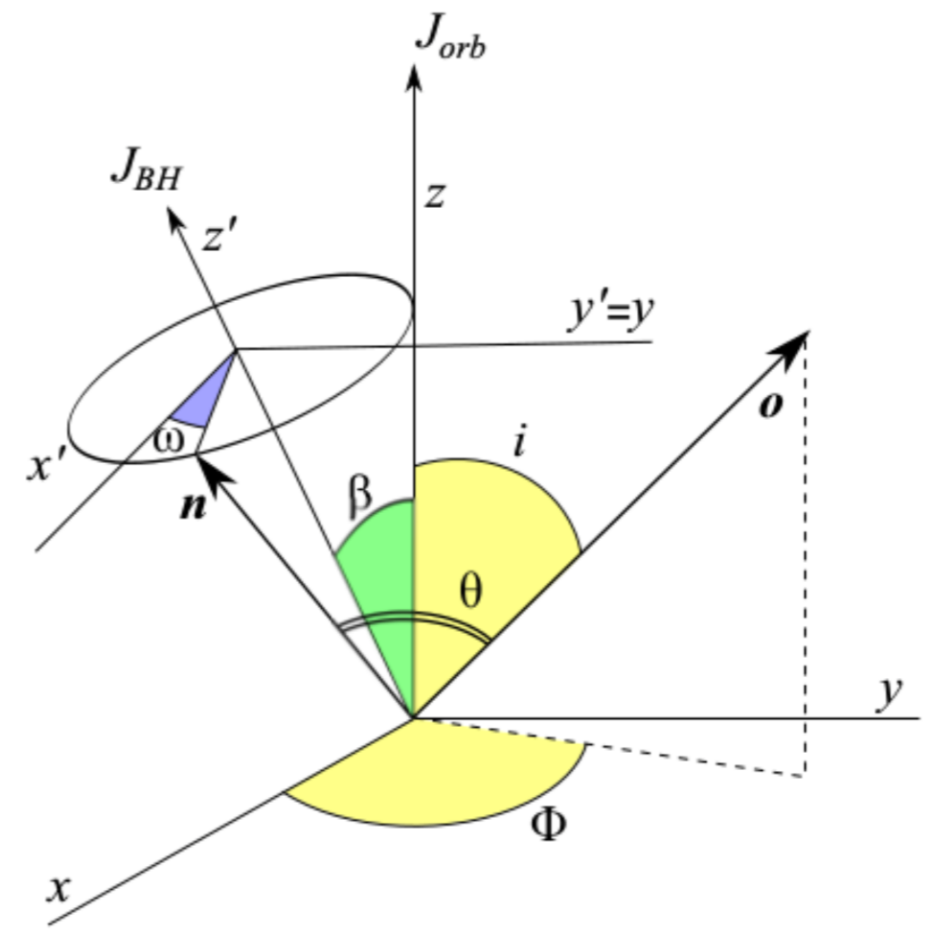
Veledina et al. 2013

The case of GX 339-4:
Combining X-ray and IR QPO information



Assuming X-ray and IR emission are both from hot accretion flow

Calculations based on precessing hot-flow model by Veledina et al. 2013



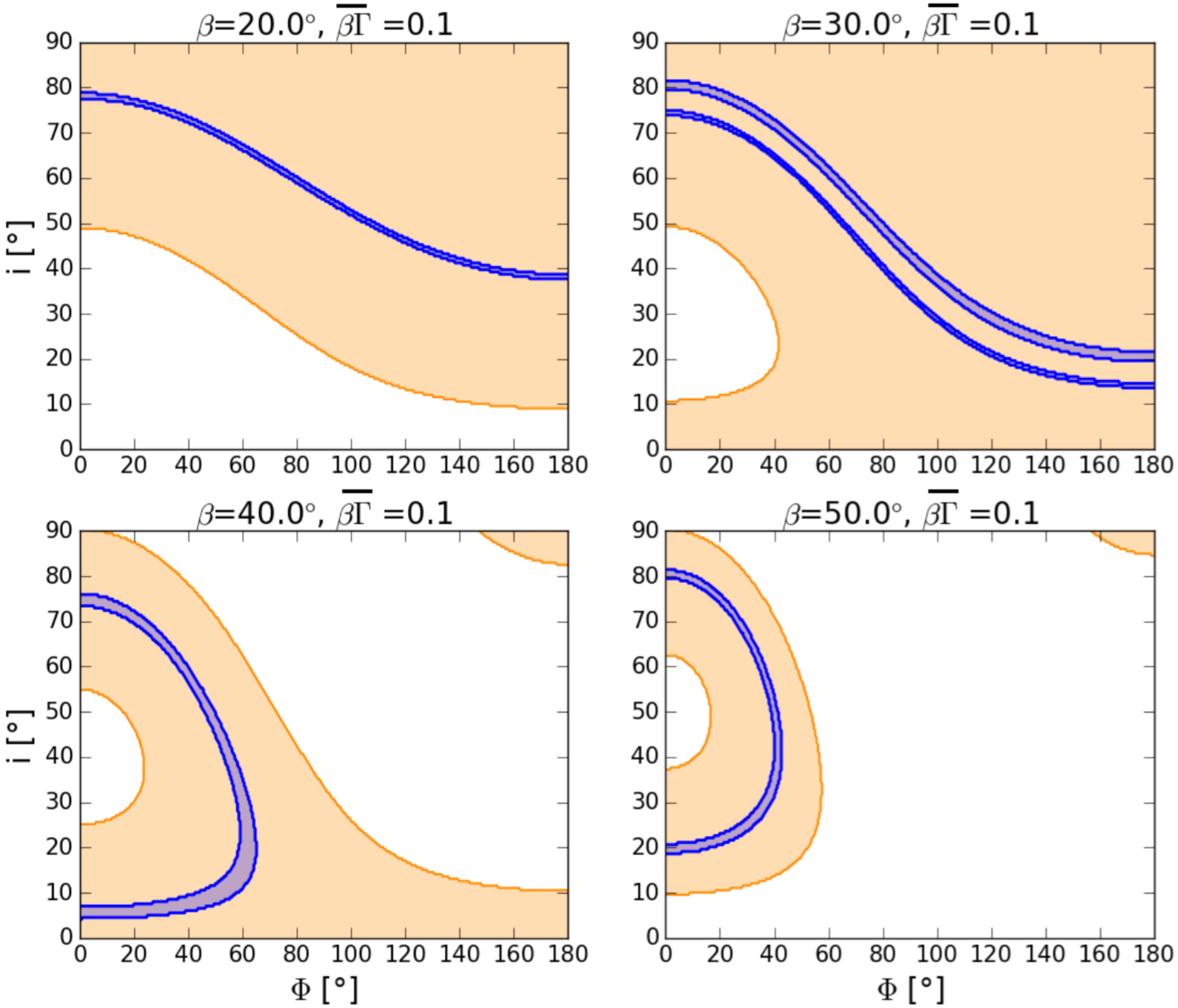
— Amplitude of both fundamental AND harmonic of X-ray QPOs

