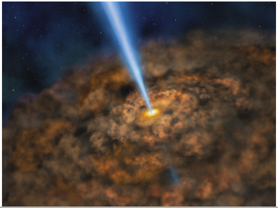
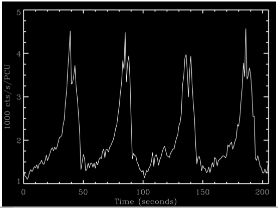
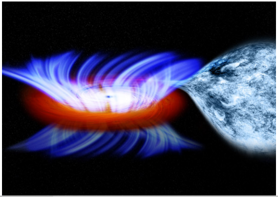
Radiation-Pressure Instability: Fifty Years On
Revisiting the Disk Instability Paradigm

Agnieszka Janiuk
Center for Theoretical Physics / Polish Academy of Sciences

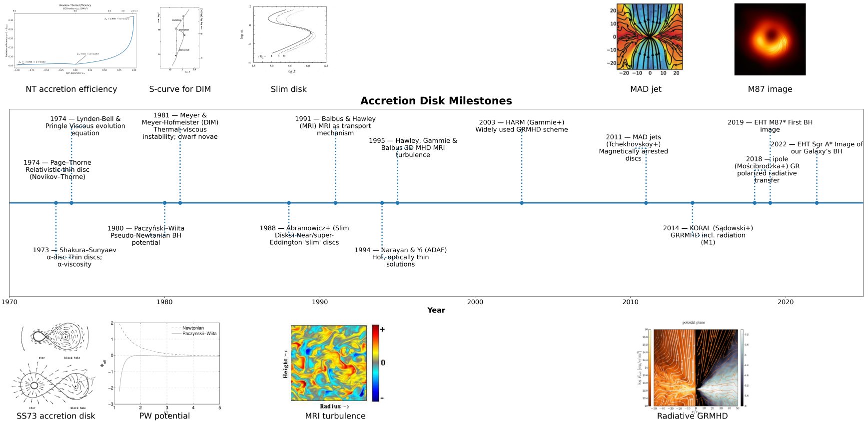
Conference on Disk Instabilities — 50th Anniversary
September 2025





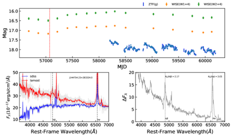


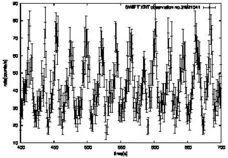
Historical milestones from SS73 to modern simulations

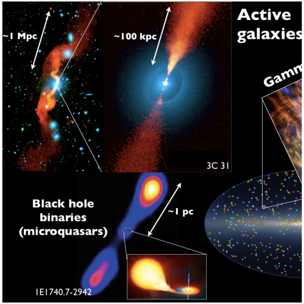


Motivation

- Accretion disks power X-ray binaries and AGN; variability encodes physical processes.
- Radiation-pressure instability produces outbursts, chaos, duty cycles—connecting micro- and macro-scales.
- Observational signatures span heartbeat states to Quasars and Changing-Look AGN.

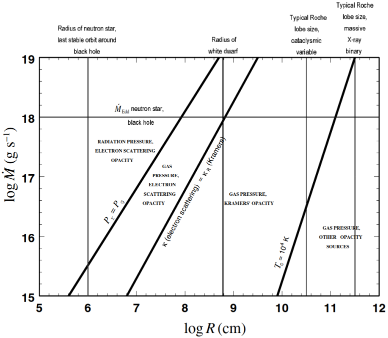






Historical Foundations

- Shakura & Sunyaev (1973); Novikov & Thorne (1973): thin accretion disk model.
- Inner disk at high accretion rate becomes radiation-pressure dominated.
- Lightman & Eardley (1974) predicted thermal/viscous instability in that regime ($T \sim \Sigma^{-1/4}$).



Physical Origin of the Instability

- Viscous heating vs radiative cooling; radiation pressure introduces positive feedback.
- Condition roughly $L/L_{\mathrm{Edd}} \gtrsim 0.1$ for inner disk to become unstable.
- Leads to limit-cycle behavior: small local perturbations amplify into global luminosity oscillations.

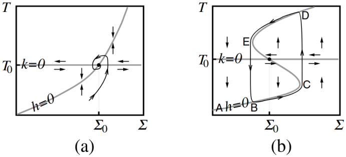


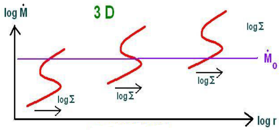
Fig. from Frank, King & Raine (2002).
Solution unstable if $\frac{\partial T}{\partial \Sigma} < 0$.

