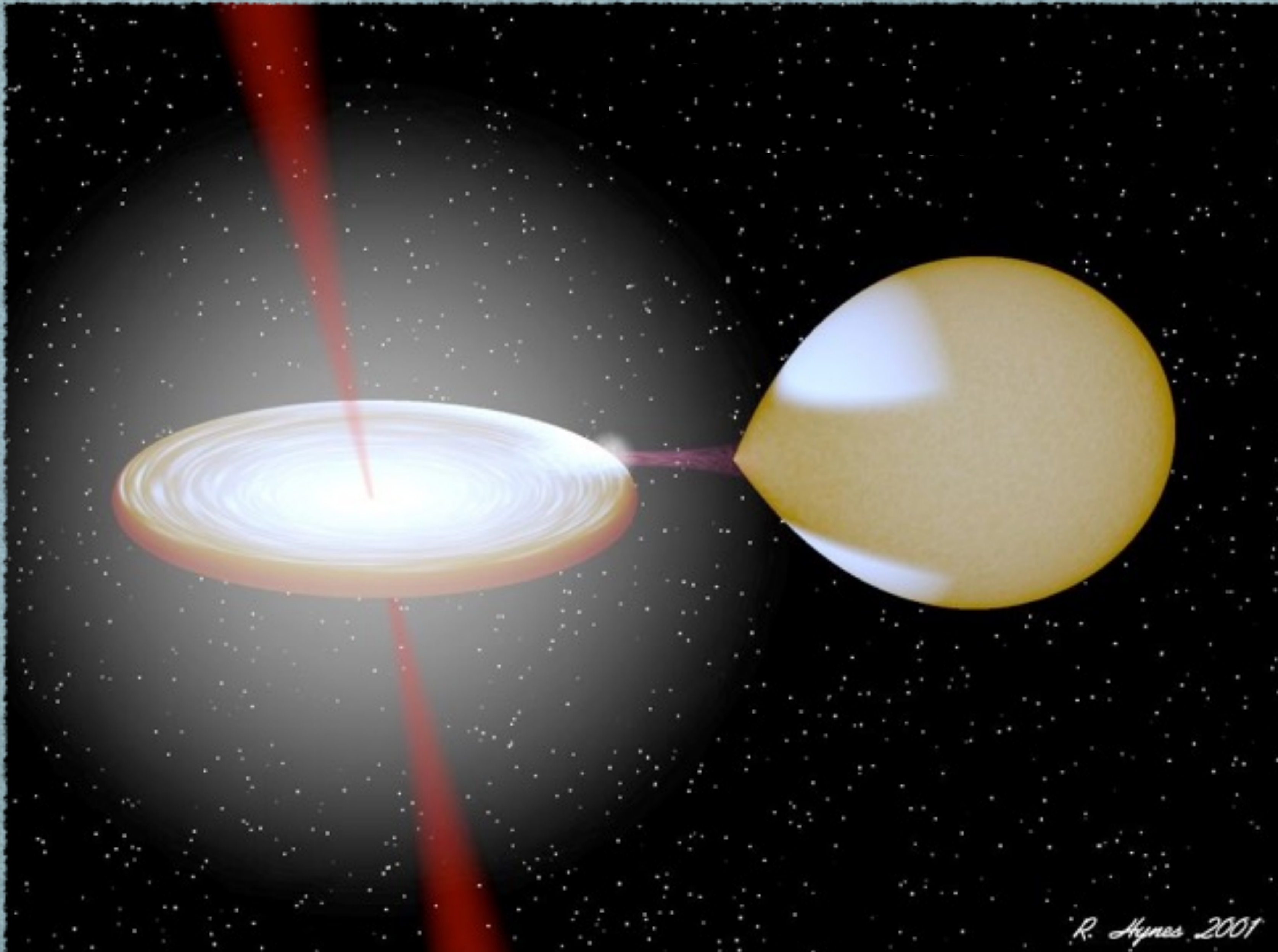
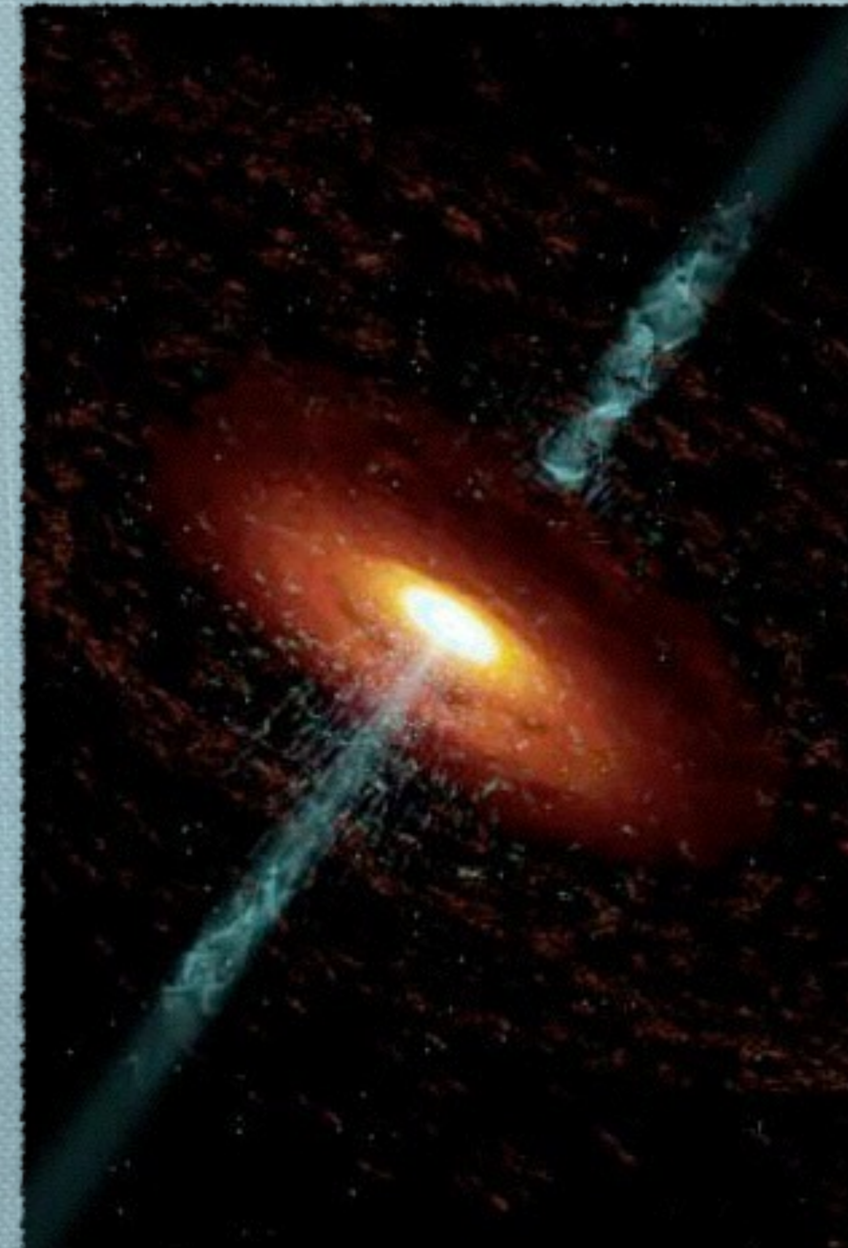




Black-hole binaries

Tomaso M. Belloni

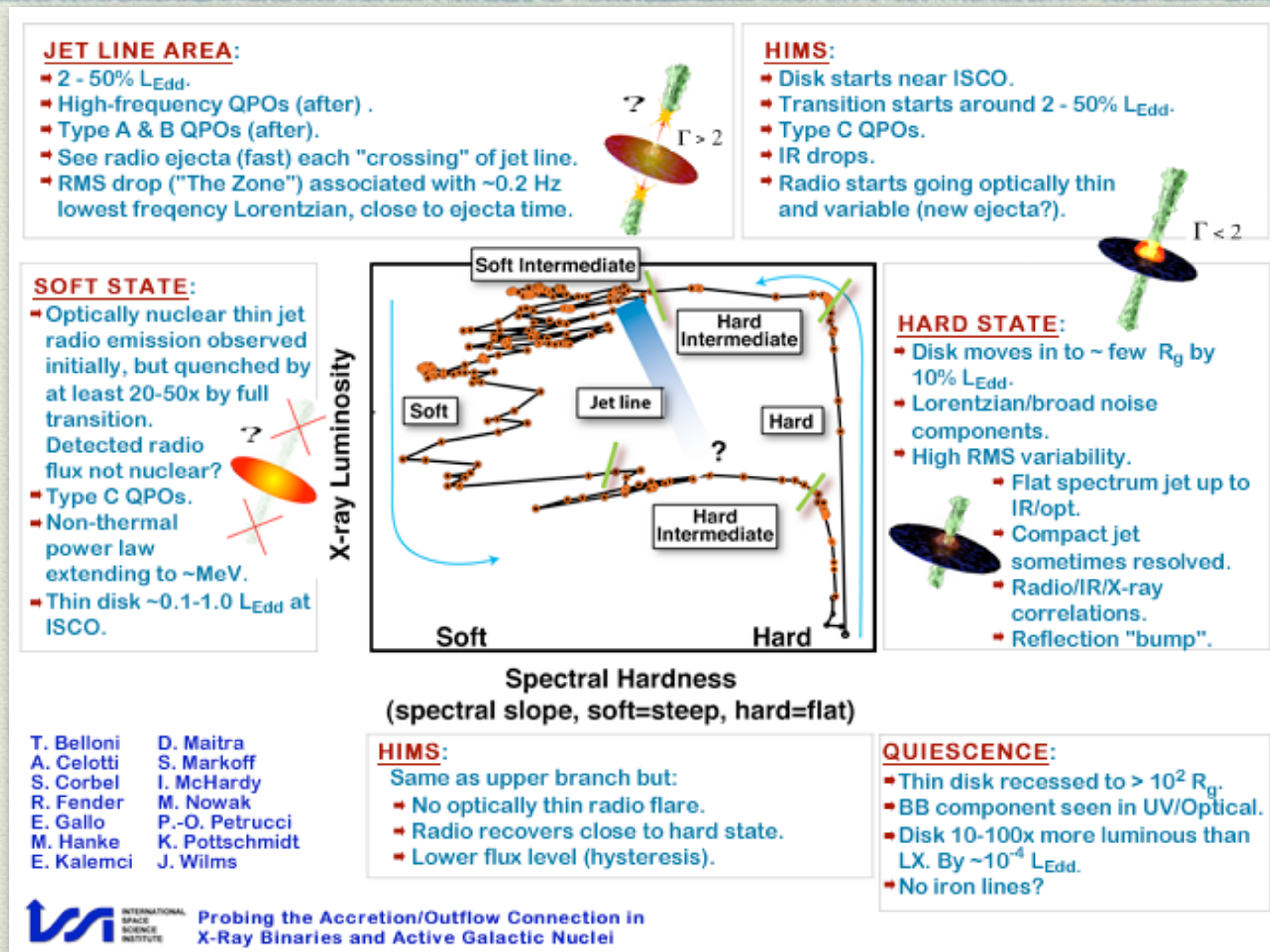
(INAF - Osservatorio Astronomico di Brera)

(Visiting Professor, Univ. of Southampton)

OUTLINE

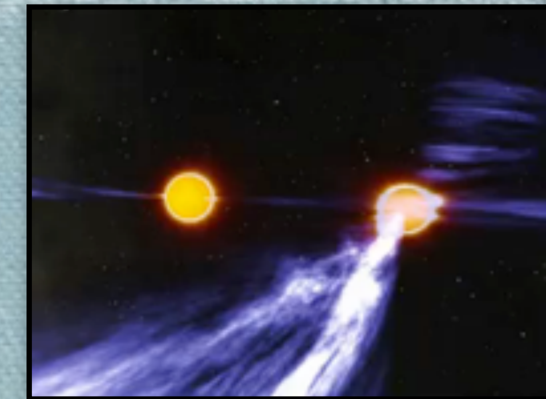
- Lecture I: Accretion onto compact objects, X-ray binaries, black hole candidates, X-ray pulsars
- Lecture II: High-energy emission and spectra
- Lecture III: Time variability on all scales
- Lecture IV: Radio emission, jets, accretion/ejection
- **Lecture V: BH parameters & GR, AGN connection**
- Lecture VI: Neutron-Star binaries + ULX + more

The full picture

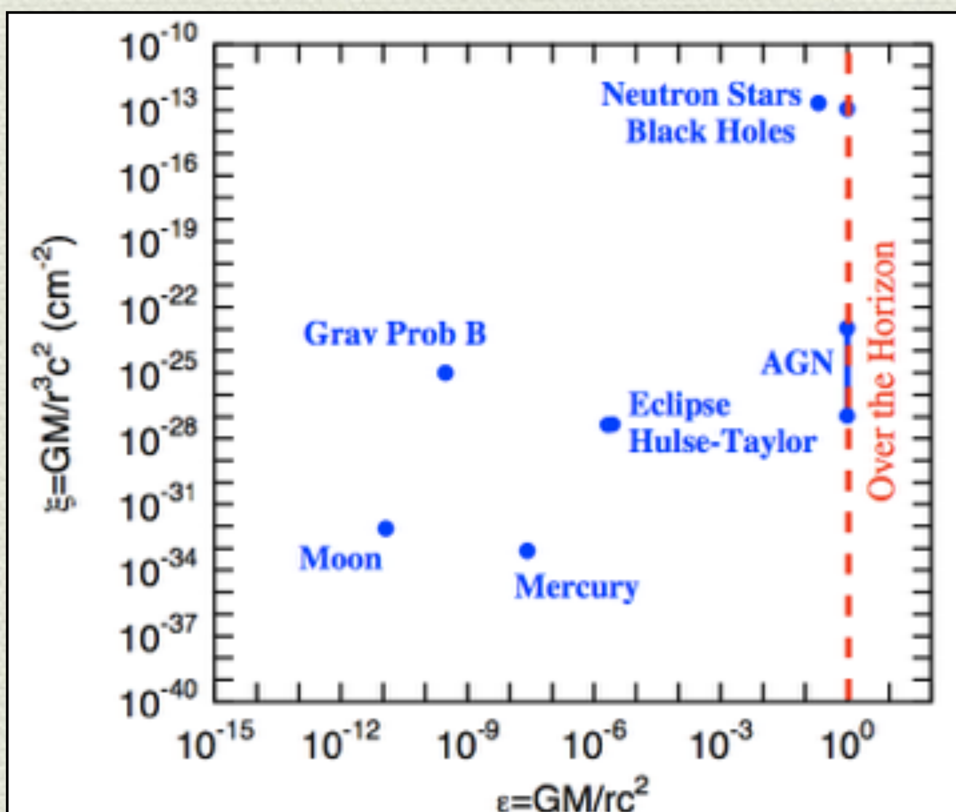


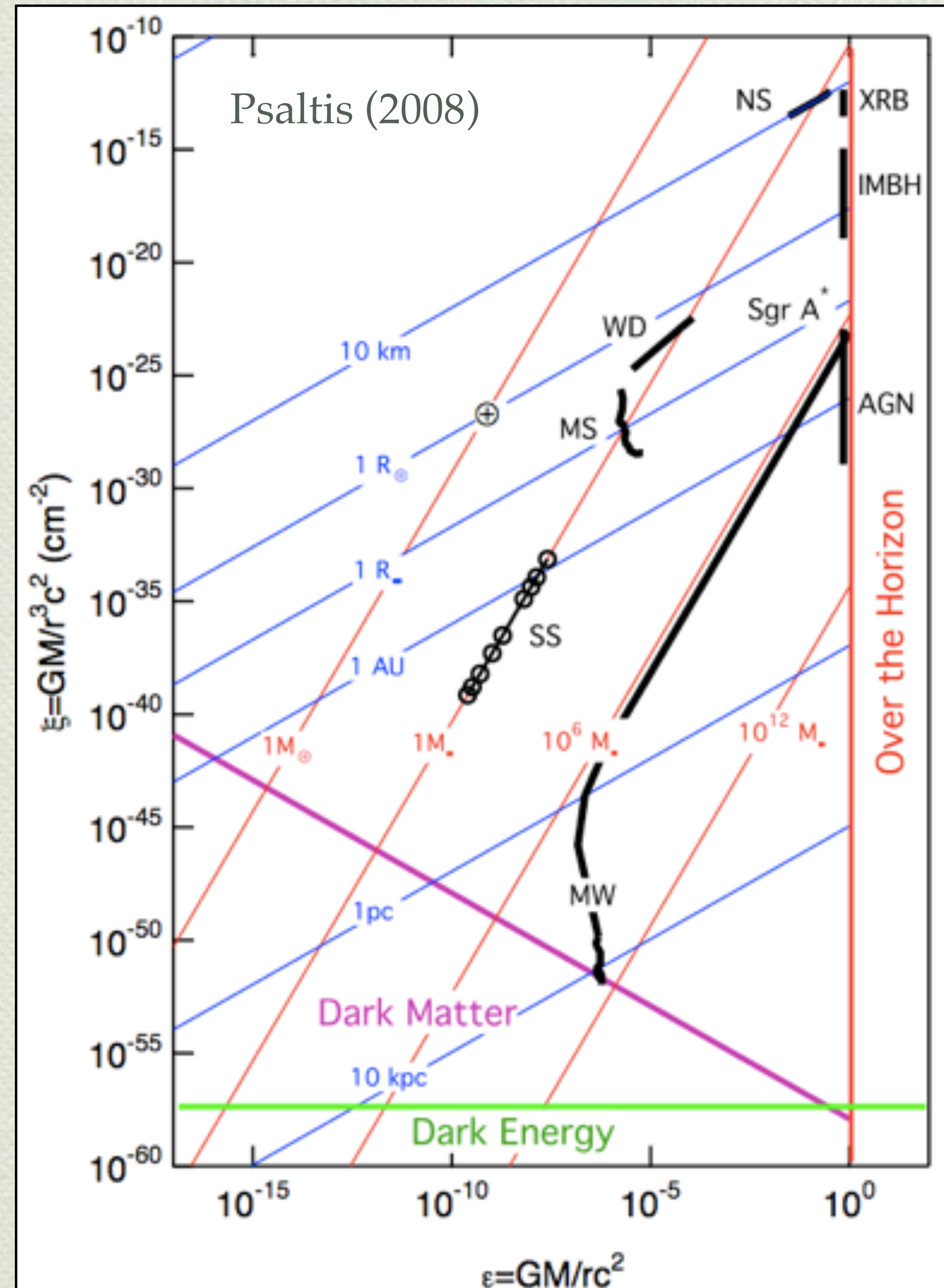
Belloni et al. (2010)

GR in strong field

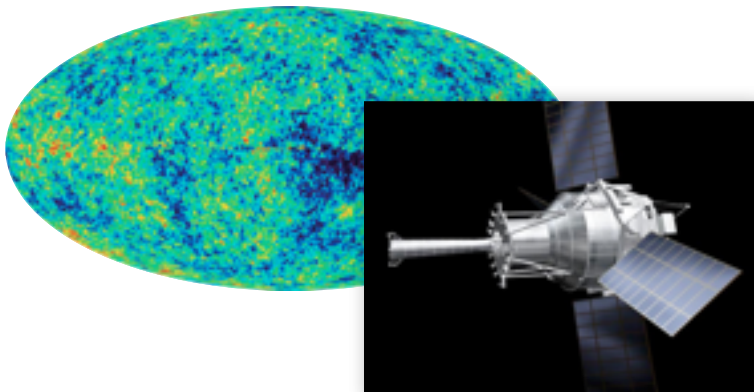


- potential $\eta = \frac{GM}{rc^2}$
- curvature $\xi = \frac{GM}{r^3c^2}$
- Messy environment