— Amplitude of IR QPO reproduced by IR synchrotron emission from hot flow

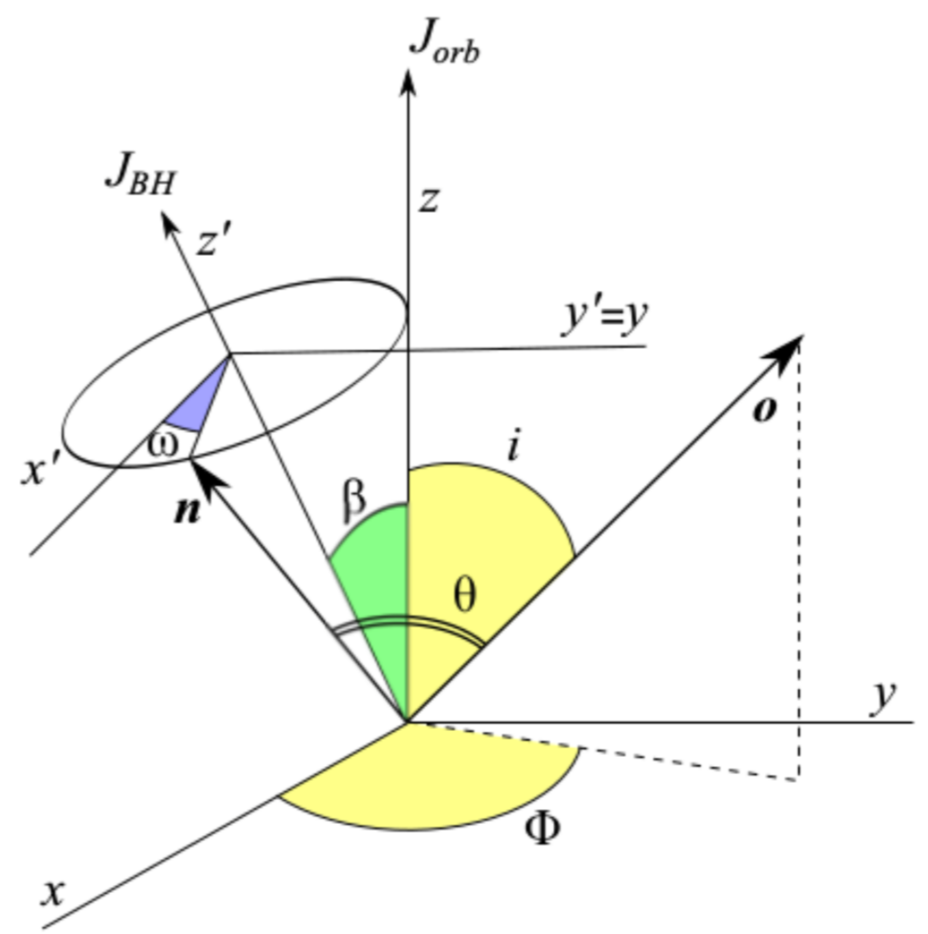
➡ **IR and X-ray QPO amplitudes cannot be reproduced simultaneously**