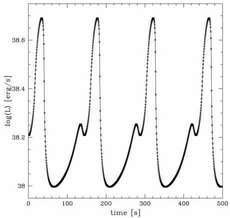
$$Q_{+} = \frac{3}{2}\alpha P H \Omega_{\mathrm{K}}; \;\; Q_{-} = \frac{4\sigma_B T^4}{3\kappa\Sigma} + Q_{adv}$$

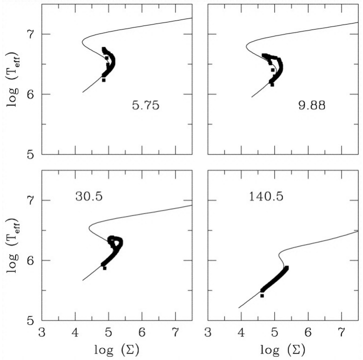
$$\frac{\partial T}{\partial t} = Q^{+} - Q^{-} = h(T, \Sigma)$$

$$\frac{\partial \Sigma}{\partial t} = (t_{th}/t_{visc})k(T, \Sigma)$$

- S-shaped thermal equilibrium curve; unstable middle branch.
- Simplified differential equations yield cyclic solutions.
- Scaling of period/amplitude with viscosity α, accretion rate.





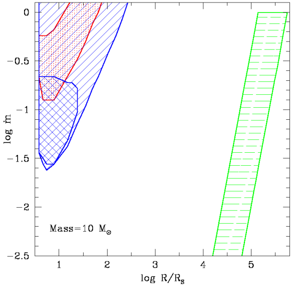


Janiuk, et al. (2002)

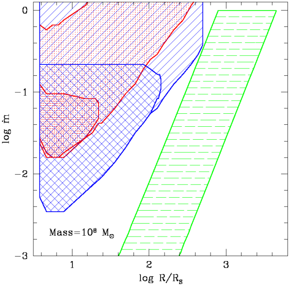
$$t_{visc} = R^2/\nu; \qquad t_{th} = (\frac{v_\phi}{c_s})^{-2} t_{visc}$$

Extension of unstable region

- Predict duty cycles, outburst amplitudes, recurrence intervals.
- Sensitivity to model parameters (viscosity law, mass supply).



Viscous heating given by P_{tot} (blue) or $\sqrt{P_{gas} P_{tot}}$ (red).



Extension of Prad instability zone, in comparison with ionisation instablity Janiuk & Czerny (2011).

1D Time-Dependent Numerical Models

- Radial evolution with radiation pressure and viscosity: long-term limit cycles.
- Governing equations are viscous diffusion and energy transport

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(3r^{1/2}\frac{\partial}{\partial r}(r^{1/2}\nu\Sigma))$$

and

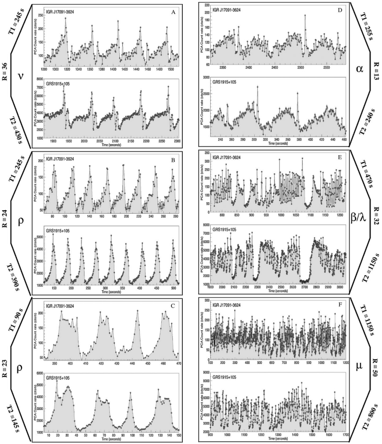
$$\frac{\partial \ln T}{\partial t} + v_r\frac{\partial \ln T}{\partial r} = \frac{4-3\beta}{12-10.5\beta}(\frac{\partial \ln \Sigma}{\partial t} - \frac{\partial \ln H}{\partial t} + v_r\frac{\partial \ln \Sigma}{\partial r})$$

$$+\frac{Q_+ - Q_-}{(12-10.5\beta)PH}$$

e.g., Paczynski & Bisnovatyi-Kogan (1981); Taam & Lin (1984); Lasota & Pelat (1991)

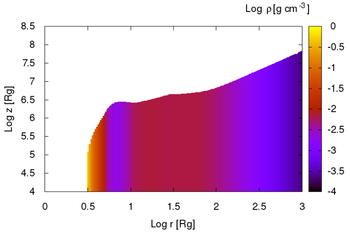
Observational Evidence: Stellar-Mass Black Holes

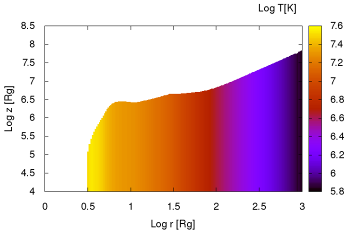
- Heartbeat oscillations in GRS 1915+105 (Belloni et al. 1999) and analogs.
- Large amplitude, quasi-periodic variability matching limit-cycle expectations.
- Timescales and luminosity swings consistent with radiation-pressure-driven cycles.