GRAVITY FROM EXPERIMENTS

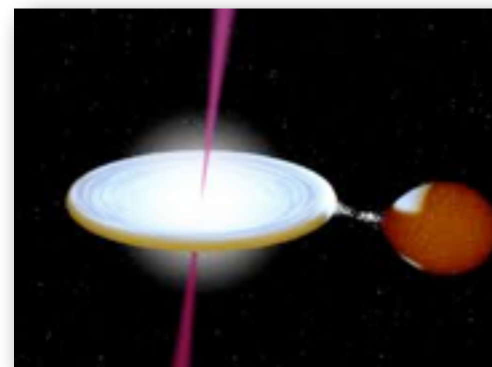


Extremely weak fields

- Laboratory
- Cosmology: Λ

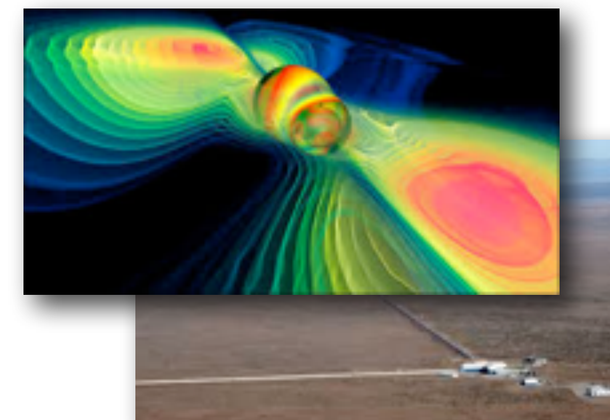
Strong fields

- Accreting binaries
- New missions ahead



STRONG CURVATURES

- Mergers, GRBs
- BH formation
- LIGO/Virgo



WEAK FIELD

STRONG FIELD

STATIONARY SPACE TIME

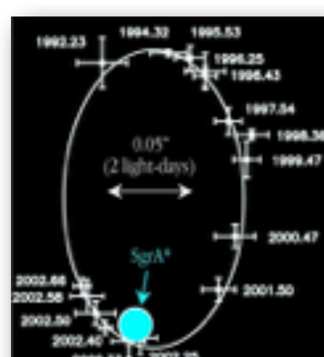
DYNAMIC SPACE TIME

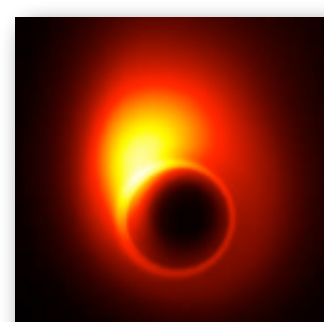
Weak fields

- Solar system
- Binary ms pulsars

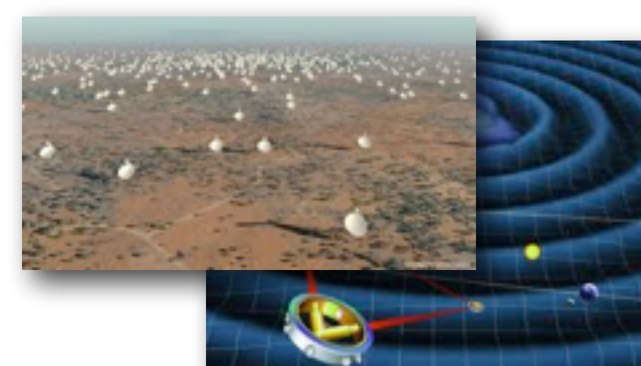
WEAK CURVATURES

- Galactic center, M87
- Event horizon telescope

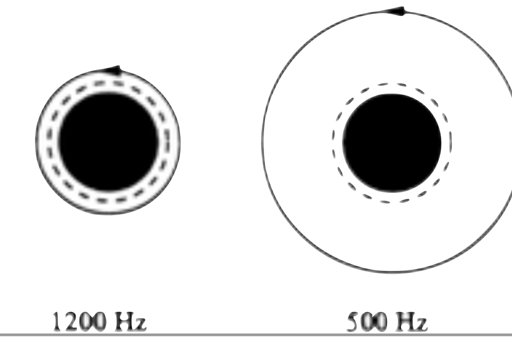




- NGO/LISA
- SKA ms radio pulsar @ Sgr A*



CHARACTERISTIC TIME SCALES

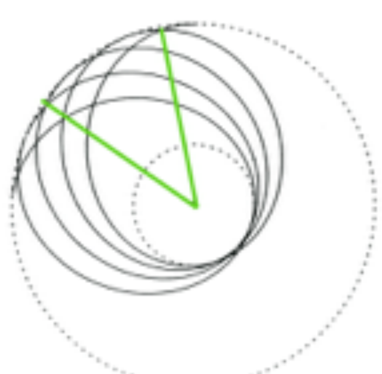


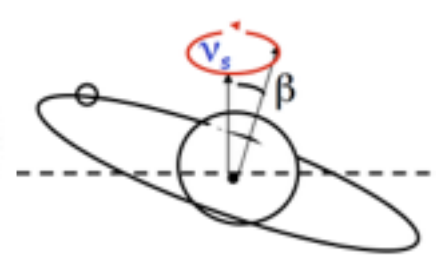
GR + OBJECT

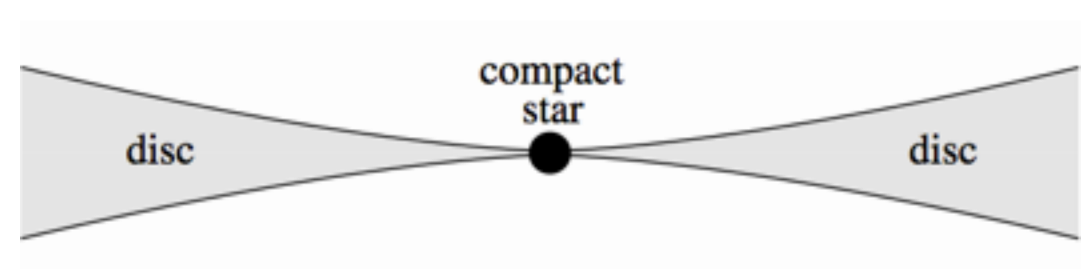
- Neutron stars: spin frequency
- Keplerian frequency
- Relativistic precessions:
  - Periastron precession
  - Lense-Thirring precession

ACCRETION

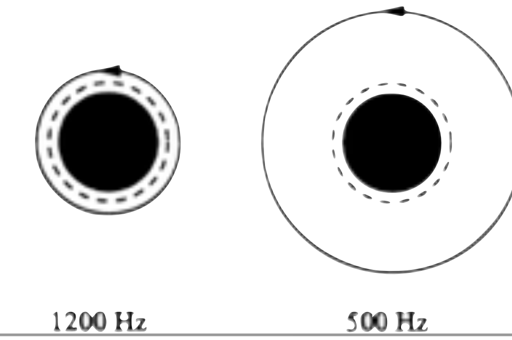
- Radial light-crossing
- Radial sound-crossing
- Free-fall
- Viscous
- Thermal







STRONG GRAVITY



- Keplerian frequency **100-1000 Hz**

  Innermost Stable Circular Orbit (ISCO) - *Black hole spin*

  Timing and spectral approach

- Periastron precession **100-700 Hz**

  Weak limit: Mercury, Double Pulsar

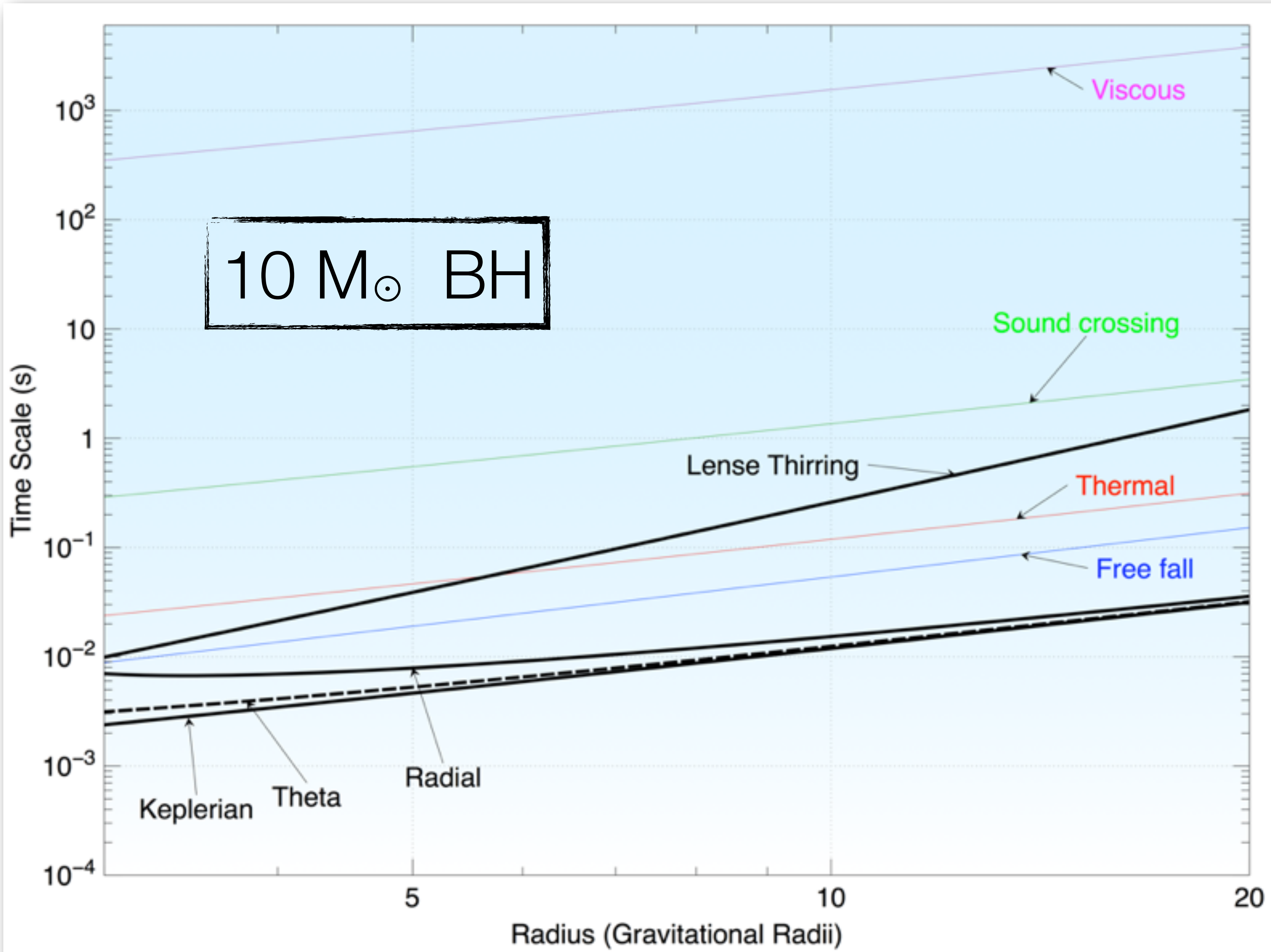
  Need timing

- Lense-Thirring precession **1-50 Hz**

  Weak limit: Gravity Probe B

  Need timing

TIME SCALES: EXAMPLE

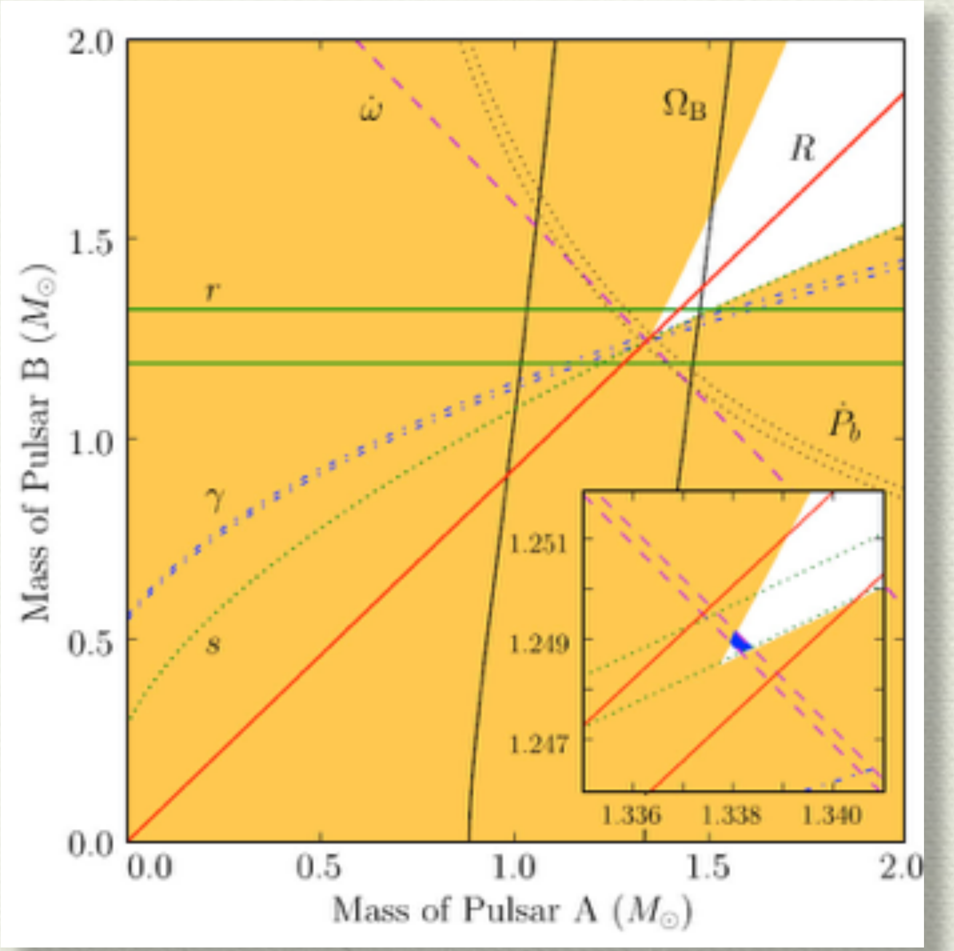


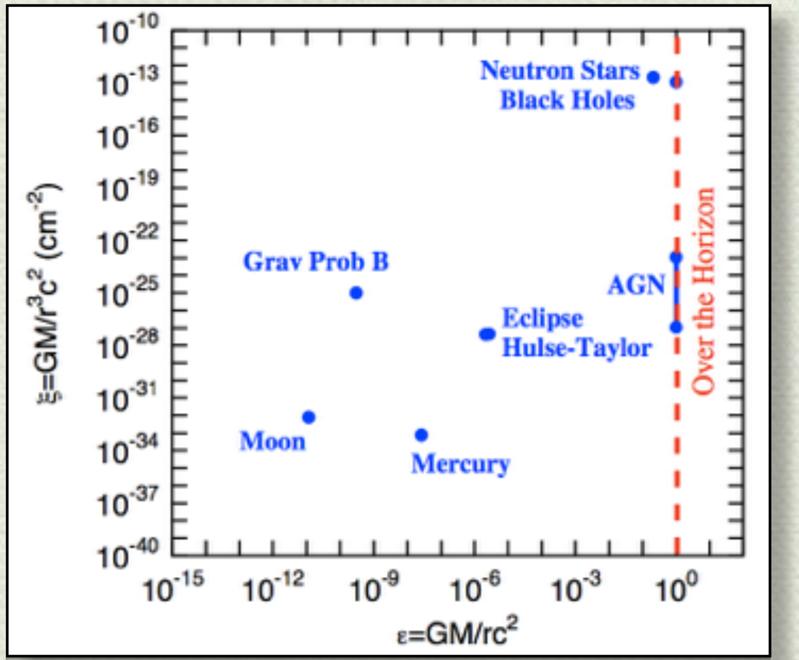
Double pulsar

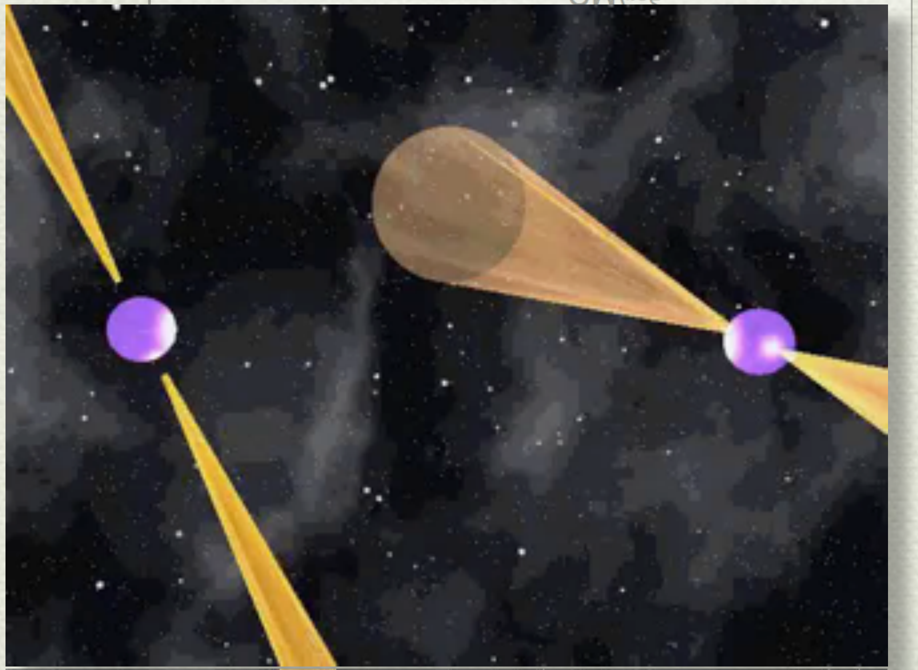
PSR J0737-3039A/B

- Clean environment
- Not so extreme

Breton (2008)





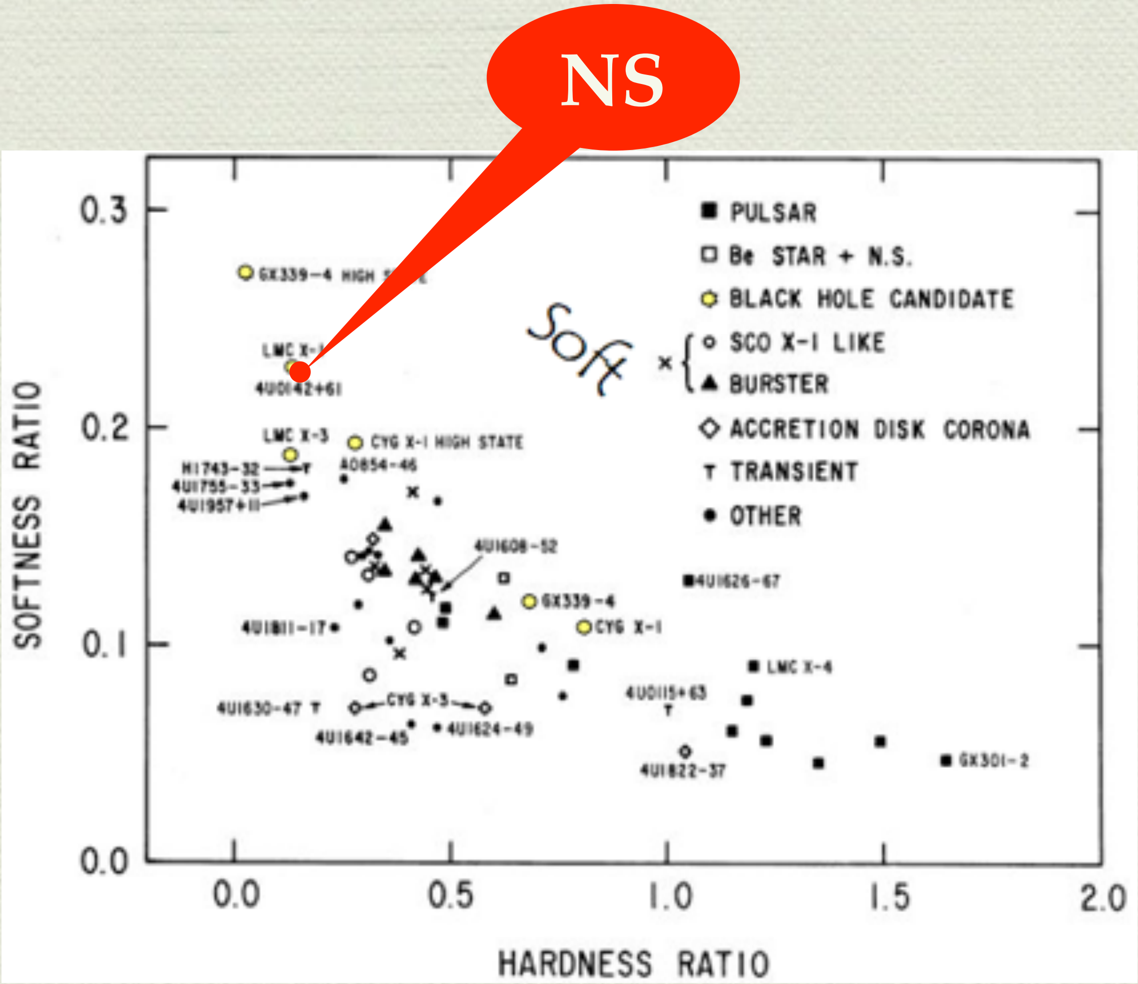


Direct mass measurement

- Evidence of BH
- Mass function is indirect
- Empirical methods:

Direct mass measurement

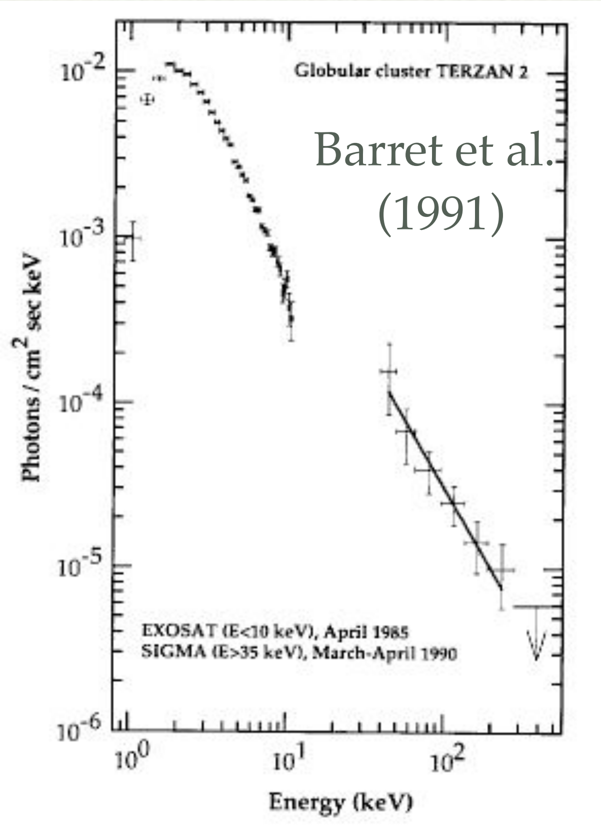
- Evidence of BH
- Mass function is indirect
- Empirical methods:
  - Ultra-soft spectrum

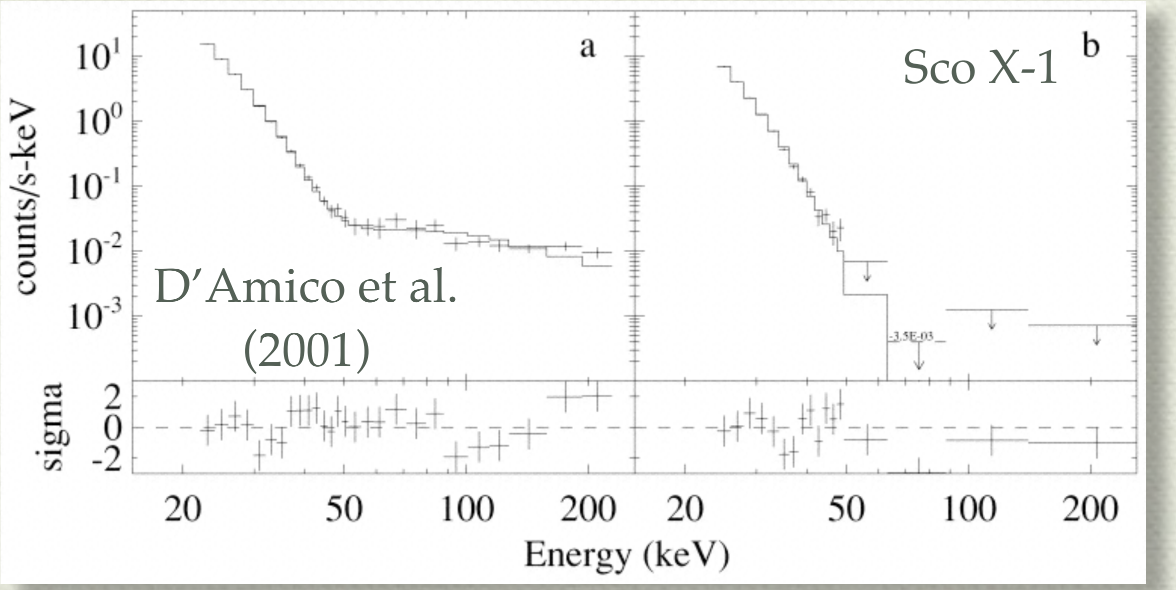


White & Marshall (1984)

Direct mass measurement

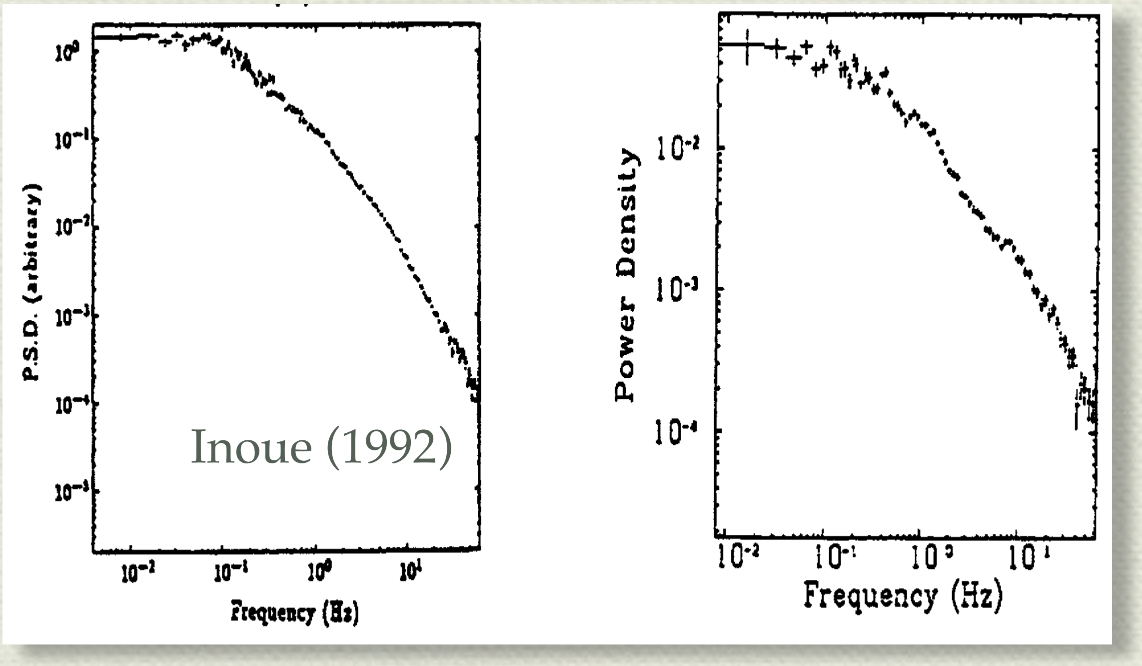
- Evidence of BH
- Mass function is indirect
- Empirical methods:
  - ✗ Ultra-soft spectrum
  - Hard spectral tails

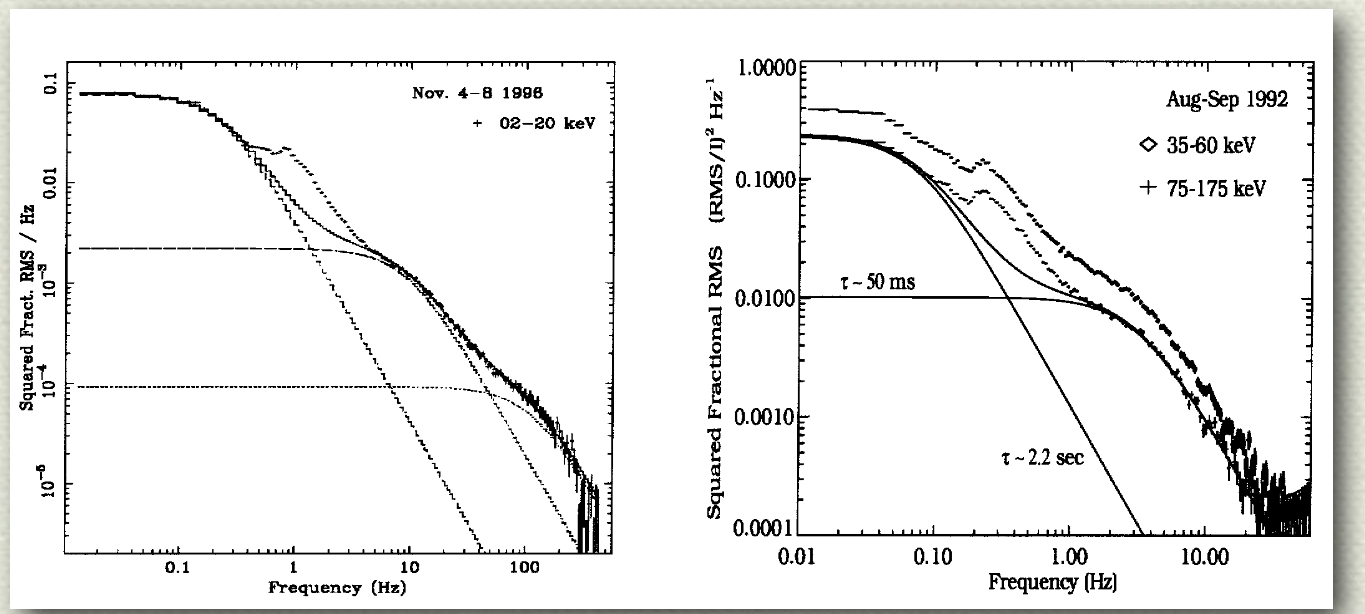




Direct mass measurement

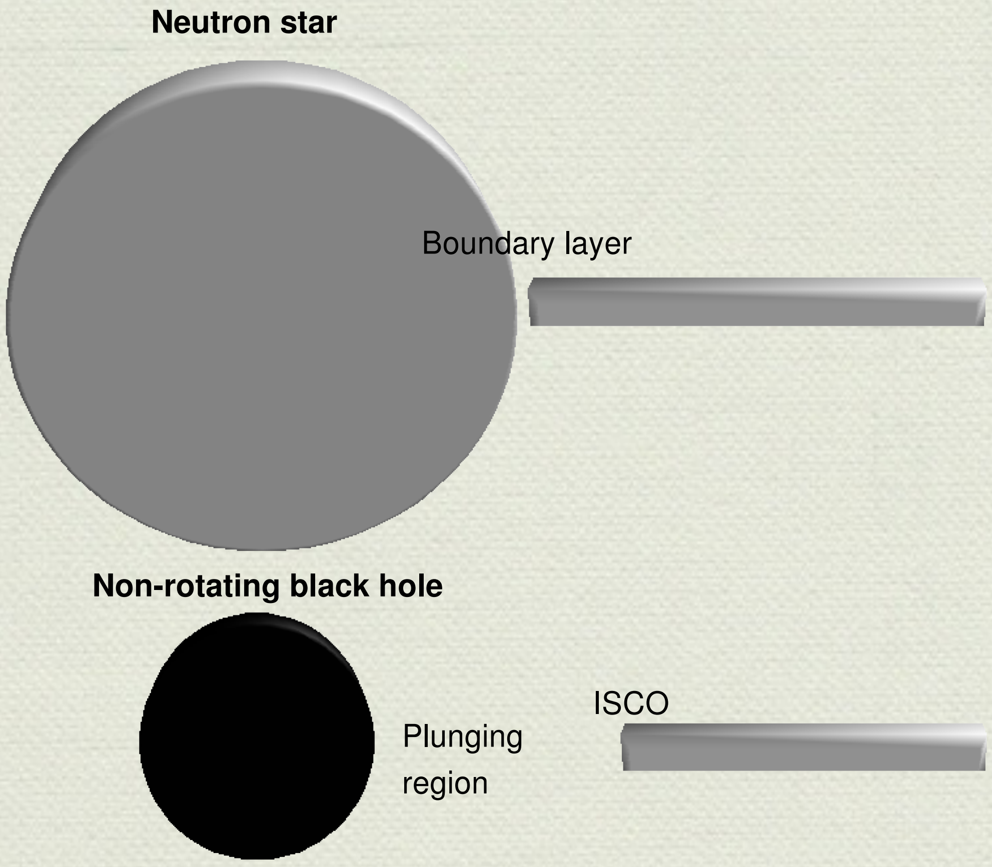
- Evidence of BH
- Mass function is indirect
- Empirical methods:
  - ✗ Ultra-soft spectrum
  - ✗ Hard spectral tails
  - ✗ Strong BLN noise





Reason is evident

- Systems are not that different
- We need a more physical approach

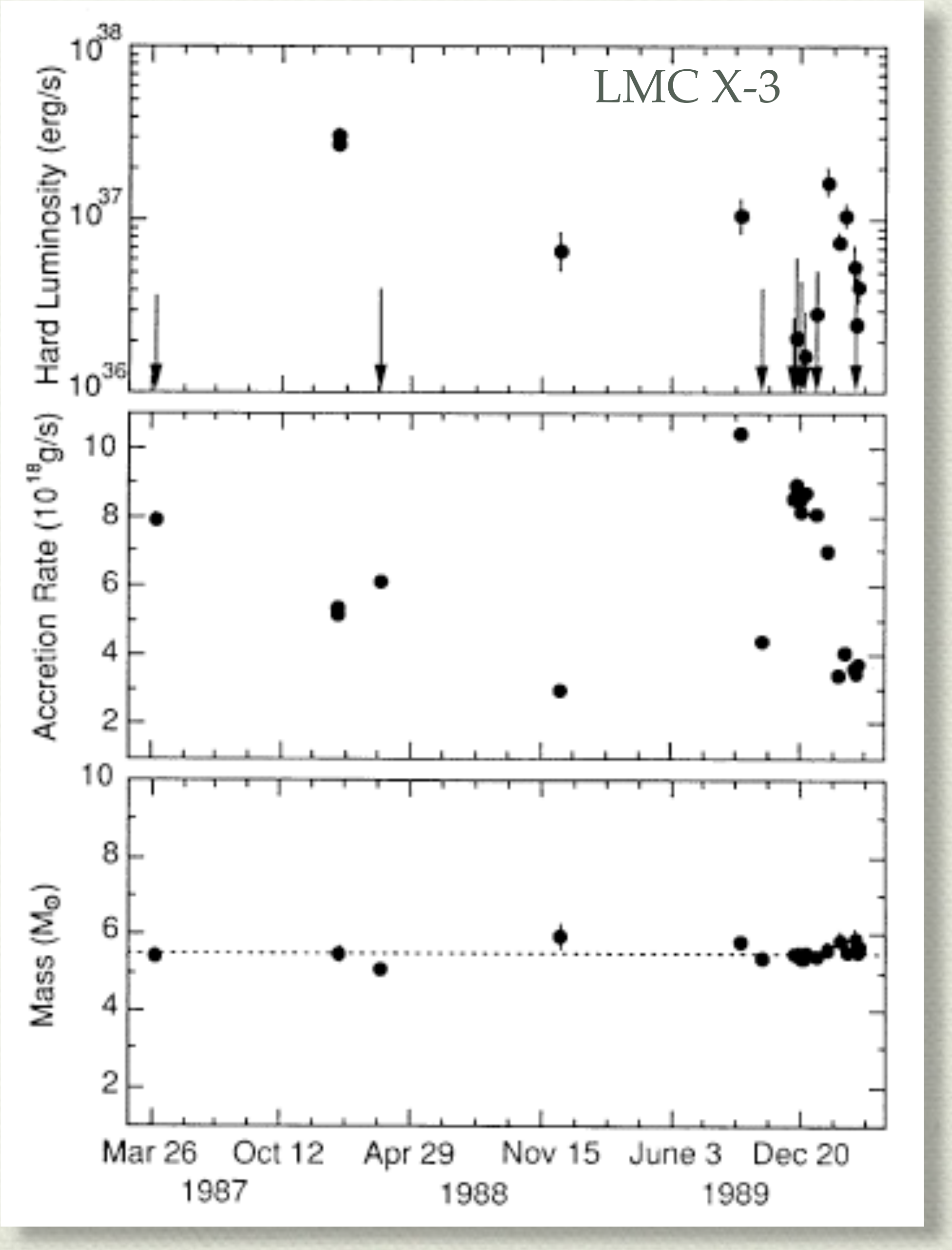


- Presence of a surface
- Inner disk radius

Reason is evident

- Disk-blackbody model
- Early attempts
- Problems:
    - Model shape
    - Full spectrum
    - Data

Ebisawa et al. (1990)



Inner disk radius

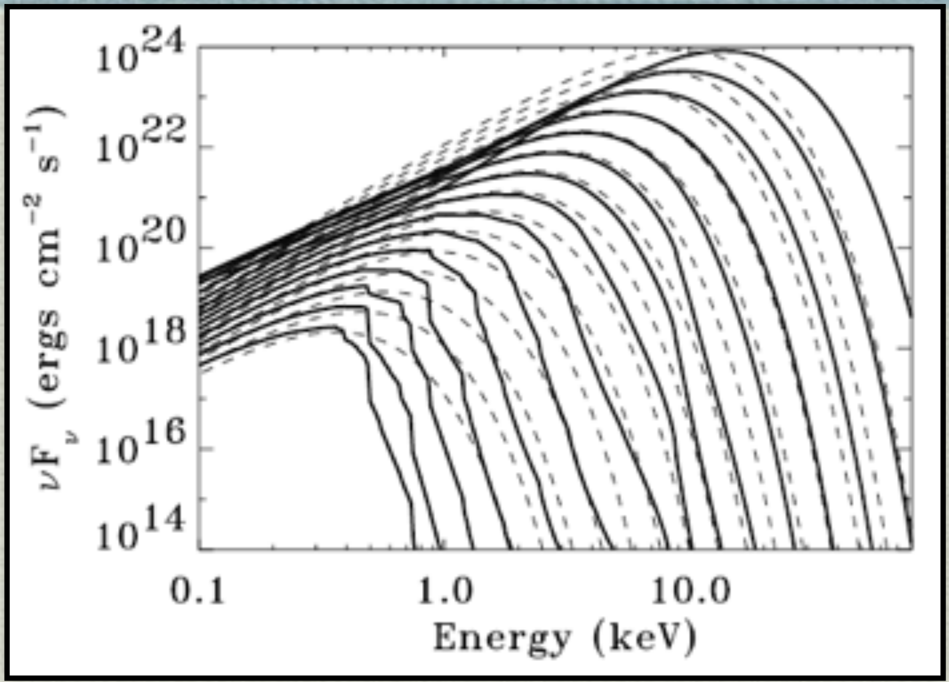
- Disk-blackbody model: $$F_\nu = \frac{4\pi h \cos i \nu^3}{c^2 D^2} \int_{R_\star}^{R_{out}} \frac{R dR}{e^{h\nu/kT(R)} - 1}$$
- Inner disk: $N = \frac{r_{in}^2}{D^2} \cos\theta$
- Absolute value: need D, need θ
- Need precise model $$f = \left[1 - \left(\frac{R_\star}{R}\right)^{1/2}\right]^{1/4}$$
- Need precise temperature (hardening factor)
- Need knowledge of absorption

~~Mass~~ Spin of the black hole

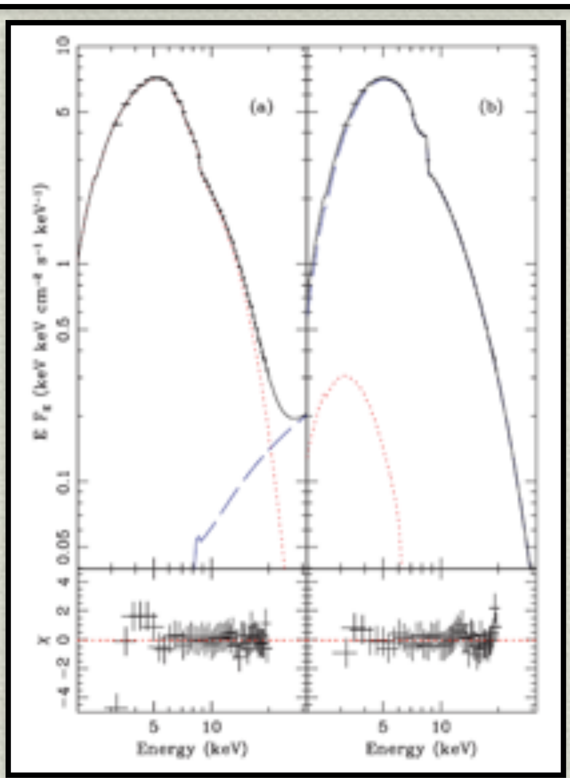
- A black hole has only two parameters
- Accept dynamical masses
- Go for the second (more elusive and interesting) parameter
- Black-hole binaries / black-hole candidates

Spin I: continuum spectra

- If you know your model..
- ..you can do it
- But:
  - Do you know your model?
  - Instrument? N_H?
  - Complete model?