Boughelilba, Master Thesis

The case of GX 339-4: Combining X-ray and IR QPO information



Assuming X-ray QPO from hot flow
IR QPO from jet precession



— Amplitude of both fundamental AND harmonic of X-ray QPOs produced

— Amplitude of IR QPO produced by IR synchrotron emission from JET

➡ **both IR and X-ray QPOs amplitudes can be reproduced**

➡ **Jet velocity must be < 0.16 c**

Boughelilba's Master Thesis

Scaling of compact jets

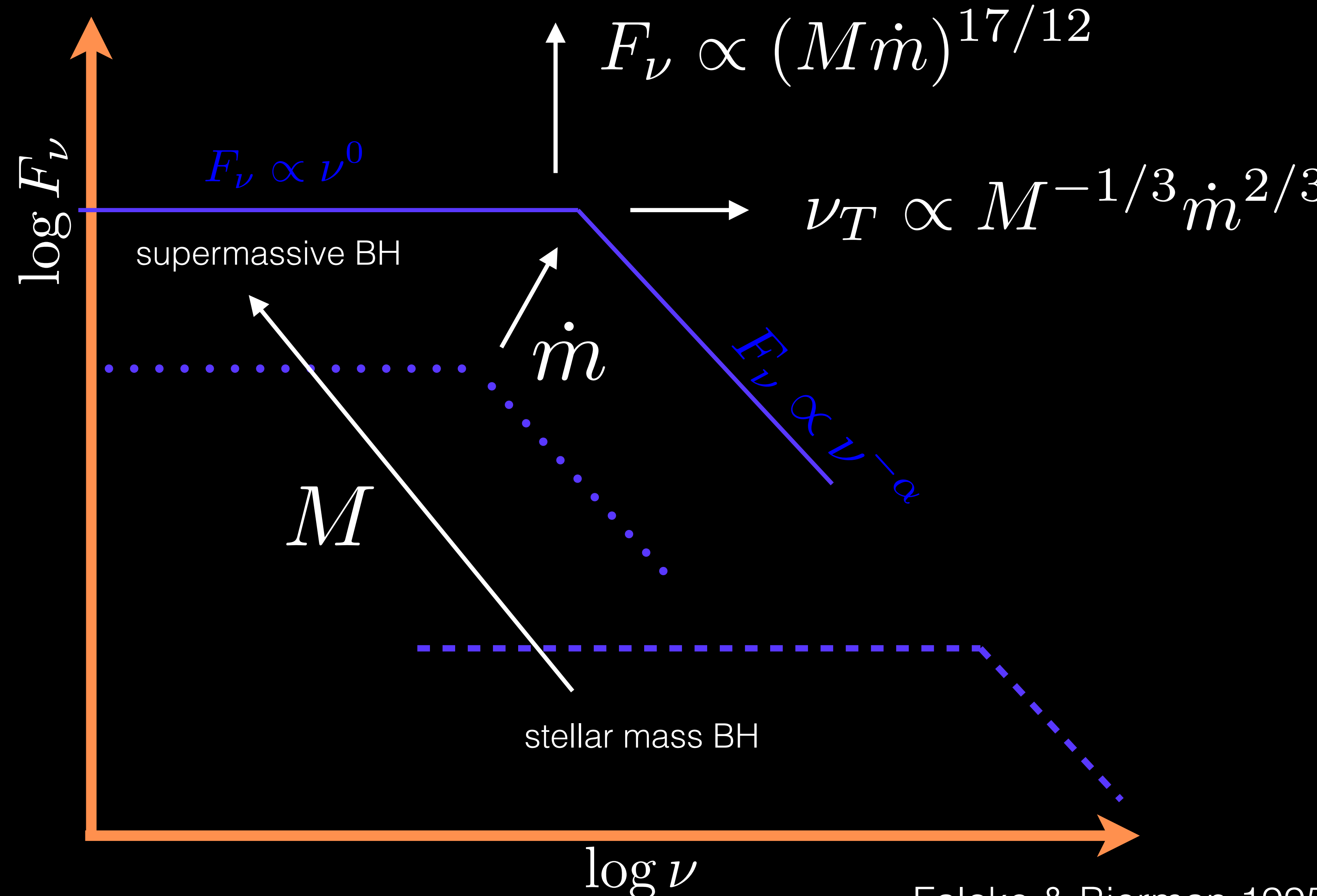
Assuming universal dimensionless parameters, simple scaling laws for the SED can be derived analytically.