Altamirano et al. 2011

Temperature and density oscillations, global simulation





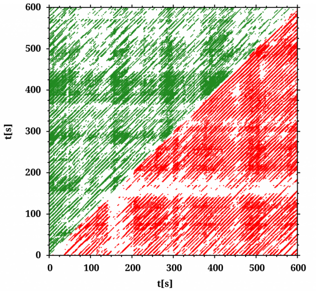
- Model parameters: IGR J17091
- black hole mass $M = 6M_\odot$, spin $a = 0$,
- accretion rate $\dot{M} = 0.86 - 2.12 \times 10^{-8} M_\odot/yr$
- viscosity $\alpha = 0.1$
- 1.5-D hydro code GLADIS.
- Disk partially stabilized by wind outflow

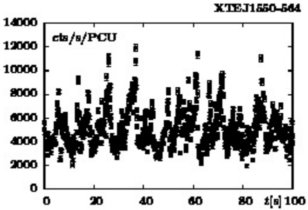
Janiuk, Grzedzielski, Capitanio, Bianchi (2015)

github.org/agnieszkajaniuk/GLADIS

Deterministic Chaos in Light Curves

- Nonlinear diagnostics: recurrence plots, attractor reconstruction, Lyapunov exponents.
- Evidence for low-dimensional deterministic structure, not pure noise.
- Interpretation via radiation-pressure-instability-driven limit cycles with modulations (Sukova & Janiuk, 2016).





Recurrence analysis

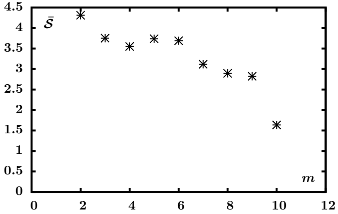
Recurrence matix (RM):

$$\mathrm{R}_{i,j}(\epsilon) = \Theta(\epsilon - \| \vec{x}_i - \vec{x}_j \|), \qquad i,j = 1, ..., N,$$

where $\vec{x}_i = \vec{x}(t_i)$ is (N) points in phase space, reconstructed from time series as:

$$\vec{y}(t) = \{x(t), x(t+\Delta t), x(t+2\Delta t), \ldots, x(t+(m-1)\Delta t)\}.$$

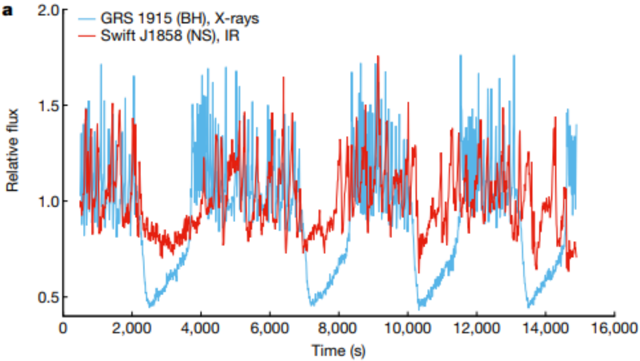
- Significance of chaos: Renyi entropy difference ($\ln K_2$) of the surrogate and real data.
- Apart from GRS and IGR, traces in: GX 339-4, XTE J1550-564 and GRO J1655-40



Example: source GX 339-4 (Sukova et al. 2016)

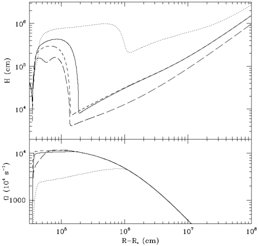
Shared instability in black holes and neutron stars

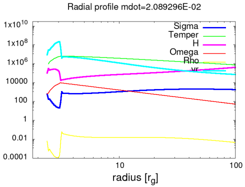
- Neutron star SWIFT-J1858.6-0814 shows limit-cycle oscillations (Vincentelli et al. 2023)
- Observational evidence for shared instability.
- Obscuration, reprocessing and jet emission: detectability in other wavelengths.



Extending to Other Compact Objects: neutron stars

- Neutron star accretion: boundary layer alters disk–star coupling (Popham & Sunyaev 2001).
- Observational degeneracies between disk and surface/boundary emission.