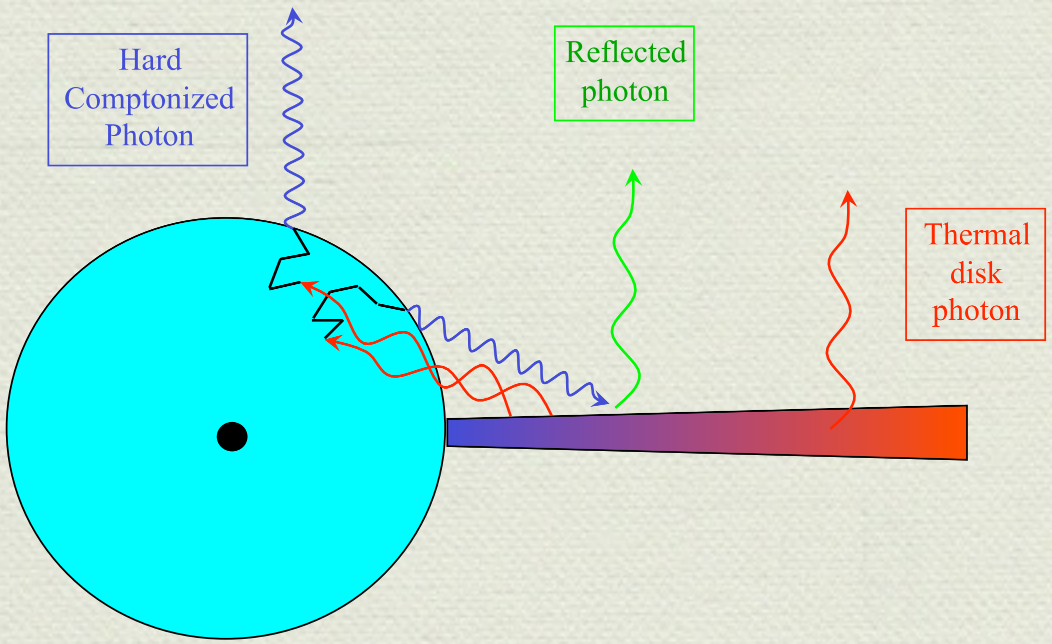
DAVIS & HUBENY (2006)

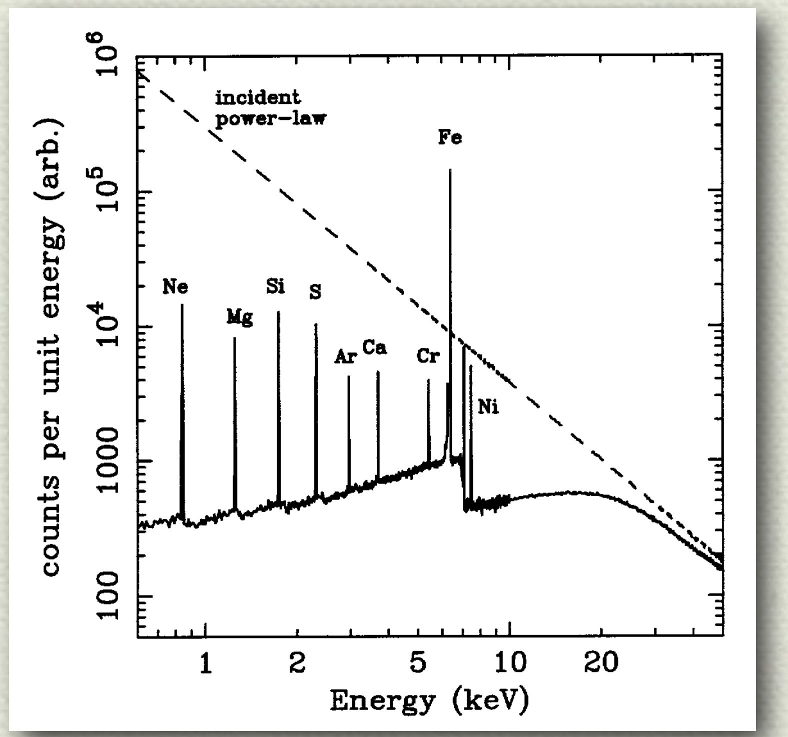


MIDDLETON ET AL. (2006)

Spin II: iron lines

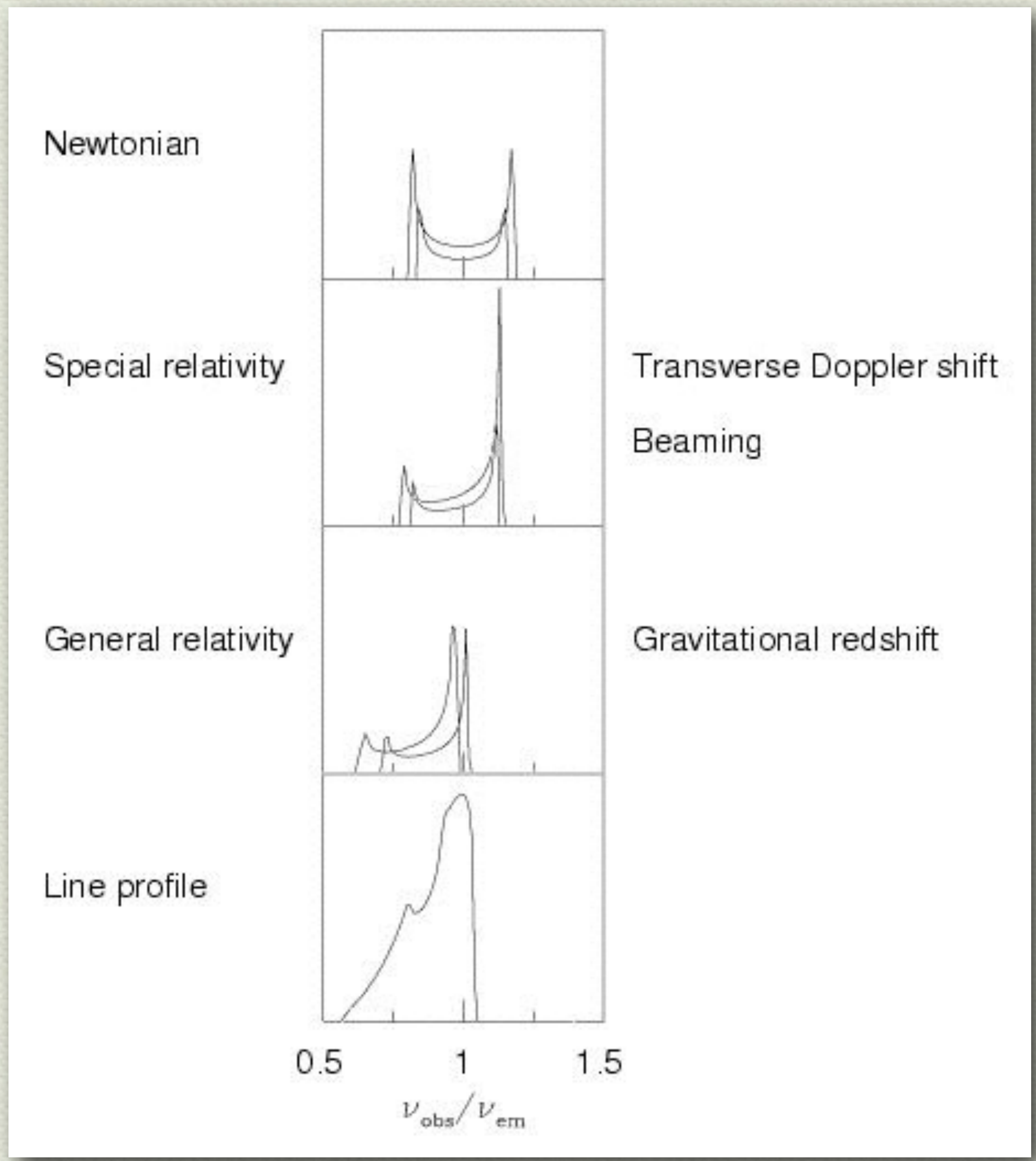
- Narrow lines expected
- Relativistic distortions:
  - Doppler effect
  - Relativistic aberration
  - light bending
  - redshift





Spin II: iron lines

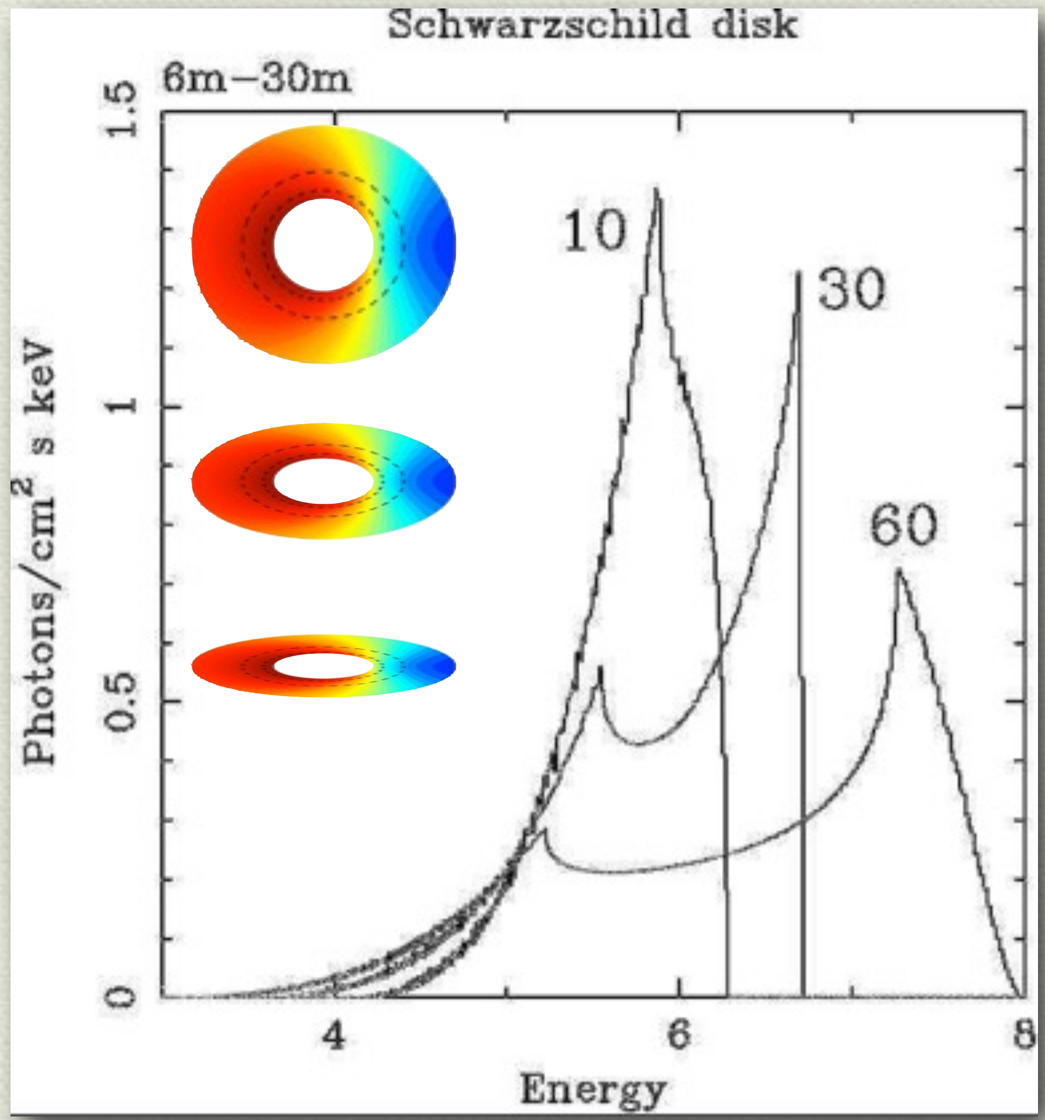
- Broad line expected
- Broadening can be used
- Relativistic effects
- GR evidence
- (Fifth lecture) now



Spin II: iron lines

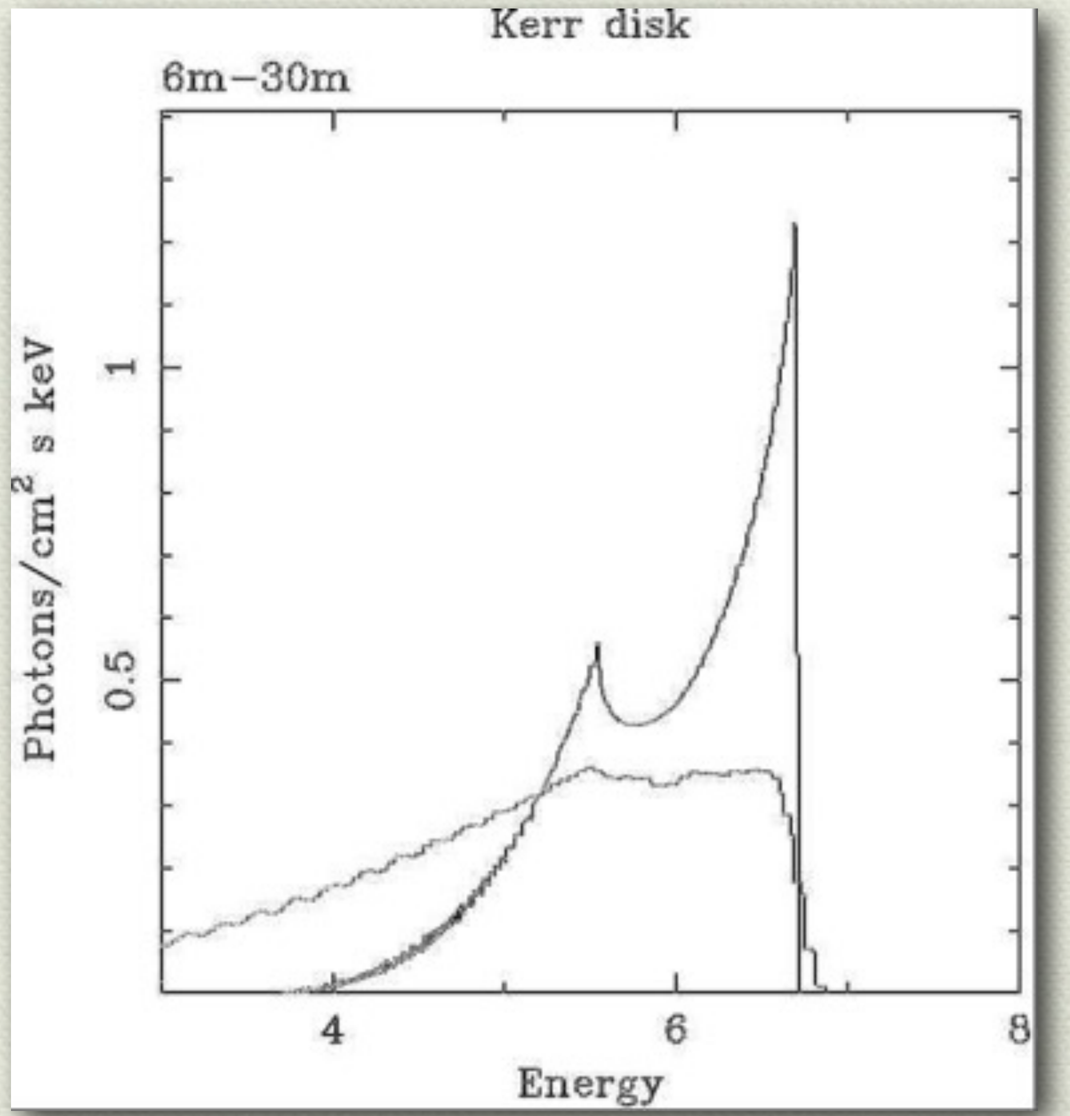
- Inclination of disk
- Blue wing
- Red wing

- The blue wing gives you the inclination



Fabian (2002)