Accretion rate in Eddington units: $\dot{m} \propto \frac{\dot{M}}{M}$

Assuming $L_{\rm X} \propto M\dot{m}^{\xi}$

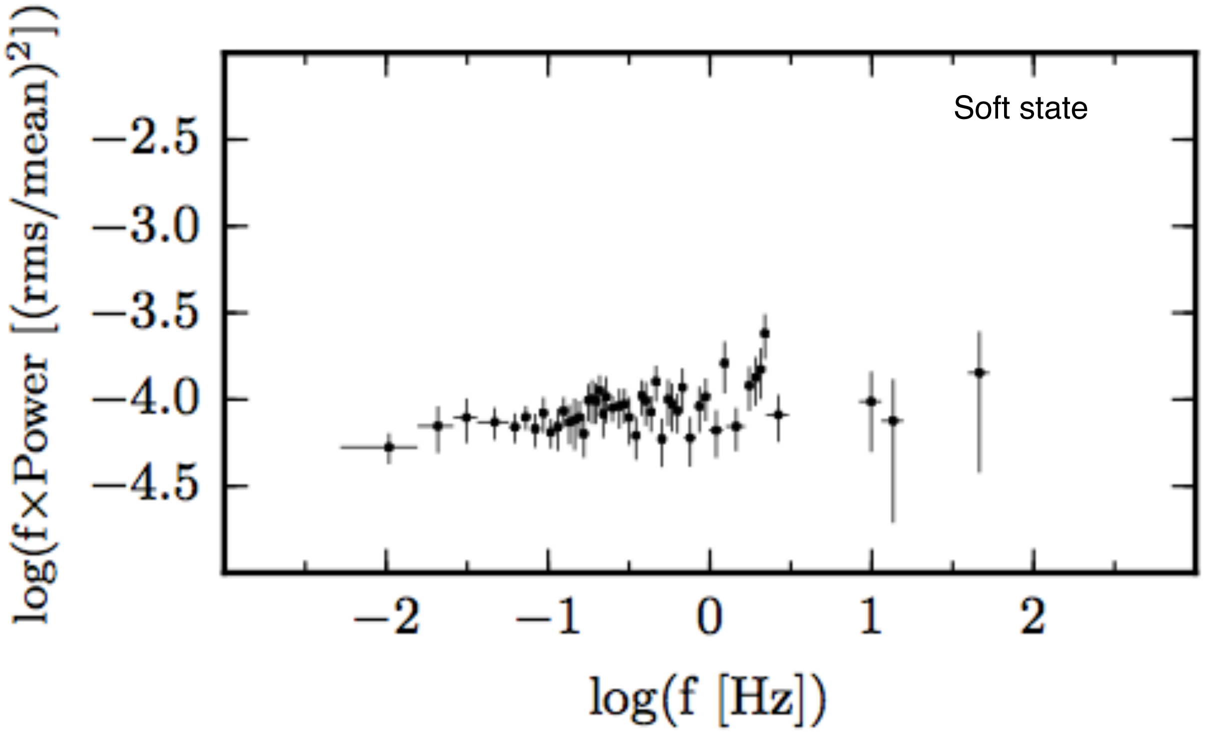
then

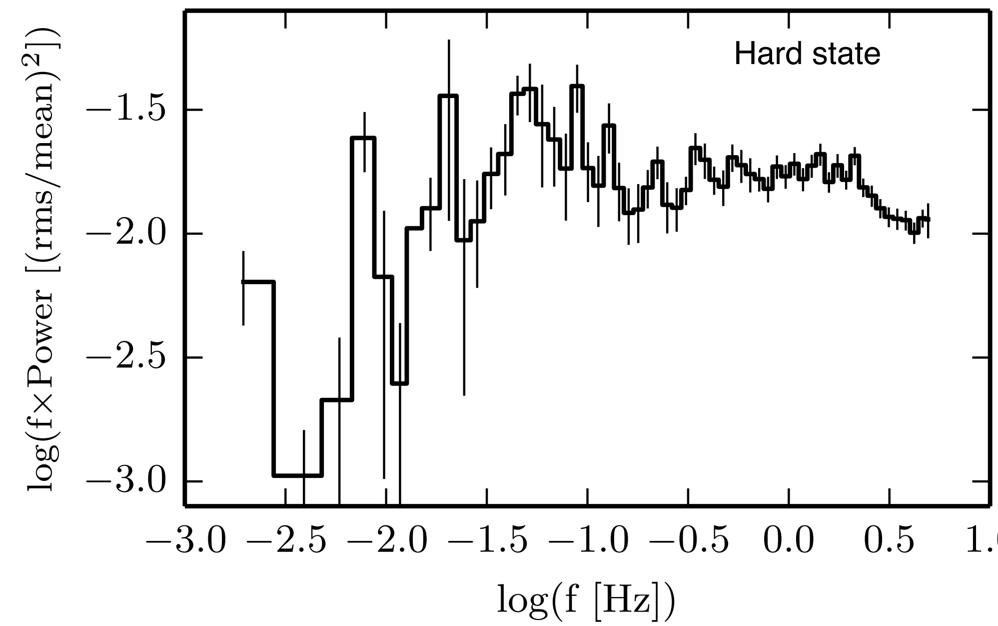
$$\log F_{rad} \simeq 1.4\frac{\xi - 1}{\xi}\log M + \frac{1.4}{\xi}\log L_{\rm X} + \text{constant}$$