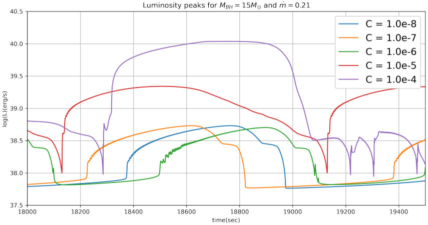


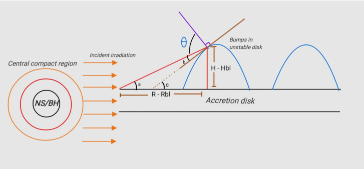


- Sub-Keplerian accretion within $\sim 1.5 R_{NS}$.
- Redistribution of energy and angular momentum.
- Radial pressure gradient.

Accretion onto neutron star

- Neutron star accretion: boundary layer irradiates accretion disk; affects instability signature.
- Observational consequences for irradiated disk emission.



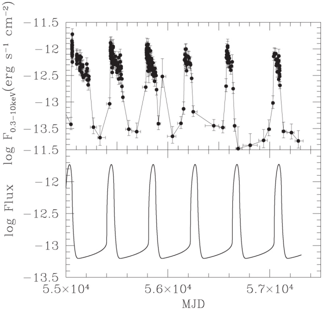


- Irradiation coefficient $C = \eta(1 - \epsilon)C(\theta)$.
- Accounts for disk albedo, radiative efficiency, and geometry (cf. Dubus et al. 1999).
- Modifies the disk effective temperature.

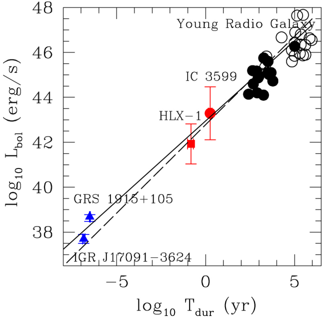
(Ojha, Cavecchi, AJ, et al. in prep.)

Extragalactic Applications: IMBH

- RPI instability can reproduce the duration, period, and amplitude of the outbursts in the intermediate-mass black hole, HLX-1
- Radio galaxy intermittency and duty cycles explained by long-term cycles (Czerny et al. 2009).
- Mass scaling maps microquasar behavior to AGN timescales.

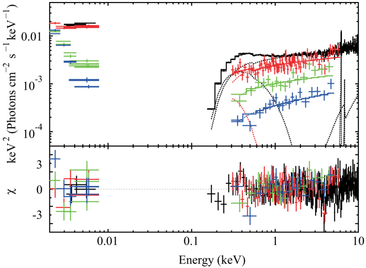


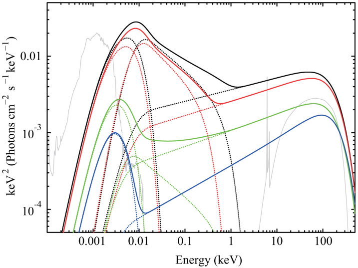
Wu, Czerny, Grzedzielski, AJ, et al. (2016)



Extragalactic Applications: CL AGN

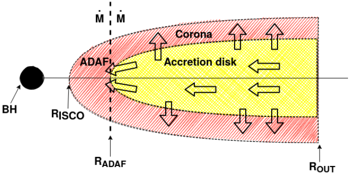
- Changing-Look AGN: rapid spectral-state changes possibly tied to disk instability (e.g. Mrk 1018, Noda & Done, 2020)
- Recurrent outbursts in Broad Line region (e.g. NGC 1566; Alloin et al. 1986), explained by limit cycle in a narrow ring ('0-D' model by Śniegowska 2020)
- Transition timescale of about 5-20 years (sample in Panda & Śniegowska 2022)



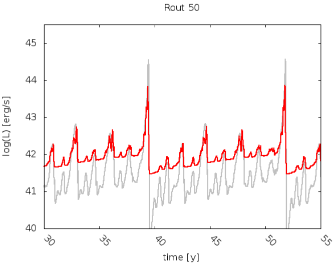


Case study: QPEs

- Instability proposed to explain GSN069 (Miniutti et al. 2019)
- Disk truncation and magnetic can tune the instability pattern.
- Role of inner ADAF and disk corona relatively unimportant.