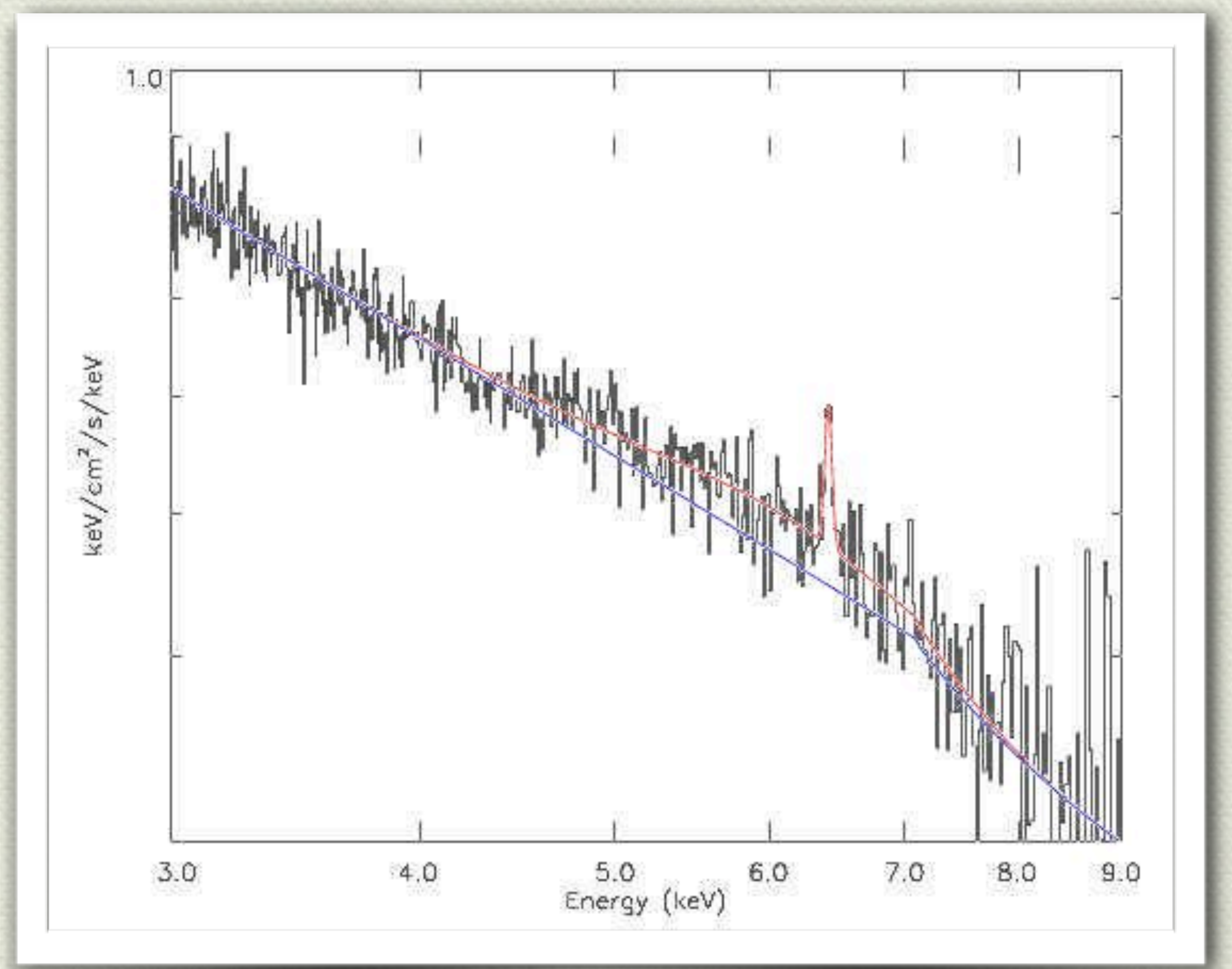
- Inner disk radius
- Blue wing
- Red wing
- The red wing gives the inner radius
- Again: continuum effects

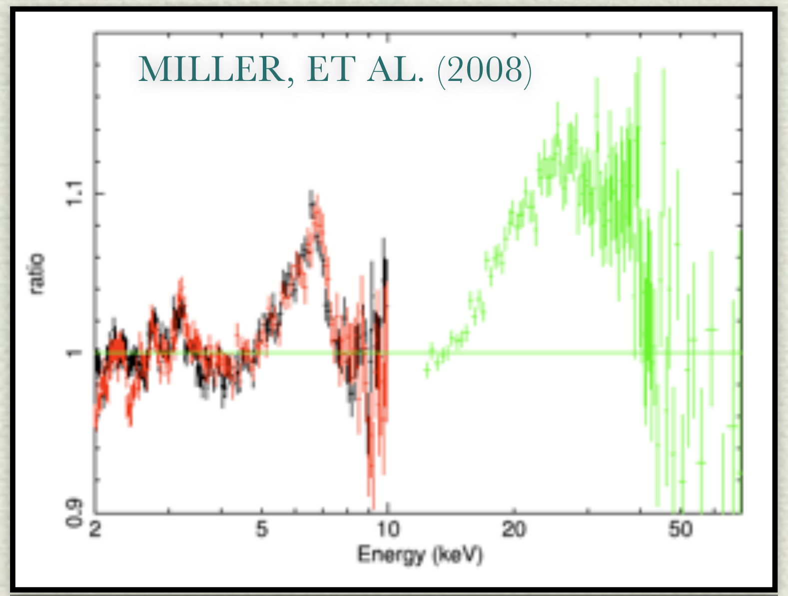


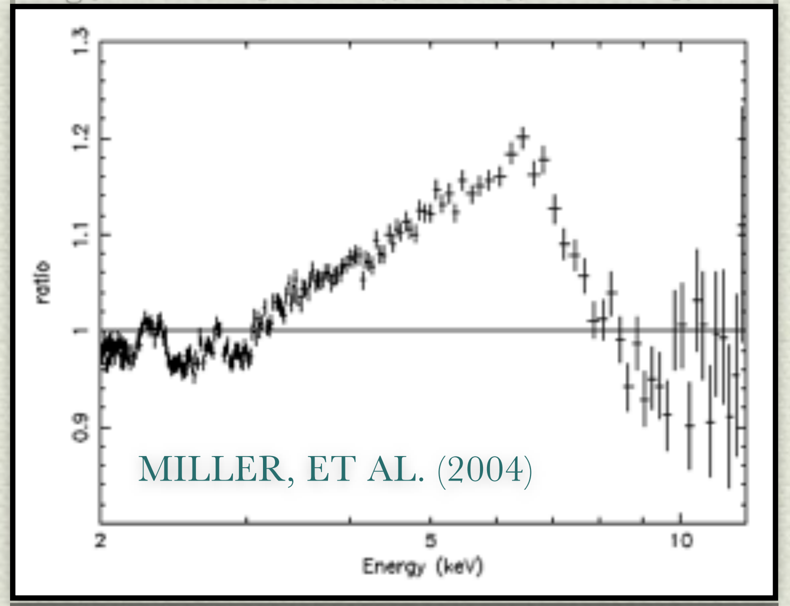
Fabian (2002)

Tricky points

- Ratio plots
- These are "not" lines

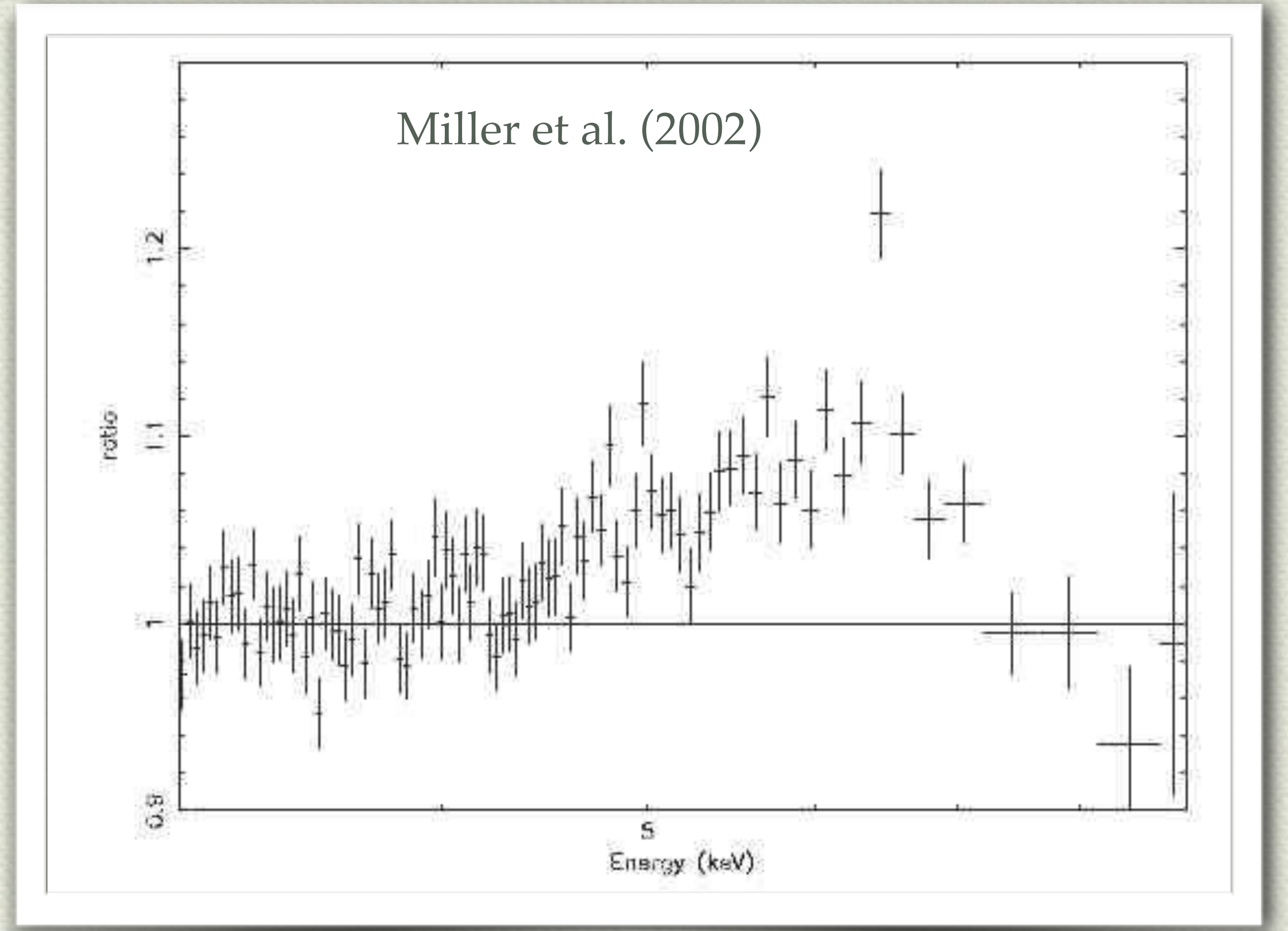






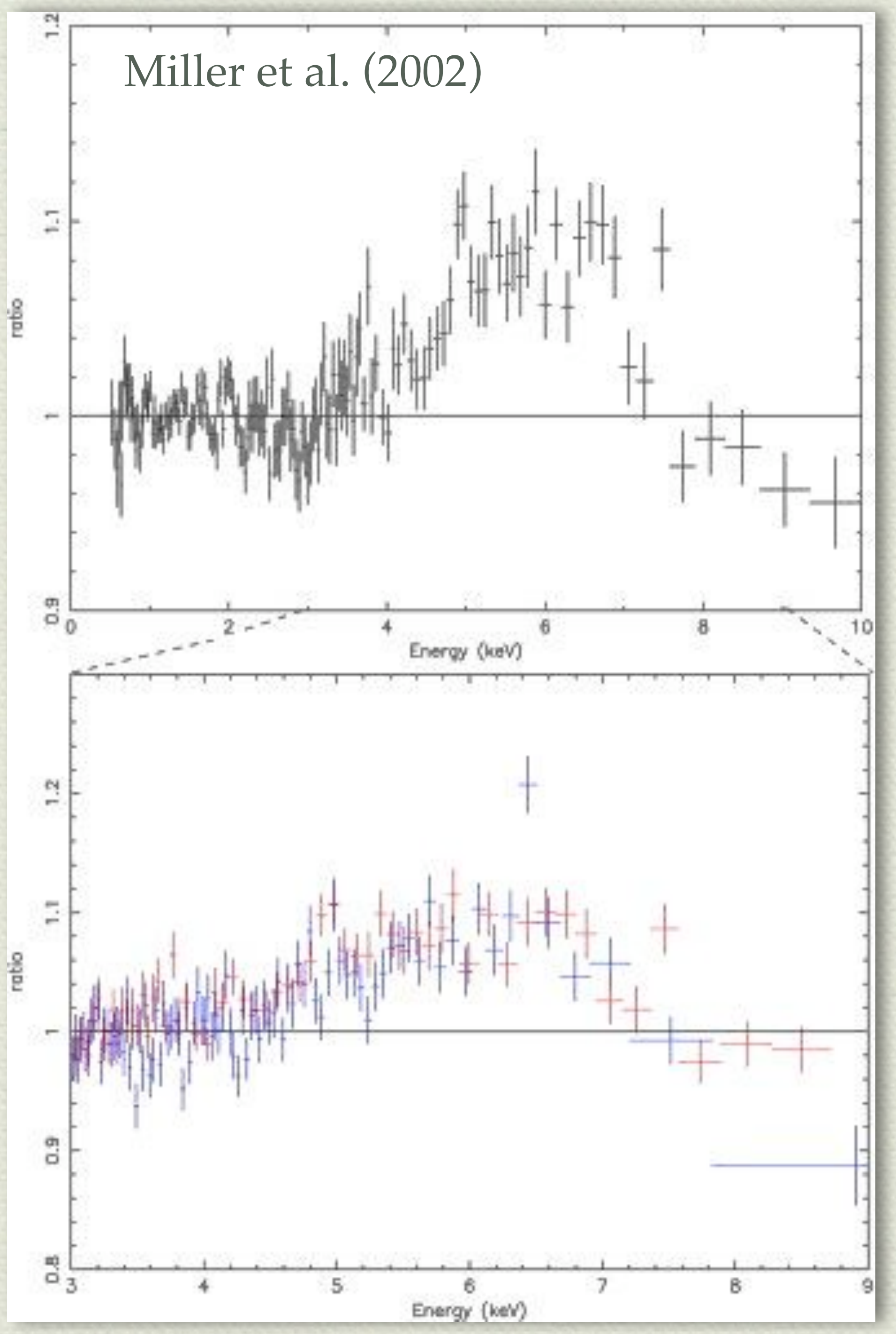
Examples

- Cygnus X-1
- Narrow lines: reflection in outer disk
- Broad line
- Consistent with $\theta \sim 40^{o}$ $R_{in} = 7R_g$
- Also consistent with Gaussian



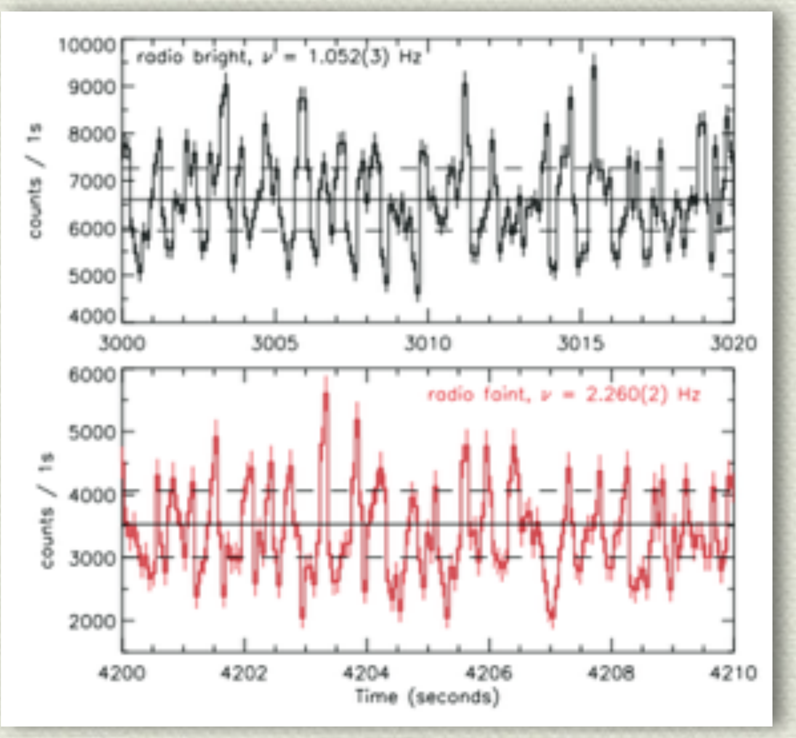
Examples

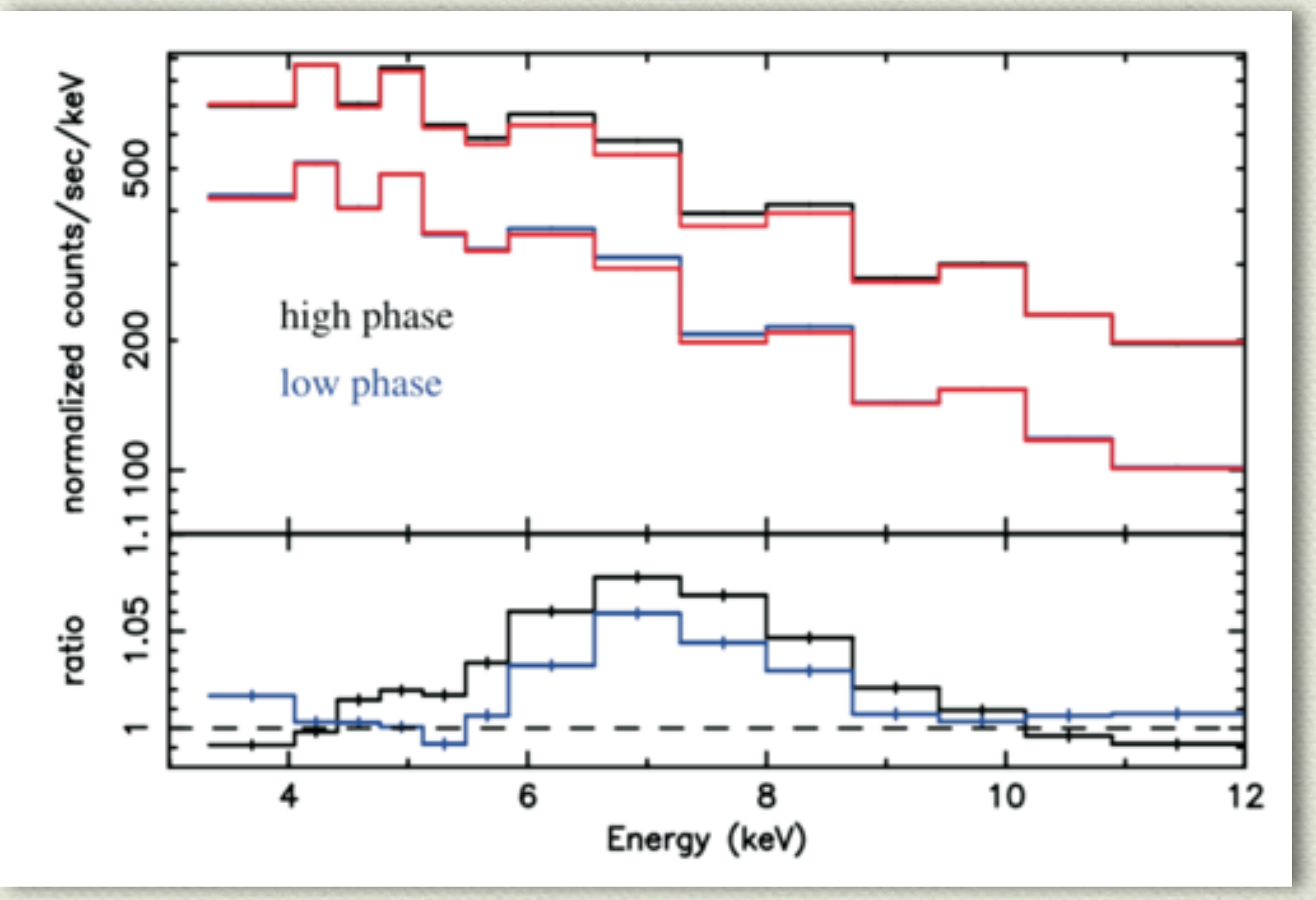
- XTE J1650-500
- Very broad skewed line
- $R_{in} = 1.24\ R_g$
- $a = 0.998$



Iron-line & timing

- In GRS 1915+105: line varies with oscillation   Miller & Homan (2005)
- Flux & equiv. width vary