Falcke & Bierman 1995, Heinz & Sunyaev 2003

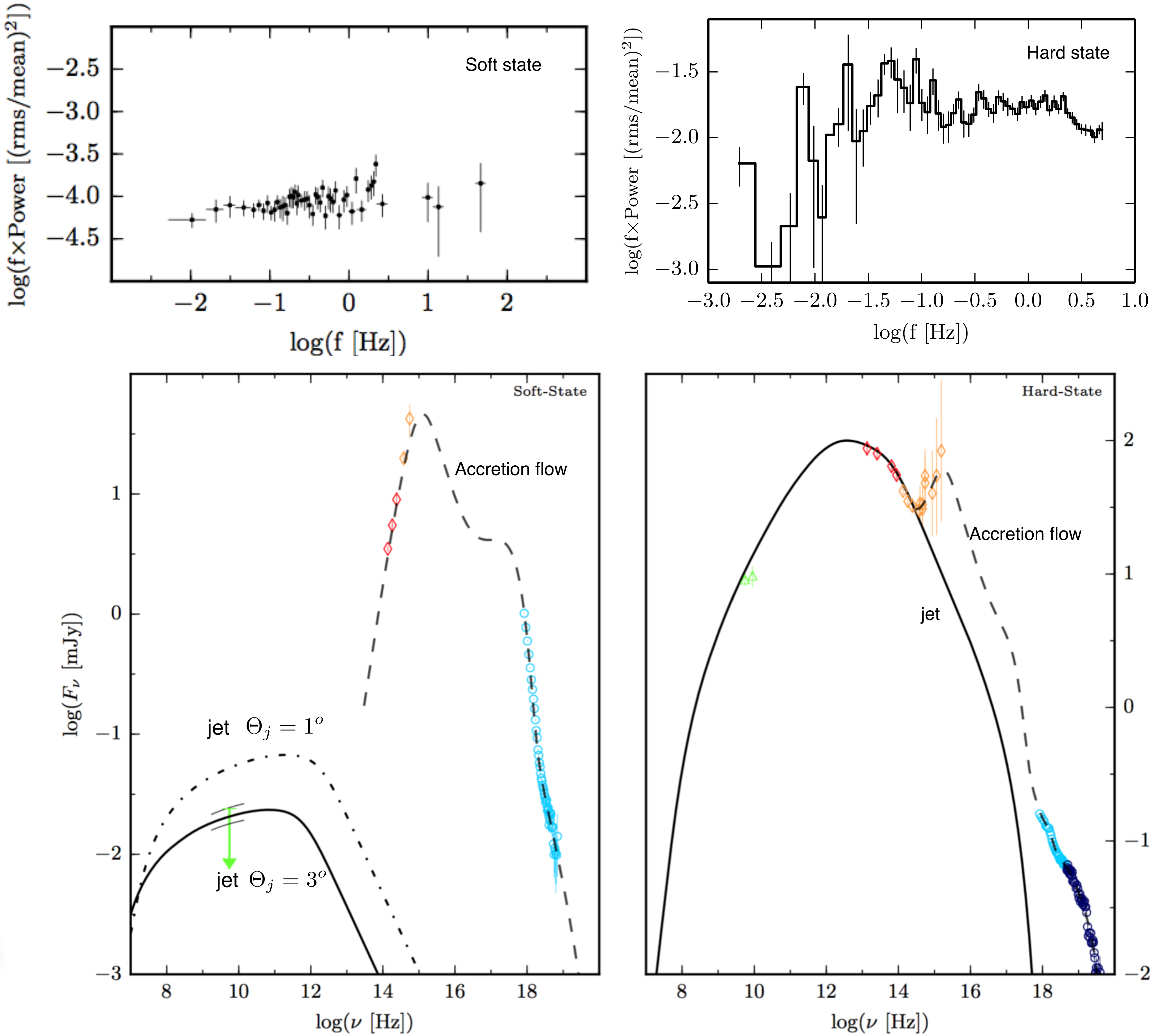
A dark jet in the soft state ?





- Jet luminosity very sensitive to rms amplitude of fluctuations
- Disappearance of the jet in soft state associated to drop in X-ray variability ??
- Jet with same kinetic power as in hard state but radiatively inefficient ??

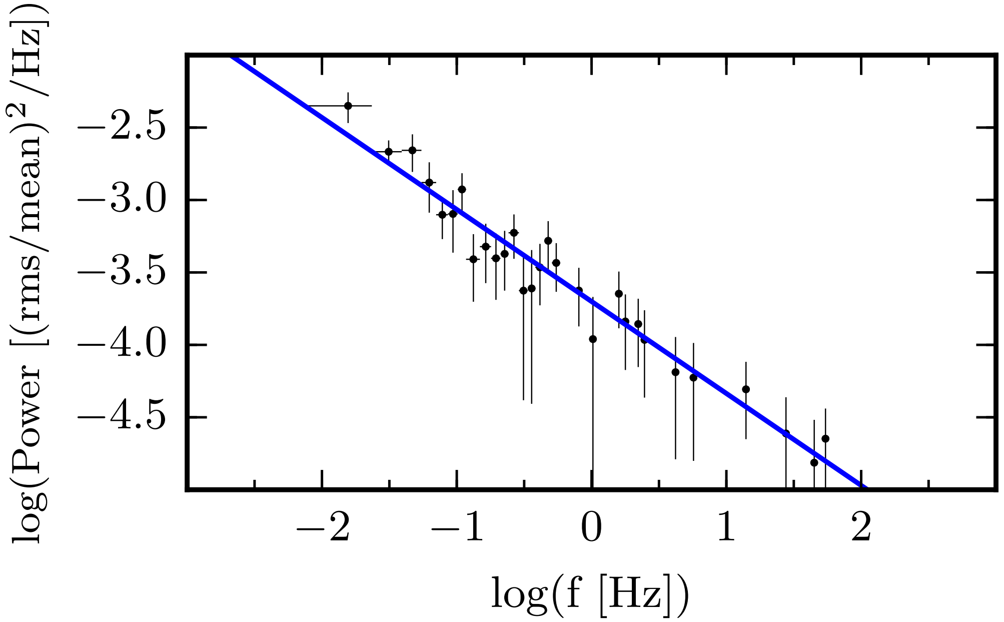
A dark jet in the soft state ?