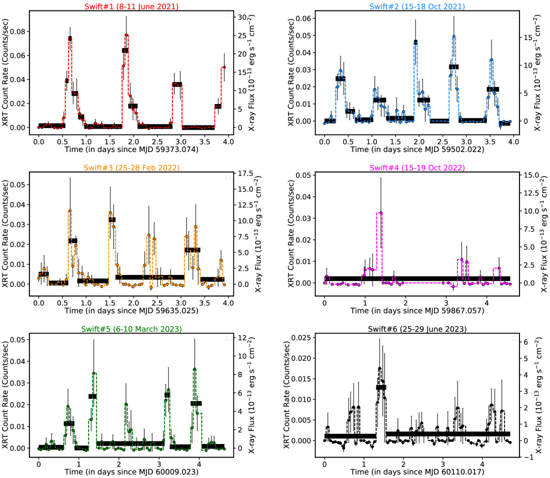


Śniegowska et al. 2023



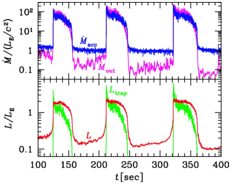
QPEs

- Recent observations of quasi periodic pattern QPE eRO-QPE1.
- Interpreted as repeated TDE or orbiting disk perturber (Pasham et al. 2024)

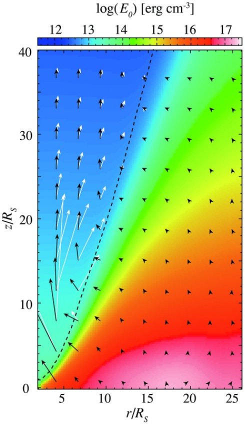


State-of-the-Art Multi-Dimensional Simulations

- R-MHD: includes MRI, field evolution, vertical structure, radiation transport.
- Resolve local thermal timescales; limited duration (cannot recover full long-term cycles).
- Technical challenges: stiffness, cost of radiation coupling.



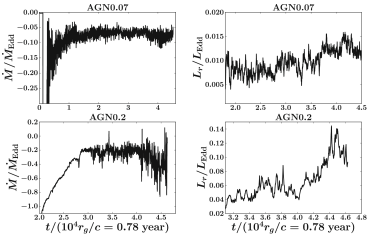
2D α-disk simulation by Ohsuga (2006)



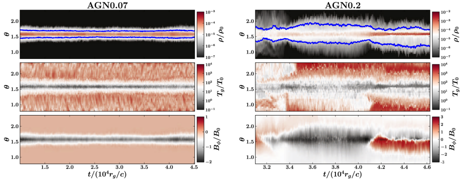
2D simulation snapshot (Ohsuga & Mineshige 2011)

Insights and Tensions

- Magnetic pressure can modify or stabilize expected instability.
- Discrepancies between 1D long-term predictions and short-term multi-D outcomes.
- Local boxes can be thermally unstable (Jiang et al. 2013), but other show magnetically suported stability (Hirose et al. 2008, 2009)
- Microphysics can modify stability of AGN disks (Iron opacity bump, cf. Grzędzielski et al. 2017).



Simulations of AGN disks by Jiang et al. 2019



Some features of numerical codes (Koral, Athena++)

Analytic instability criterion is simple: $dlogQ^{+}/dlogT > dlogQ^{-}/dlogT$. Missing or simplified radiative physics in the simulations alter the balance between heating and cooling. Key candidates are:

- Pure Thomson scattering + free–free absorption. Simplified Comptonisation, e.g. Kompaneets.
- Flux-limited diffusion (FLD) or M1 closure.
- "Photon bubble" or turbulent advection often unresolved

Magnetic support and non-local transport may alter the heating term.

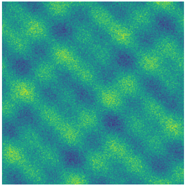
- Magnetic buoyancy lifts hot plasma and radiation away before a runaway builds.
- Turbulent stresses fluctuate on short timescales and don't scale smoothly with total pressure.
- Additional cooling channels (winds/outflows, convection) may add to the picture.

Open Questions

- What controls onset and saturation in realistic disks (fields, microphysics, advection)?
- How to merge local short-timescale physics with global long-term evolution?
- Robustly linking simulation outputs to observable variability.
- Toward a unified variability framework across masses and object types.

Outlook & Future Directions

- New observations: time-domain facilities, multiwavelength coordination, improved chaos metrics.
- Theoretical advances: longer-duration multi-D, reduced-order informed models, coupling to jets.
- Cross-disciplinary tools: ML for pattern recognition, dynamical systems for interpretation.



Summary & Takeaways

- Radiation-pressure instability connects analytic intuition, long-term 1D modeling, and detailed short-term multi-D physics.
- Observational anchors span stellar to extragalactic systems.
- Magnetic fields remain a key uncertain regulator.
- The instability is both probe and driver of accretion variability.

Thank you.

Questions?