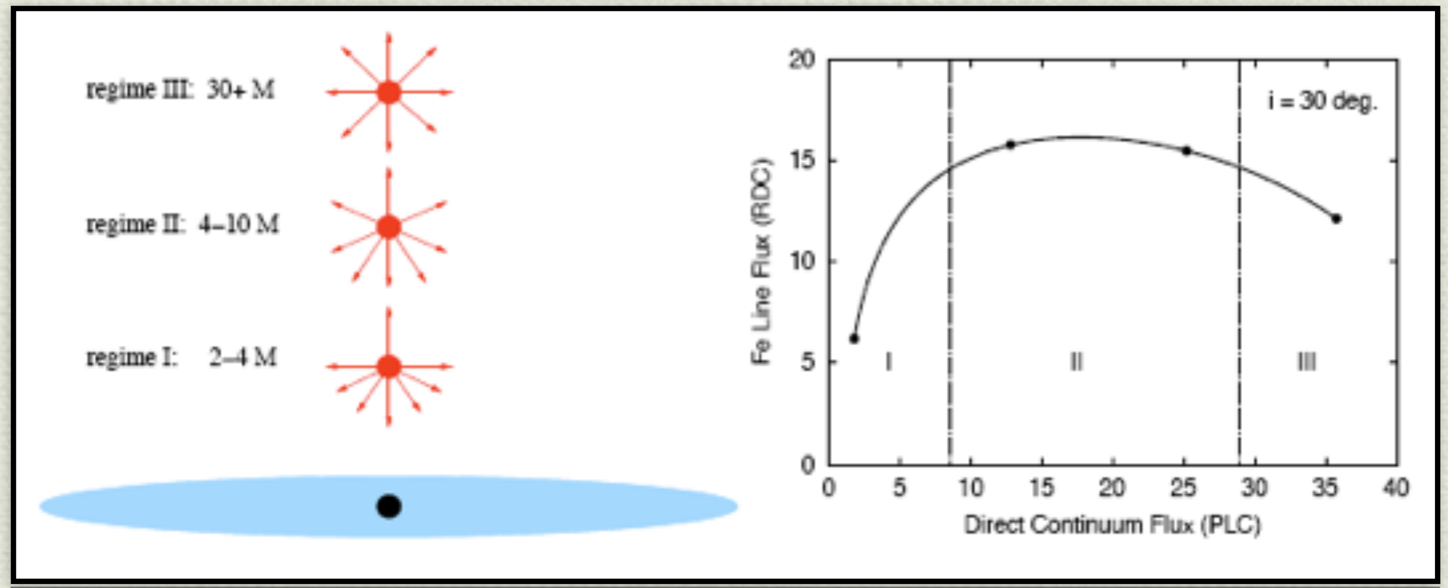


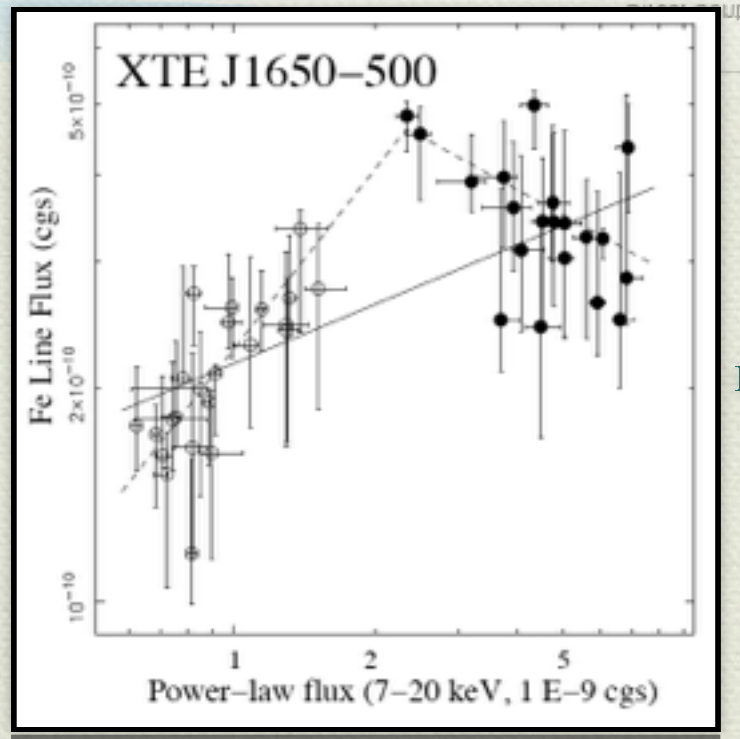


Light bending

- In some AGN, line & continuum vary independently
- Light is bent
- Variable height
- Seen in XTE J1650-500?

MINIUTTI & FABIAN (2004)





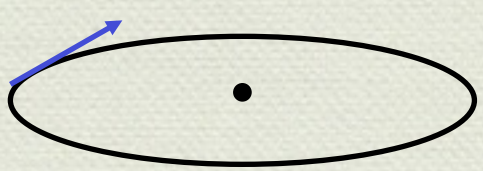
ROSSI ET AL. (2005)

Spin III: timing features

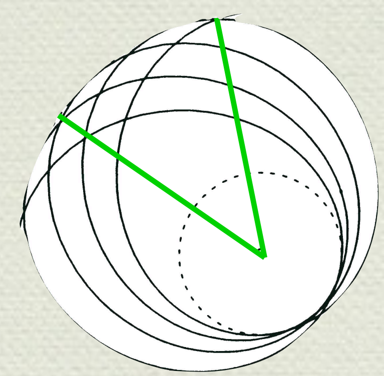
- What do all these QPOs and noises mean?
- We are not sure
- In NS, highest frequency: Keplerian?
- Lower frequencies?
- Unified models needed from correlations
- NS connection

Relativistic precession

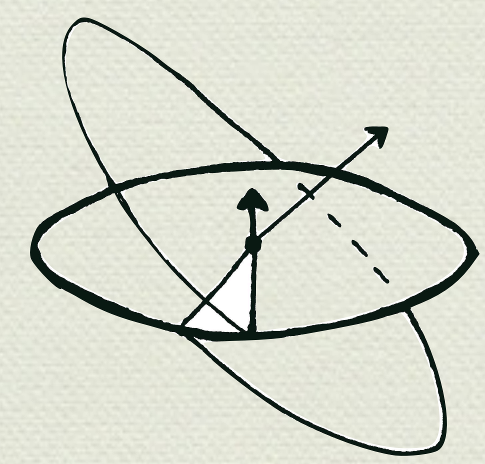
- A "model"
- Take a test particle in a field



φ–Frequency ν_φ

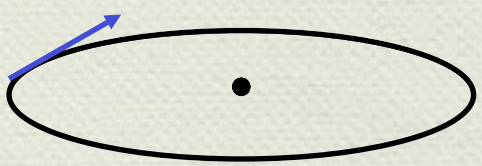


Periastron Precession Frequency: ν_{per}

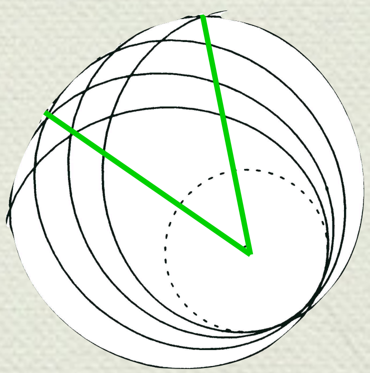


Nodal Precession Frequency: ν_{nod} (or $2\nu_{nod}$)

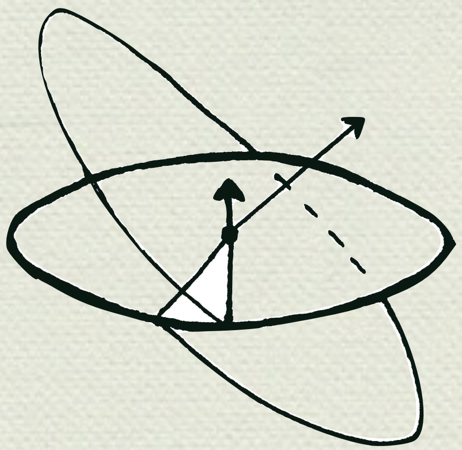
Relativistic precession



φ–Frequency
ν_φ



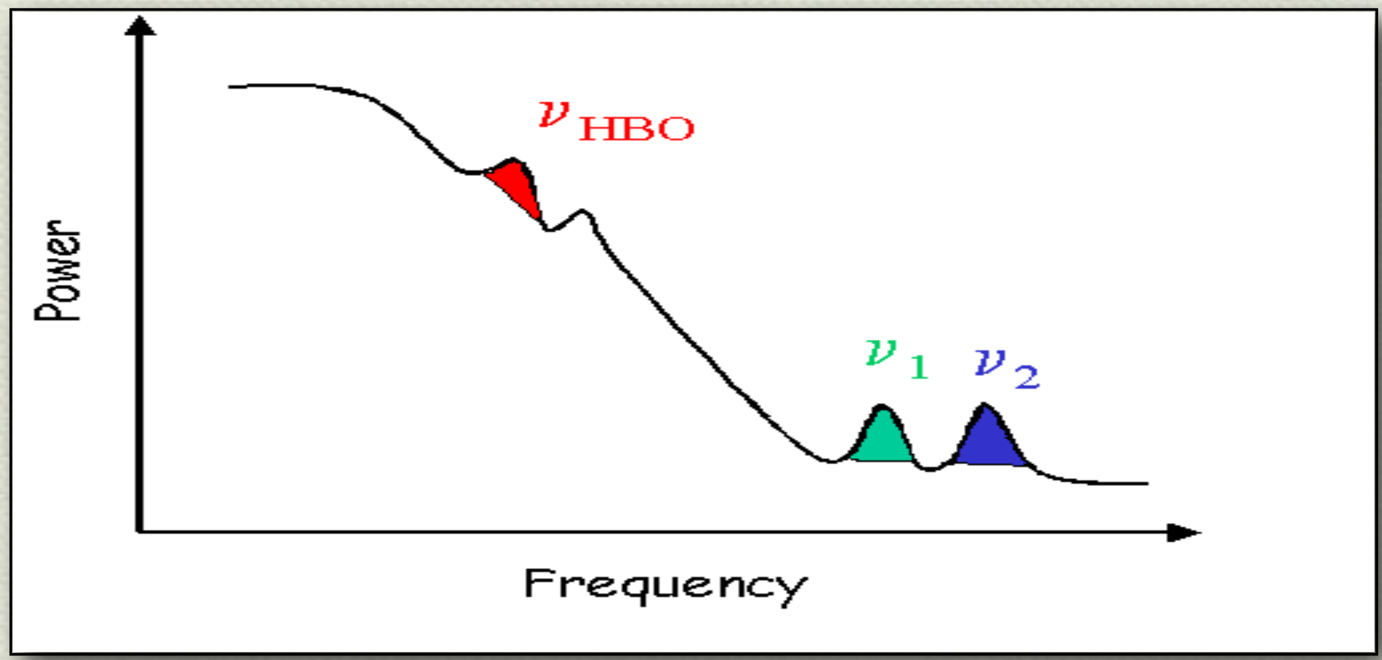
Periastron Precession
Frequency: ν_{per}



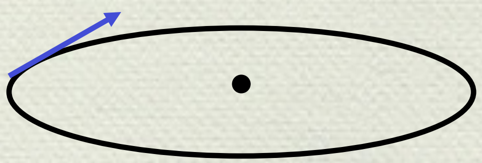
Nodal Precession
Frequency: ν_{nod}
(or $2\nu_{nod}$)

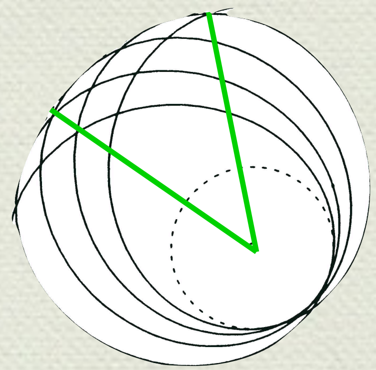
Neutron Star LMXB
(High Flux)

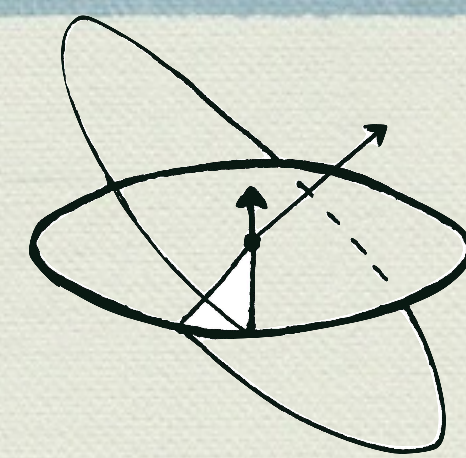
Stella, Vietri & Morsink (1999)



Relativistic precession







φ-Frequency

ν_{φ}

Periastron Precession

Frequency: ν_{per}

Nodal Precession

Frequency: ν_{nod}

(or $2\nu_{nod}$)

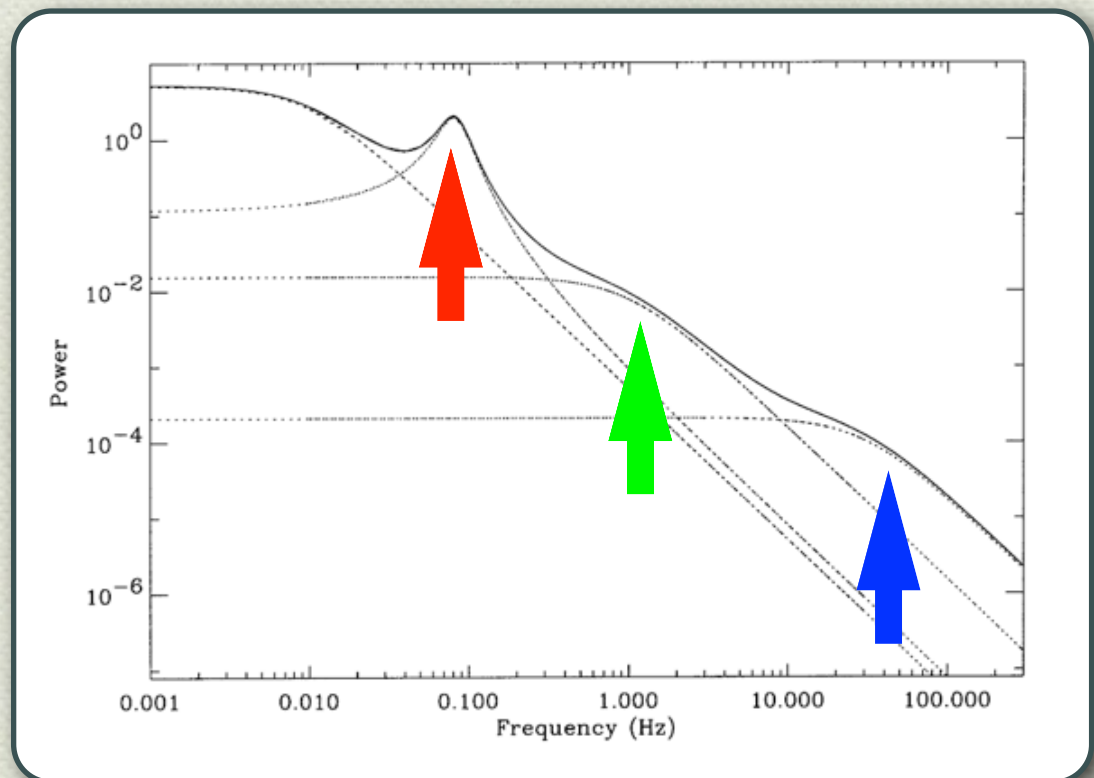
Neutron Star LMXB

(Low Flux)

+

Black Hole Binary

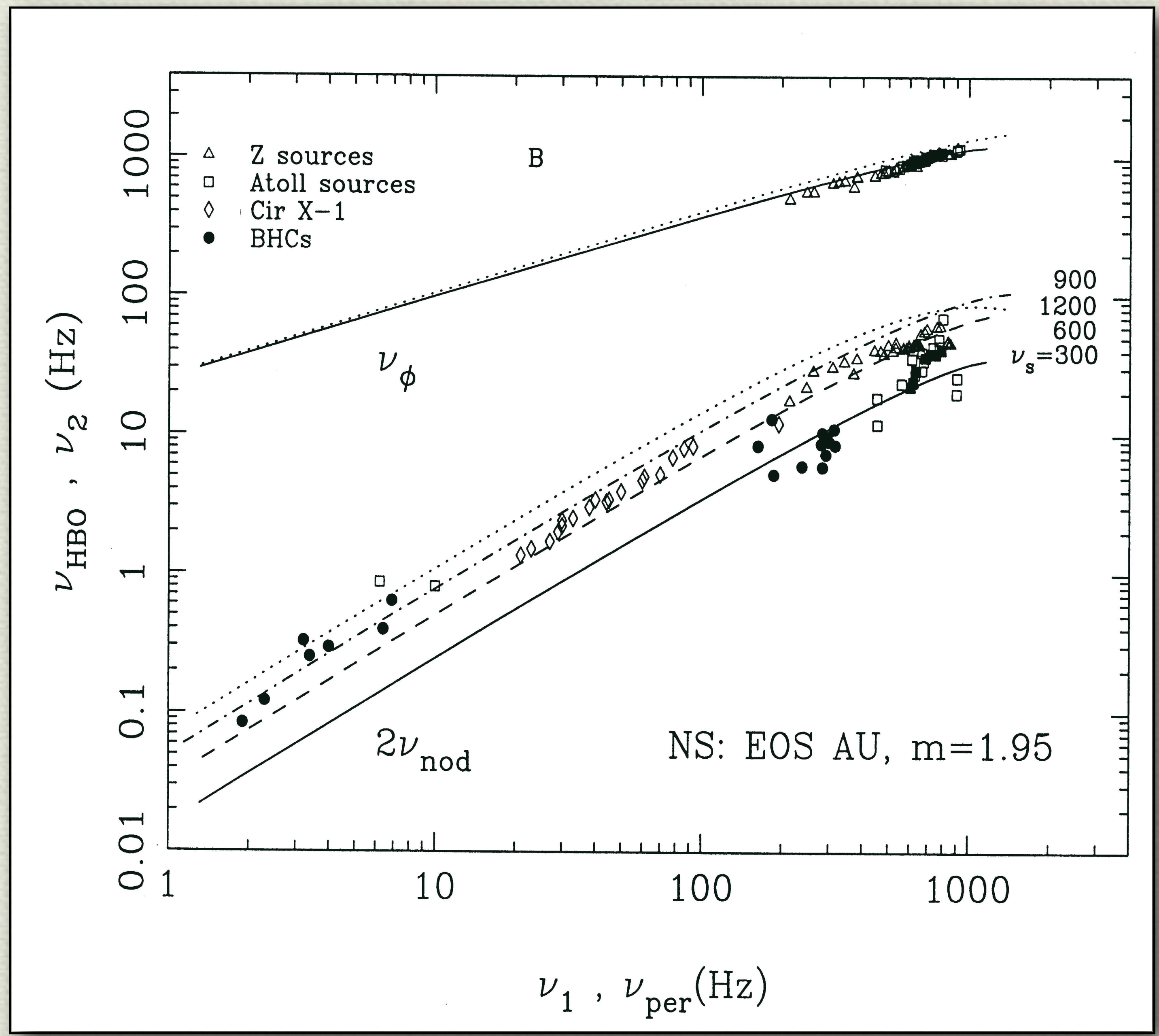
Stella, Vietri & Morsink (1999)



Relativistic precession

- Correlations...
- ... work

- Successes and ...
- .. limits of "model"