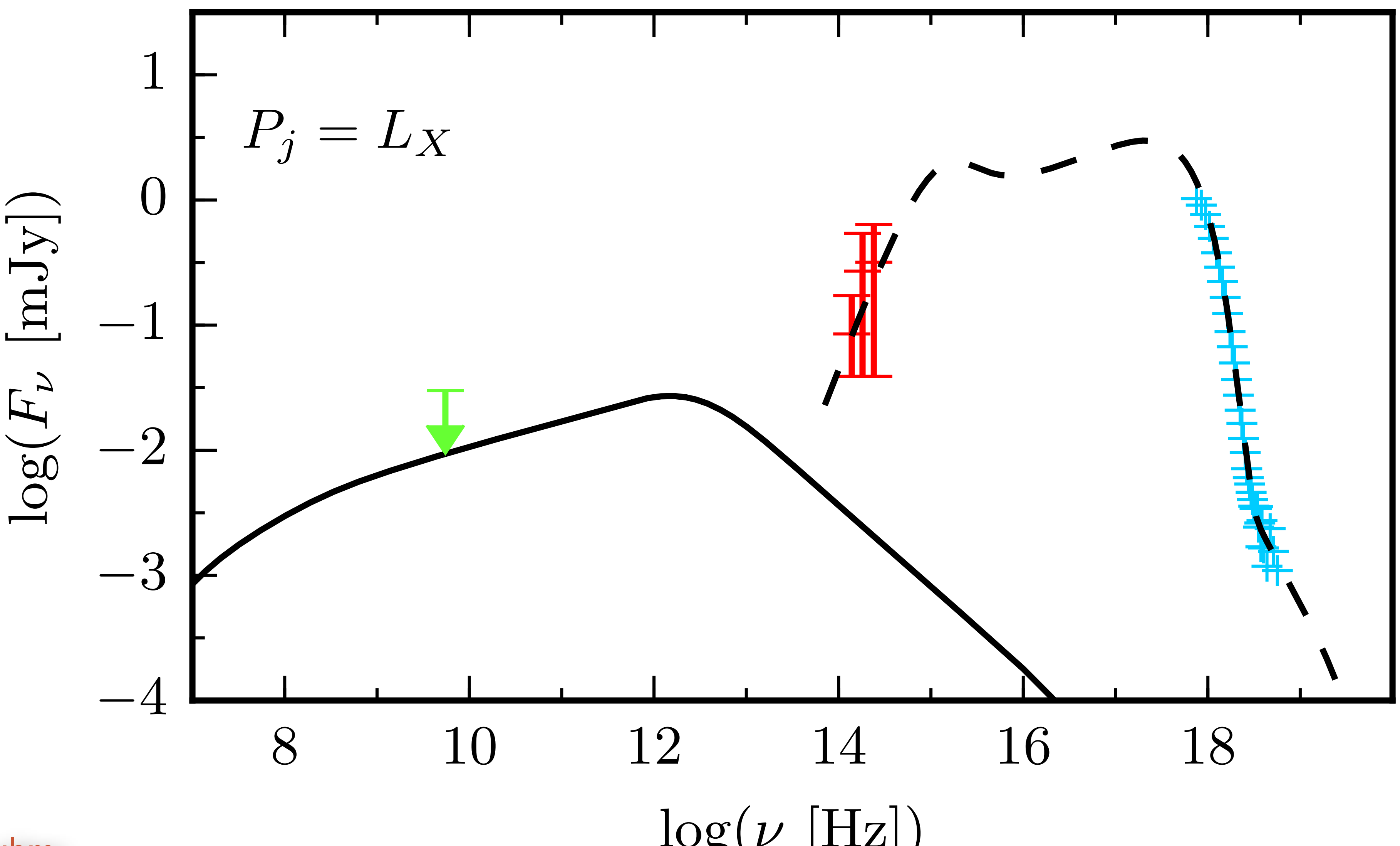


Drappeau et al.
MNRAS, 2017.

Thanks !

