MODELS OF BLACK-HOLE VARIABILITY
PROBING STRONG FIELD GRAVITY

TURBULENT DIFFUSION OF ANGULAR MOMENTUM
IS RESPONSIBLE FOR HIGH ACCRETION RATES

ACCRETION FLOWS ARE VERY VARIABLE!

BUT:
- WHY DOES VARIABILITY APPEAR AT PARTICULAR FREQUENCIES?
CHARACTERISTIC FREQUENCIES IN A DISK

- DYNAMICAL FREQUENCIES

\[ f_K = \left( \frac{1}{2\pi} \right) \frac{r^{-3/2}}{1 + \alpha \cdot r^{-3/2}} \]

\[ \kappa \equiv (1 - 6r^{-1})^{1/2} f_K \]

\[ f_{PD} = f_k - f_\perp \equiv 2\alpha f_k^2 \]

ALL HAVE STRONG DEPENDENCE ON RADIUS!

TRAPPING OF GLOBAL MODES
KATO, NOWAK, WAGONER, PEREZ, SILBERGLET, ORTEGA-RODRIGUEZ, ...

RADIAL DISPERSION RELATION:

\[ \left[ f^2 - nf_k^2 \right] \left( f^2 - \kappa^2 \right) = f^2 c_s^2 k^2 r \]

\[ \text{MODE} \quad \text{FREQUENCY} \quad \text{KEPLER} \quad \text{EPICYCLIC} \]

\[ \text{e.g., g-modes: } f \leq \kappa \]

A PURELY RELATIVISTIC EFFECT!
GLOBAL DISK MODES
A NUMBER OF DISK-OSEISMIC MODES ARE TRAPPED

- **g-mode: INERTIAL-Gravity**
  PEREZ et al. 1997
  \[ f_k \approx K + mf \]

- **c-mode: CORRUGATION**
  SILBERGLEIT et al. 2001
  \[ f_c \approx f_k - f_\perp \approx f_{FD} \]

- **p-mode: INERTIAL-PRESSURE**

WHAT ARE THE DIFFERENT OBSERVED QPOS?

- **LOWEST g- AND c- MODES**
  WAGONER et al. 2001

- **VARIOUS RESONANT g-MODES**
  KATO 2001; ABRAMOWICZ & KLUZNIAK 2001

MEASUREMENT OF BLACK-HOLE SPIN!
WHERE DOES THE BROAD-BAND VARIABILITY COME FROM?

SLOW PHENOMENA CLOSE TO THE BLACK HOLE!

EVERY POWER SPECTRUM IS DESCRIBED BY ONLY A FEW FREQUENCIES!
QPO - theory

CHARACTERISTIC FREQUENCIES ARE VARIABLE

CHARACTERISTIC FREQUENCIES ARE CORRELATED

WIJNANDS & VAN DER KLIS 1999
PSALTIS et al. 1999
BELLONE et al. 2002

CORRELATIONS ENCOMPASS NEUTRON STARS & BLACK HOLES
A SINGLE PARAMETER DETERMINES ALL FREQUENCIES?

STELLA & VIETRI; PSALTIS & NORMAN

A TUNABLE CLOCK NEAR THE BLACK-HOLE HORIZON,
PROVIDES MEASURE OF BLACK-HOLE MASS AND SPIN!

A SHARP TRANSITION IN DISK PROPERTIES

e.g., DISK-MAGNETOSPHERE INTERACTION

QPO FREQUENCY AND TORQUE CORRELATIONS IN PULSARS
FINGER ET AL. 1996

HEATING/COOLING FRONT

DWARF NOVAE OSCILLATIONS

YAMASHIKA ET AL. 1995

TRANSITION PRODUCED BY RADIATION DRAG

MILLER, LAMB, & PSALTIS 1998
QPO - theory

Filtering of Perturbations at Transition

\[ \text{DRIFT} \quad \text{NODAL} \quad \text{PERIASTRON} \quad \text{ORBITAL} \]

\[ A_{00}: \text{ISOTROPIC} \]
\[ A_{10}: \text{AZIMUTHAL} \]
\[ A_{11}: \text{VERTICAL} \]

What do we learn about disk physics?
- For isotropic turbulence modes have:
  \[ Q \sim \frac{1}{\alpha_{\text{ms}}} \]

Highest observed coherence for GRO J1655-40:

\[ Q > 23 \]

Hence near the inner boundary:

\[ \alpha_{\text{ms}} < 0.04 \]

Look for answers in MHD simulations?

Dimitrios Psaltis, Princeton (ITP Black Holes Conference 2/26/02)
**CONCLUSIONS**

- Models of black-hole variability are more than weather forecast
- Variability is described by a small number of characteristic frequencies
- Power spectra probe:
  - Strong gravitational fields
  - Physical properties of accretion disks
  - Masses and spins of black holes

**A young research field with great data!**

With room+need for theoretical models!
THE BELLONI-HASINGER EFFECT

BELLONI & HASINGER 1990; BELLONI, PSALTIS, & VAN DER KLIS 2002

FRACTIONAL RMS OF FIRST COMPONENT IS ~CONSTANT

SIMILAR EFFECT FOUND IN AGN

UTTLEY 2001