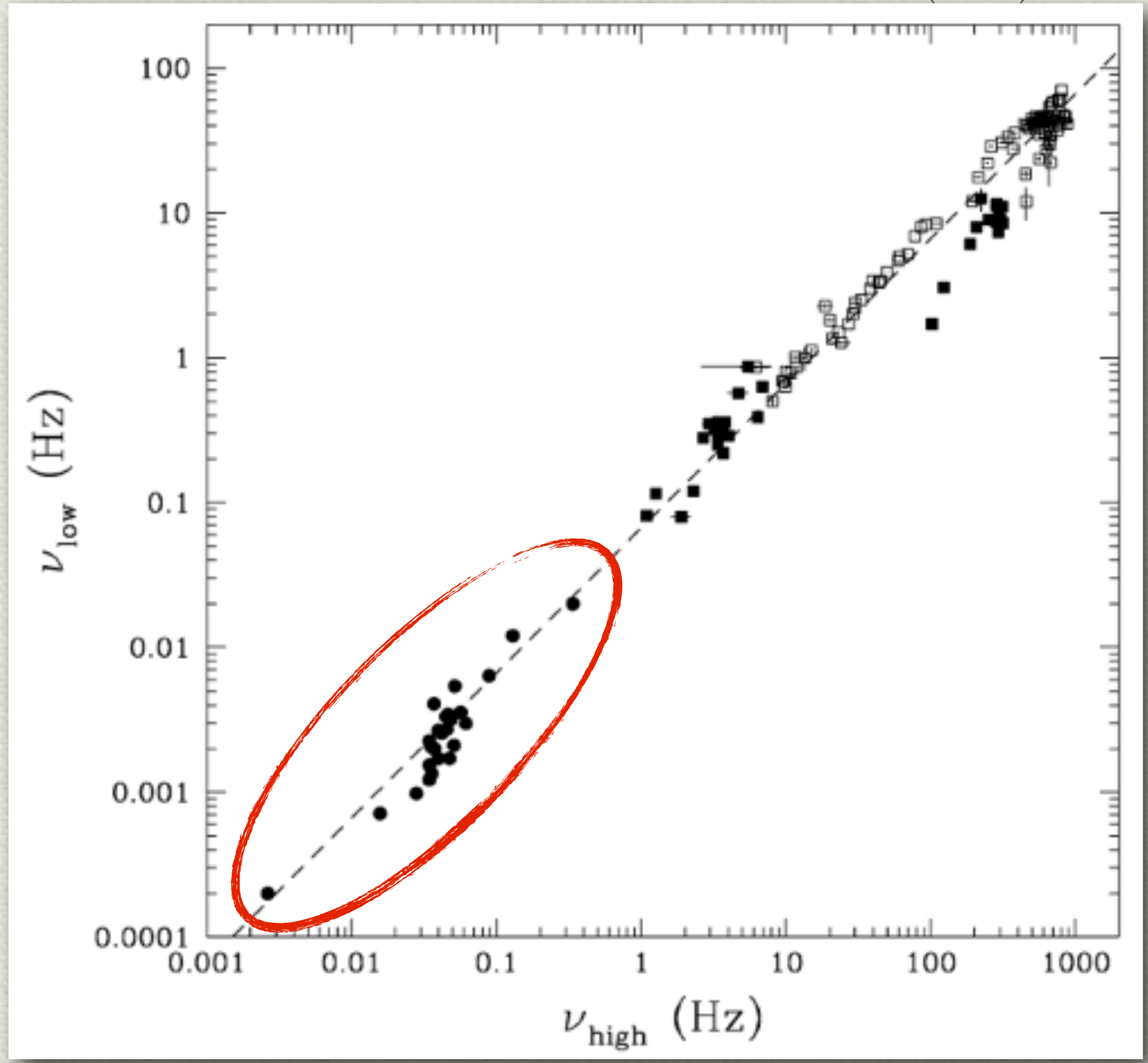


Stella, Vietri & Morsink (1999)

White dwarfs again

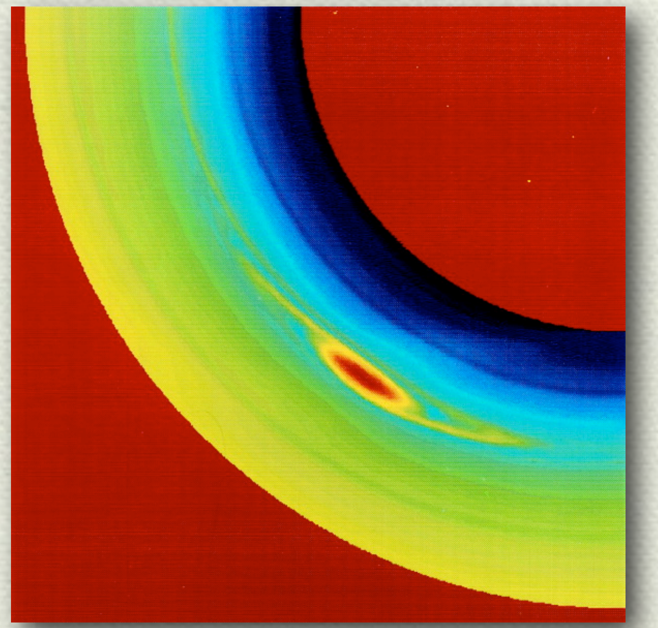
- Dwarf nova oscillations
- Problems...
- Same oscillations?

Warner, Woudt & Pretorius (2003)



Some caveats

- CVs?
- Blobs as test particles? Q problem
- Excitation mechanism?
- More advanced model required:
  - Disk annulus response — Psaltis & Norman (2000)
  - Vortices in the viscous disk — Vietri (2001)



Godon & Livio (1999)

Other models

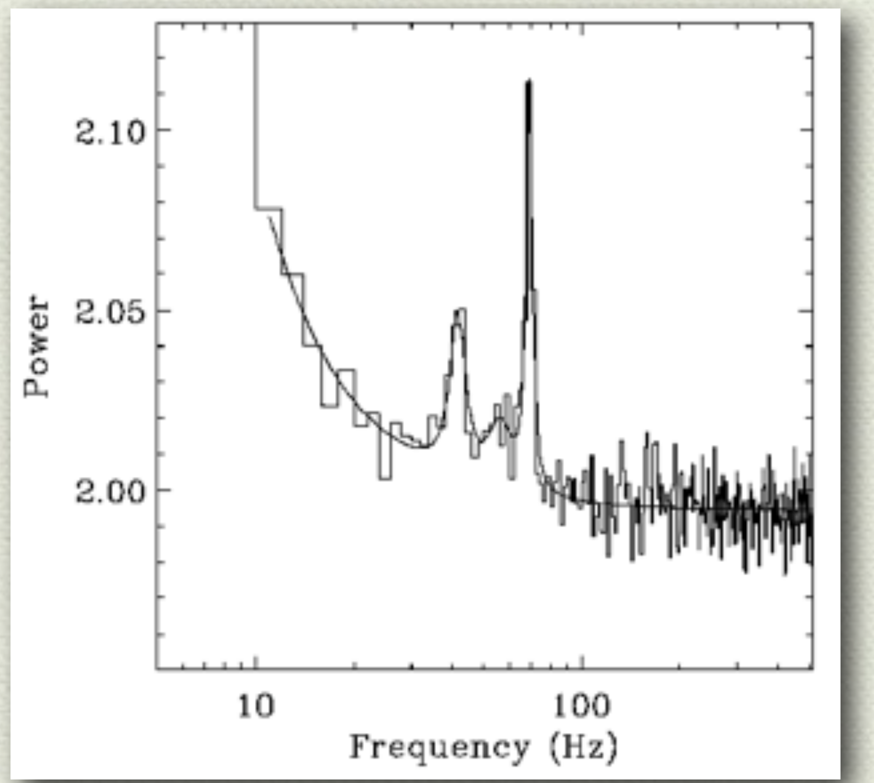
- Disk oscillations and trapped modes
- Disk warping (nodal precession)
- Parametric epicyclic resonance
- Titarchuk's model within sub-keplerian region

- All relate to GR frequencies
- Strong regime!

HFQPO and resonances

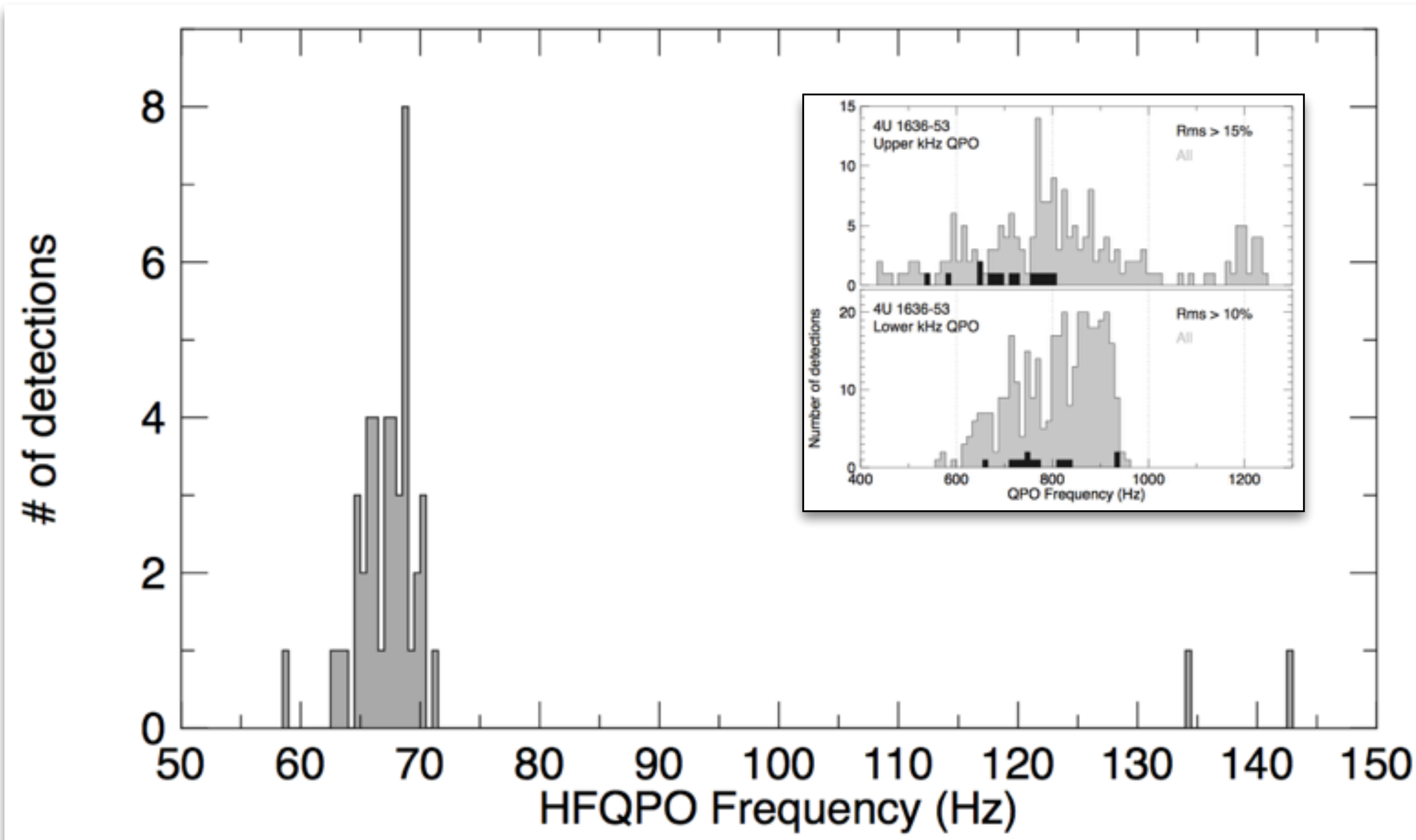
Abramowicz & Kluzniak (2001)

- 2:3 ratios, fixed frequencies
- Resonance between orbital and epicyclic frequencies
- It could work...
- ... but **not** for neutron stars
- Which should not be a problem



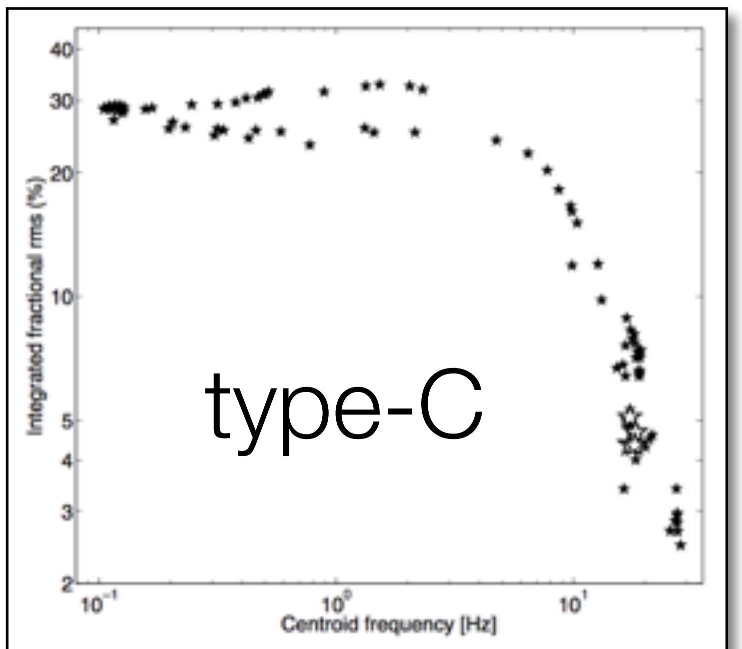
GRS 1915+105

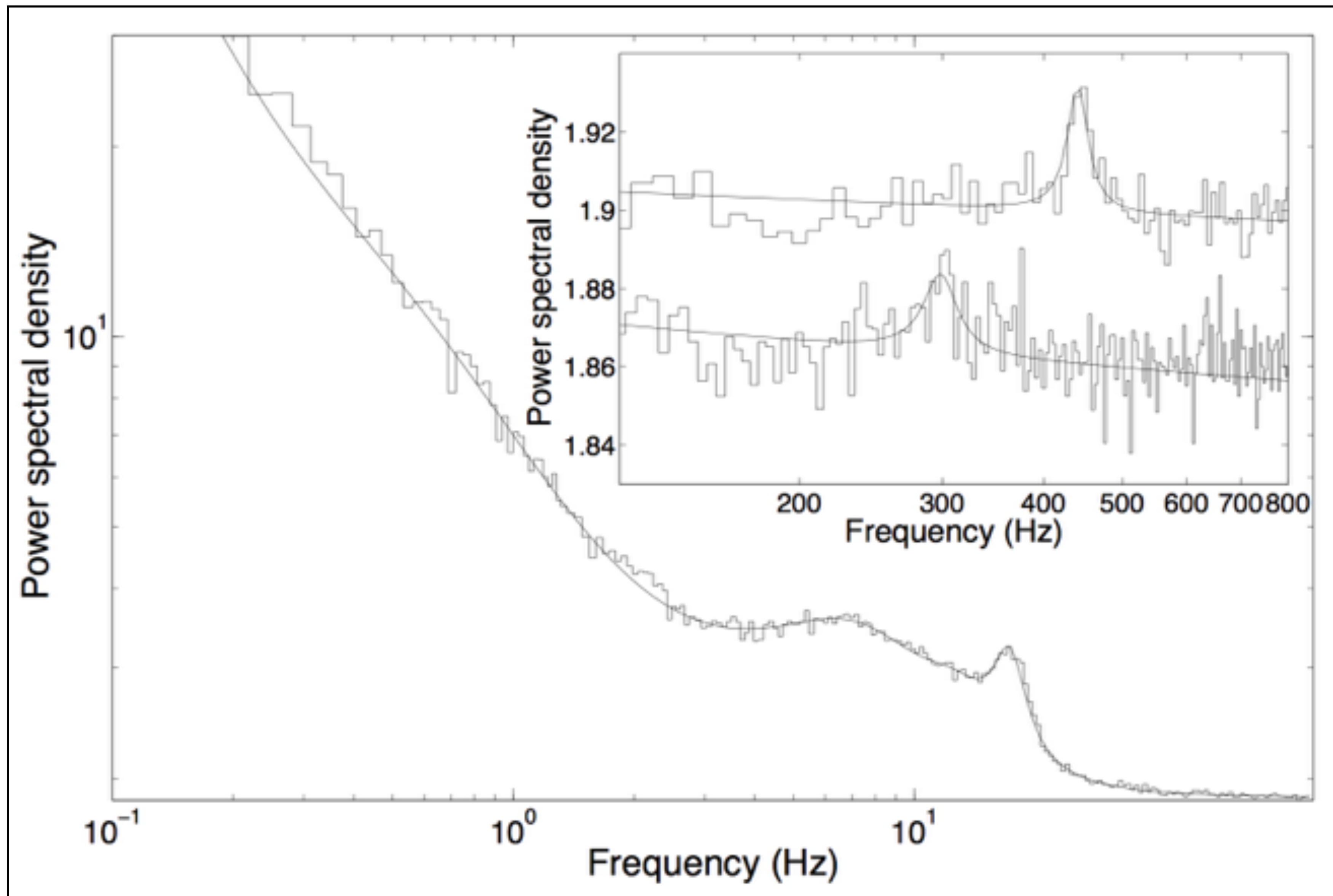
Belloni & Altamirano (2012)



GRO J1655-40: UNIQUE SOURCE

Only source which shows simultaneous type-C and 2xHFQPO



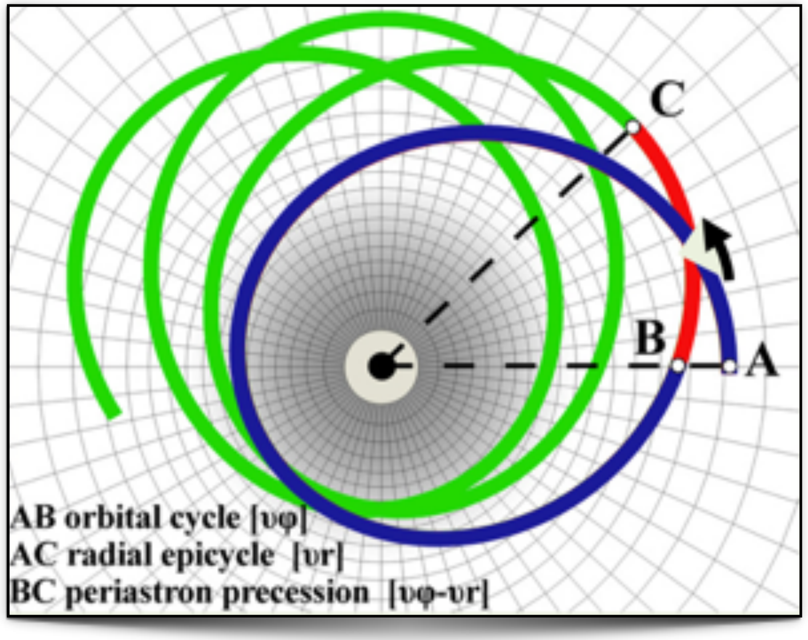


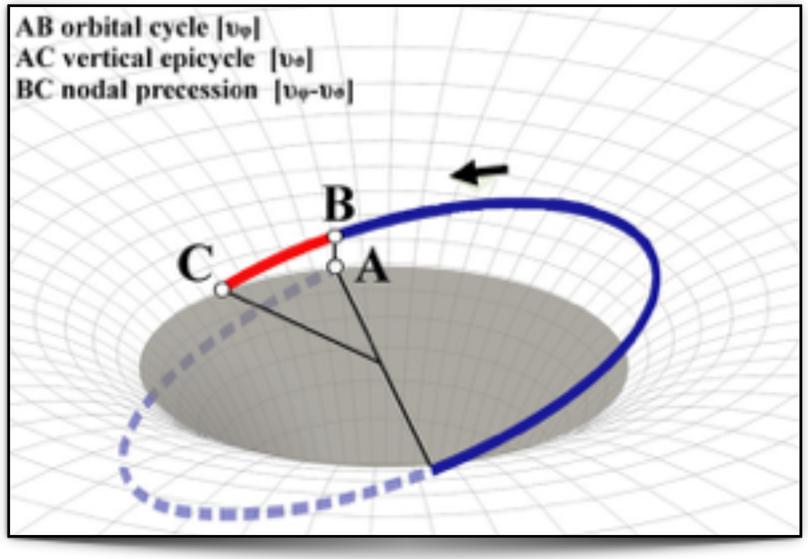
MOTTA, BELLONI ET AL. (2014A)