Soft state of H1743-322

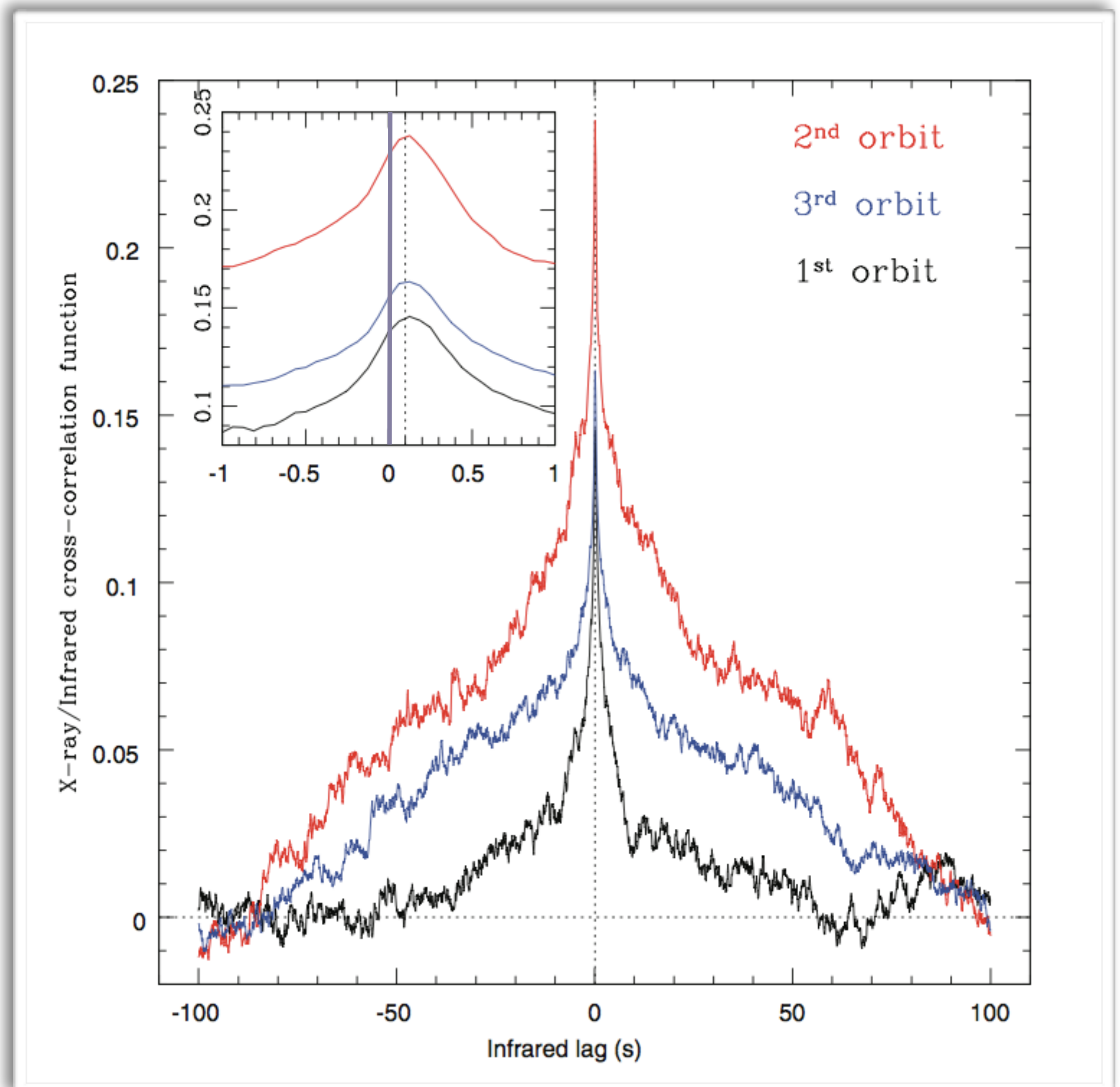




Drappeau et al. subm.

IR /X-ray correlation

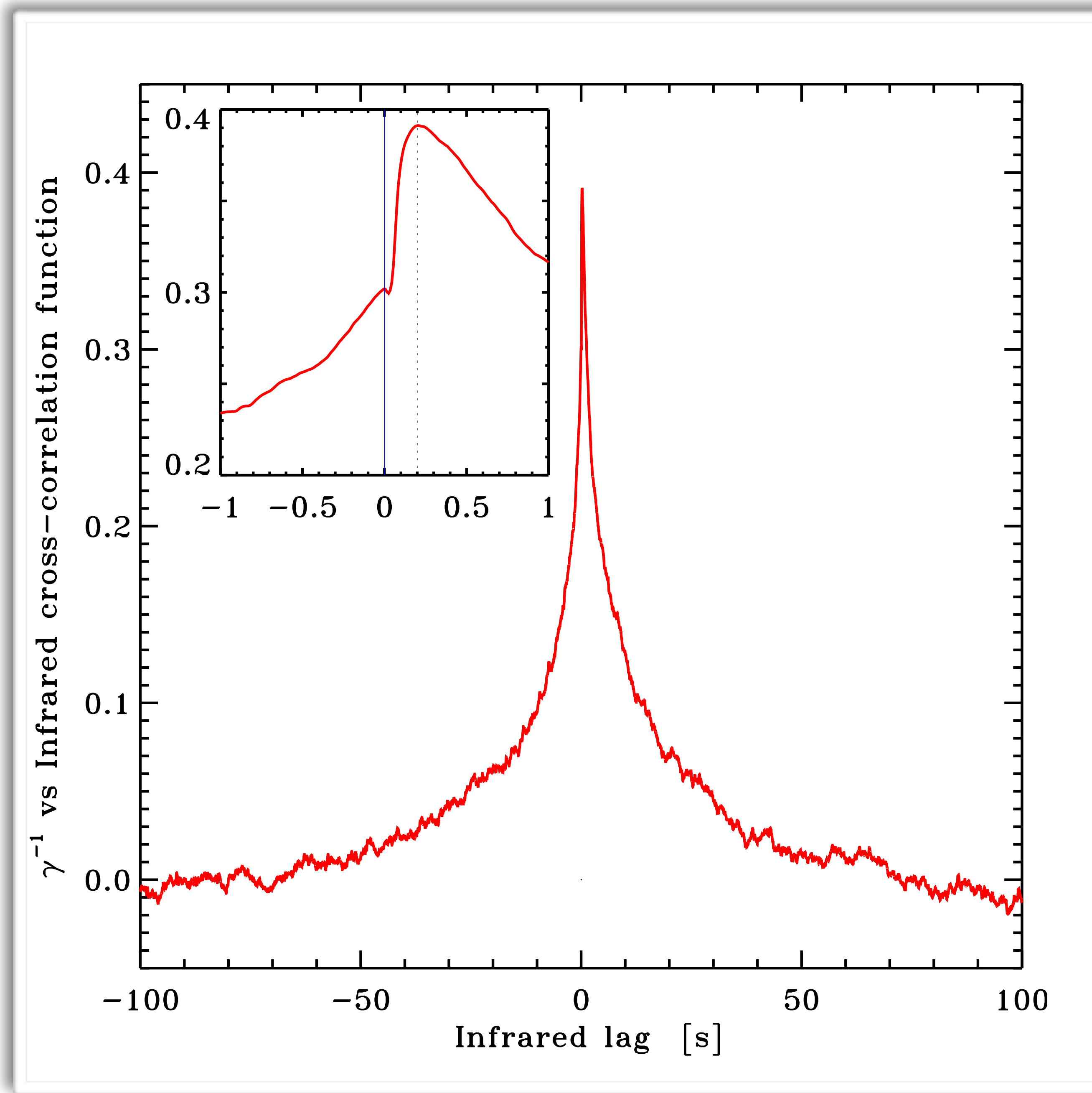
Observations



GX 339-4

Casella et al. 2010

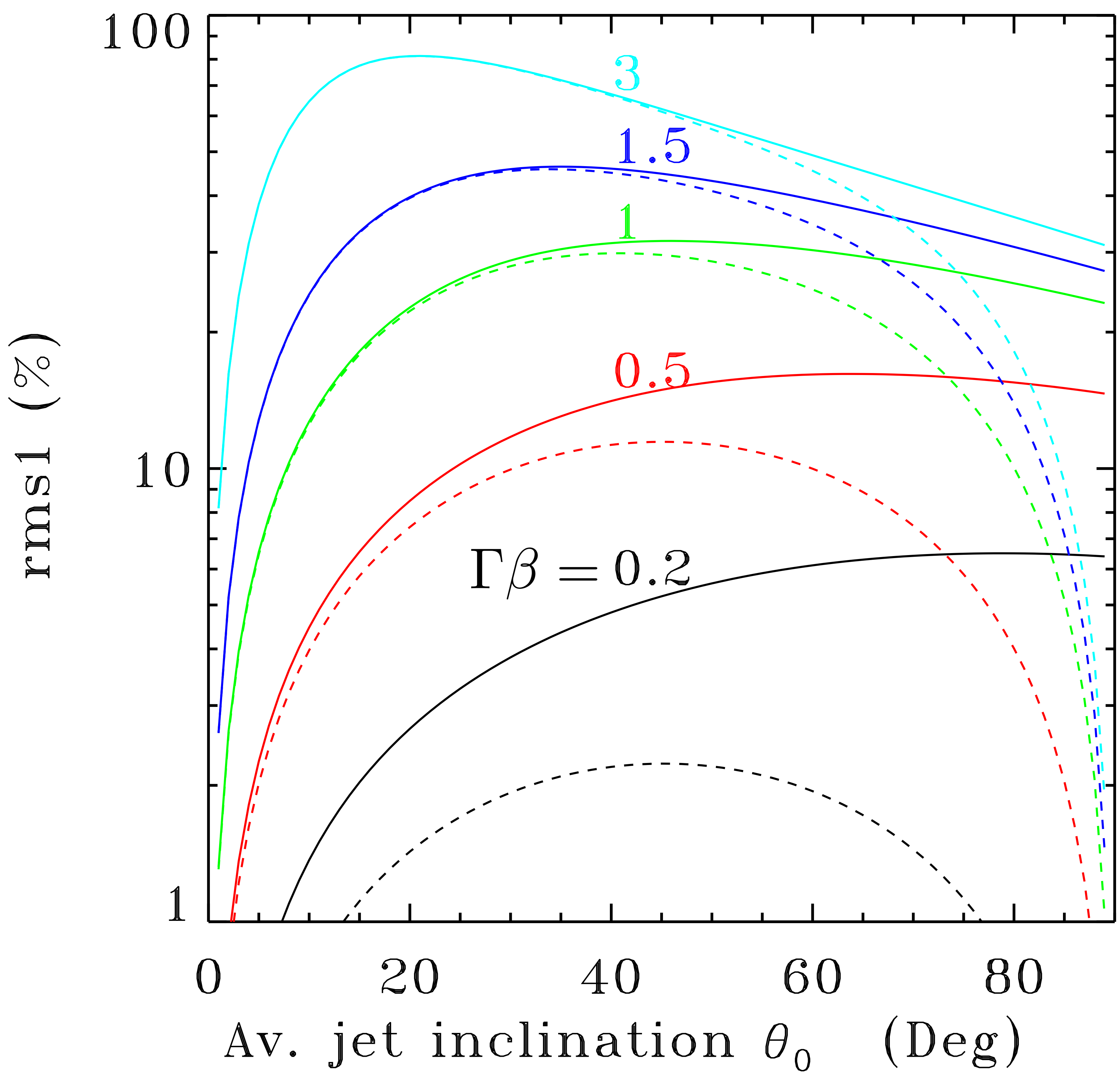
Simulation



Assuming X-ray flux $\propto 1/\Gamma$

Malzac 2014

Optical/IR QPOs from jet precession



Kalamkar et al. 2015, Malzac et al. in prep