MODELS CAN BE TESTED

- The Relativistic Precession Model (RPM) predicts three frequencies
- Relativistic frequencies: keplerian, nodal, Lense-Thirring
- We have three frequencies

typeC = 17.3 +- 0.1 Hz
lower = 298 +/- 4 Hz
upper = 441 +/- 2 Hz





STELLA & VIETRI 1998; STELLA, VIETRI & MORSINK 1999

THREE EQUATIONS

$$\nu_\phi = \pm\frac{1}{2\pi}\left(\frac{M}{r^3}\right)^{1/2}\frac{1}{1\pm a\left(\frac{M}{r}\right)^{3/2}}$$

$$\nu_{per} = v_\phi\left(1-\left(1-\frac{6M}{r}-3a^2\left(\frac{M}{r}\right)^2\pm 8a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)$$

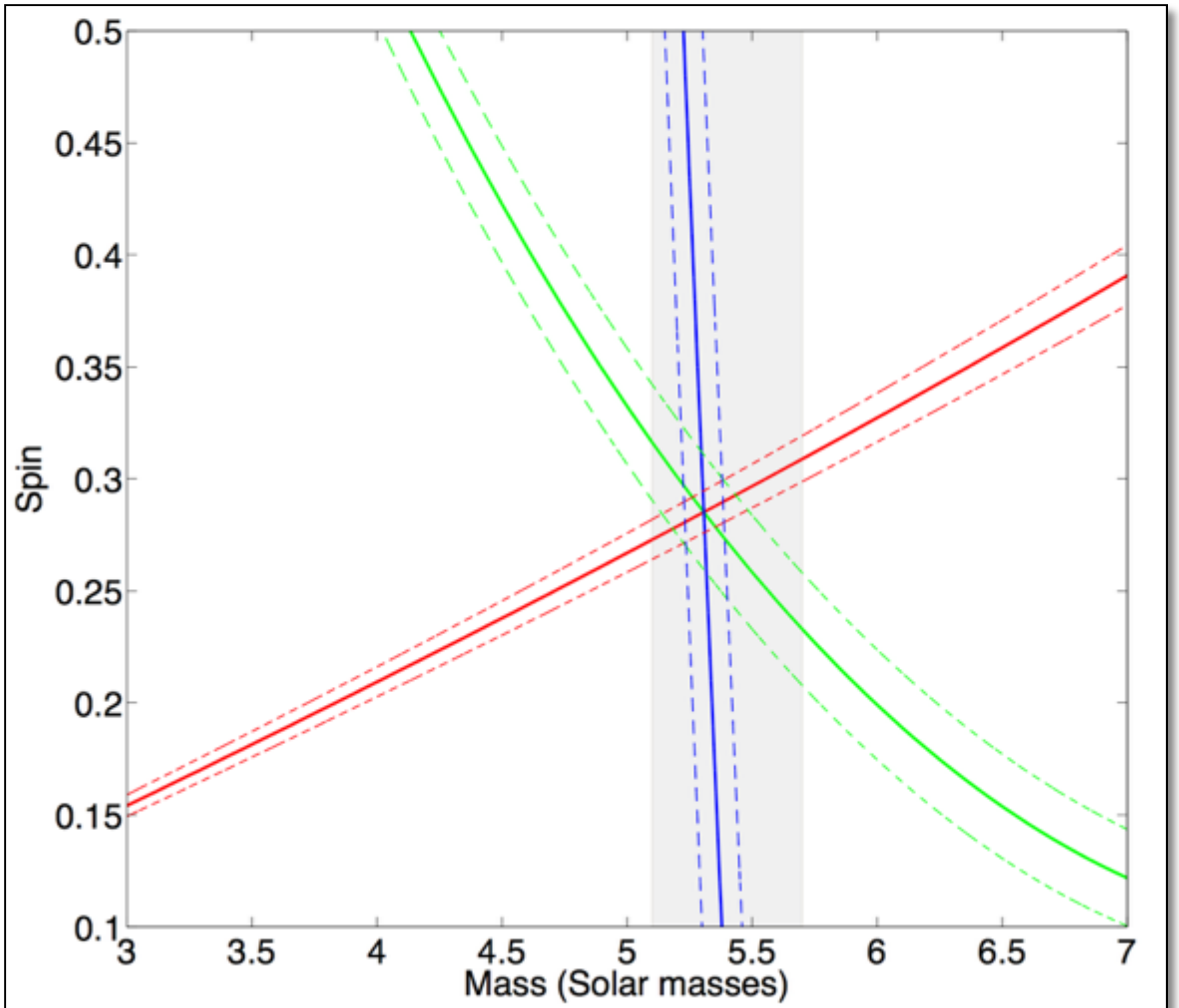
$$\nu_{nod} = v_\phi\left(1-\left(1+3a^2\left(\frac{M}{r}\right)^2\mp 4a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)$$

We have the three frequencies, we can solve for *a*,*M*,*r*

MOTTA, BELLONI ET AL. (2014A)

THREE EQUATIONS

$$
\begin{aligned}
\nu_\phi &= \pm\frac{1}{2\pi}\left(\frac{M}{r^3}\right)^{1/2}\frac{1}{1\pm a\left(\frac{M}{r}\right)^{3/2}}\\
\nu_{per} &= \nu_\phi\left(1-\left(1-\frac{6M}{r}-3a^2\left(\frac{M}{r}\right)^2\pm 8a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)\\
\nu_{nod} &= \nu_\phi\left(1-\left(1+3a^2\left(\frac{M}{r}\right)^2\mp 4a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right) \qquad (7)
\end{aligned}
$$



Solution for

$a = 0.29 \pm 0.01$

$M = 5.31 \pm 0.07\ M_\odot$

$R = 5.68 \pm 0.04\ R_g$

Dynamical mass:

$M = 5.4 \pm 0.3\ M_\odot$

MOTTA, BELLONI ET AL. (2014A)

ISCO AND MAXIMUM FREQUENCIES

$$r_{\rm ISCO} = M\left(3 + Z_2 \mp ((3 - Z_1)(3 + Z_1 + 2Z_2))^{1/2}\right)$$

$$Z_1 = 1 + \left(1 - \frac{a^2}{r_g}\right)^{1/3}\left(\left(1 + \frac{a}{r_g}\right)^{1/3} + \left(1 - \frac{a}{r_g}\right)^{1/3}\right)$$

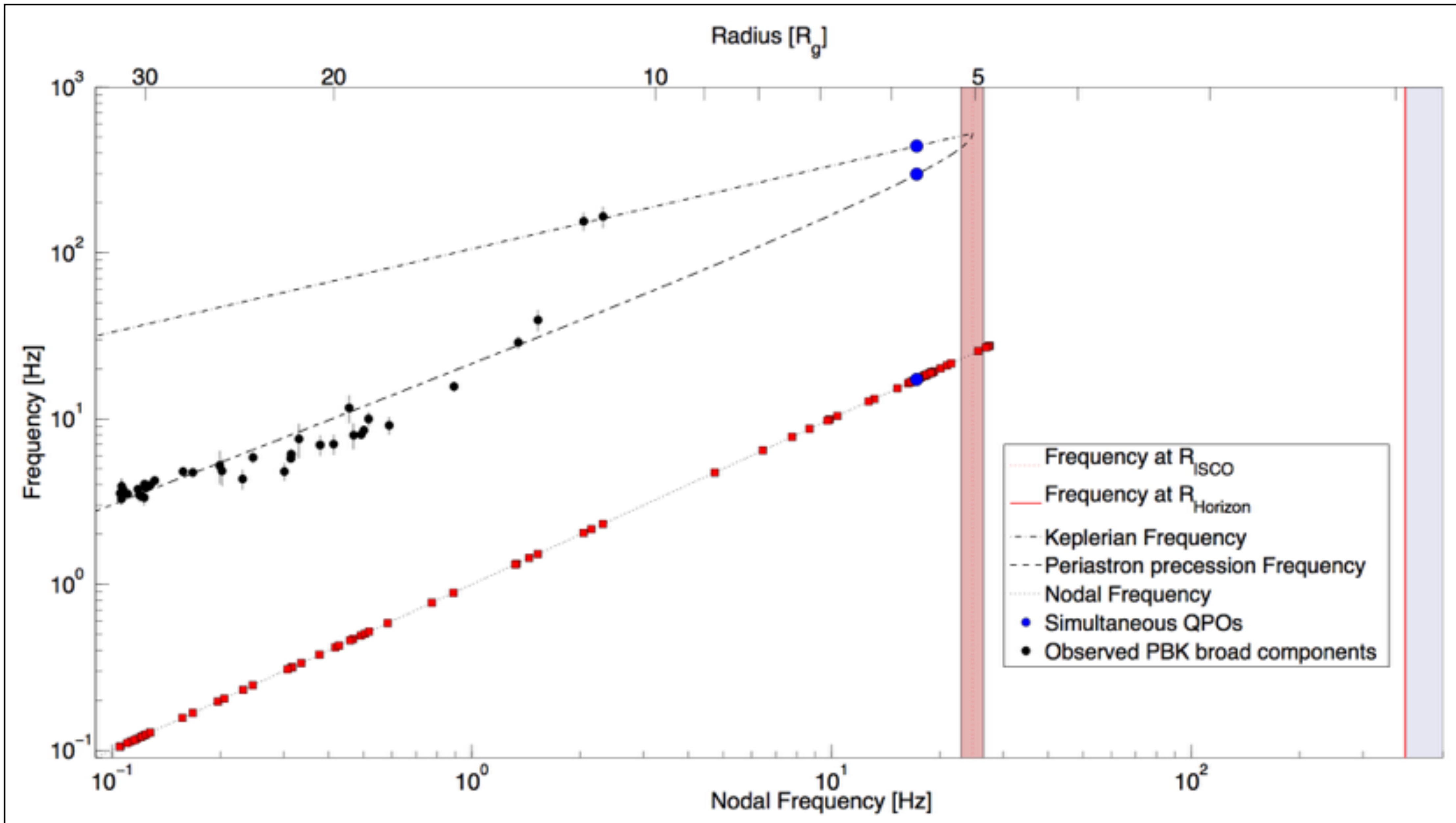
$$Z_2 = \left(\frac{3a^2}{r_g} + Z_1^2\right)^{1/2}$$

$R_{\rm ISCO} = 5.03\ R_g$

- No frequencies above maximum values
- Few HFQPO, ~same frequency
- Lots of type-C QPO 0.1-28 Hz

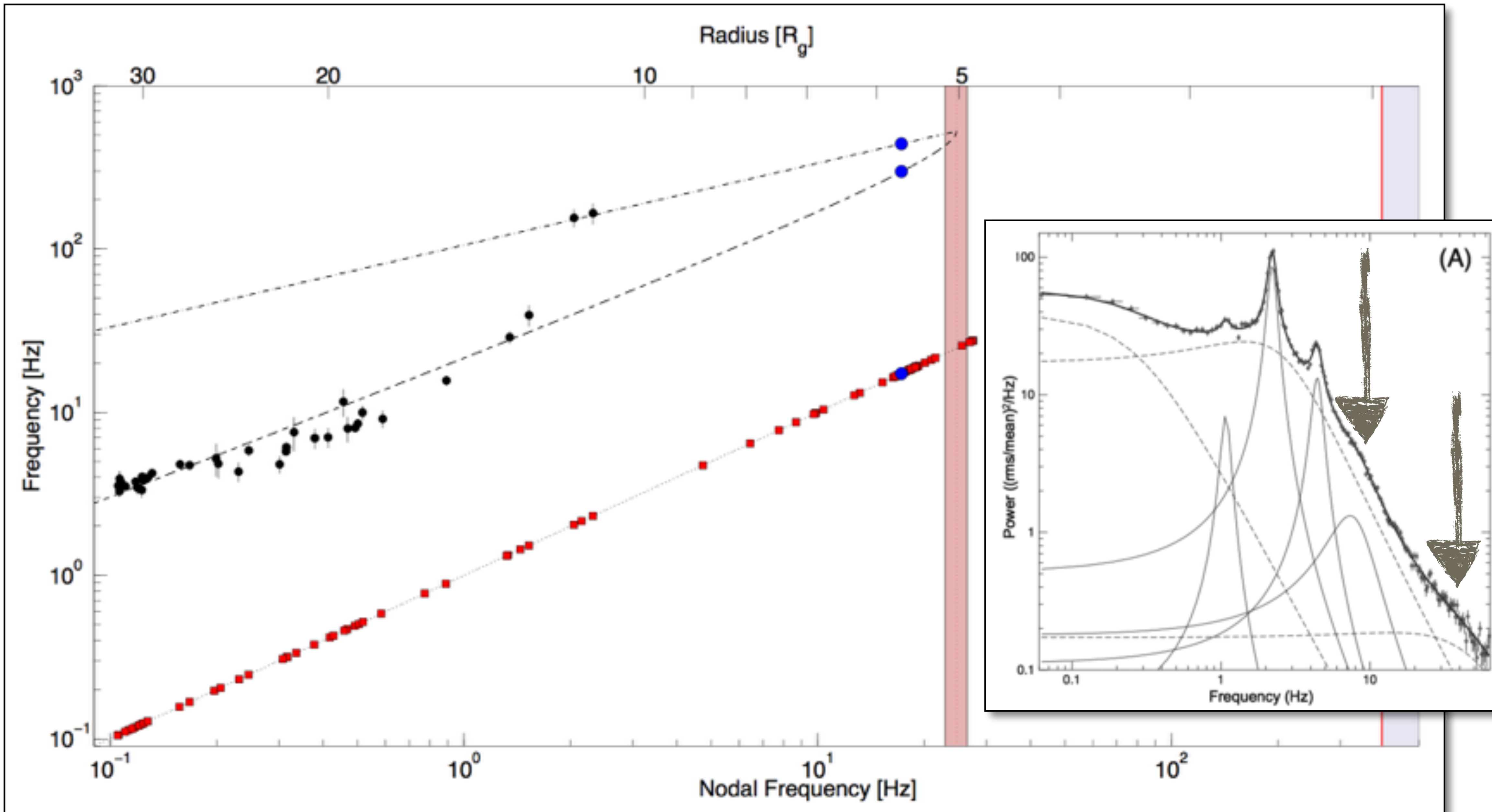
MOTTA, BELLONI ET AL. (2014A)

ISCO AND MAXIMUM FREQUENCIES



MOTTA, BELLONI ET AL. (2014A)

NOISE FREQUENCIES FIT IN



MOTTA, BELLONI ET AL. (2014A)

QPO WIDTH

- QPOs from the same radius
- Width due to radius jitter?
- We can jitter the radius: 1.74-2.4% is sufficient

QPO type	simulated width ($\Delta\nu$) $[Hz]$	Observed width $[Hz]$
Type-C QPO	2.11 - 2.90	2.1 - 4.2
Upper HFQPO	41.58 - 57.66	21.54 - 57.70
Lower HFQPO	26.77 - 36.83	24.06 - 37.74

MOTTA, BELLONI ET AL. (2014A)

SPIN COMPARISON

- Our value: a = 0.29 +/- 0.01 — MOTTA, BELLONI ET AL. (2013)
- Continuum: a = 0.65-0.75 — SHAFEE ET AL. (2006)
- Refl.+Cont: a = 0.94-0.98 — MILLER ET AL. (2009)
- Reflection: a > 0.9 — MILLER ET AL. (2009)

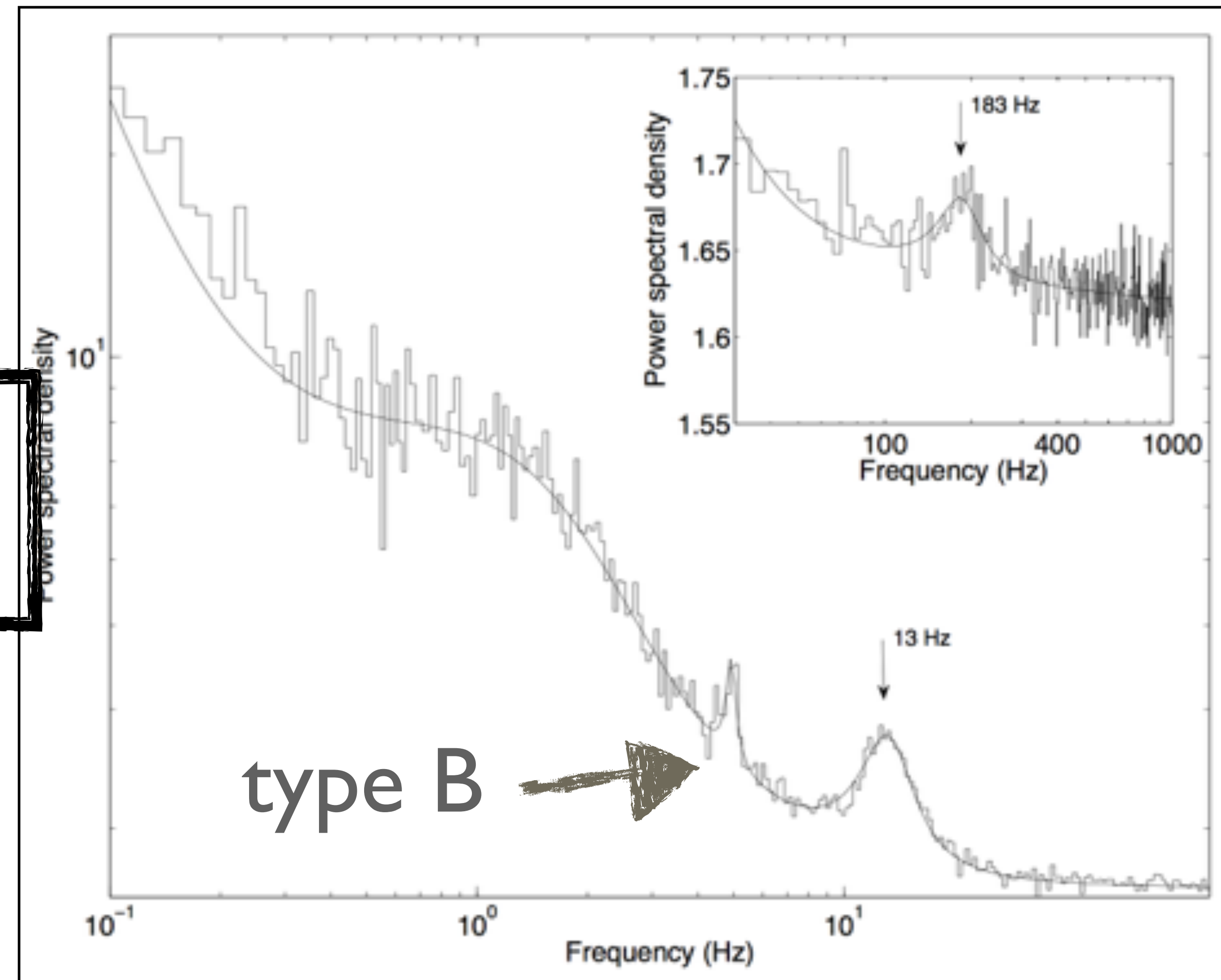
SOURCE #2 + MODEL

- GRO J1655-40 was the only source with 3 peaks (plus mass to check
- XTE J1550-564 has two peaks (type-C + HFQPO): plus dynamical mass we have again three parameters
- Use the mass instead of deriving it

XTE J1550-564: THE NEXT BEST

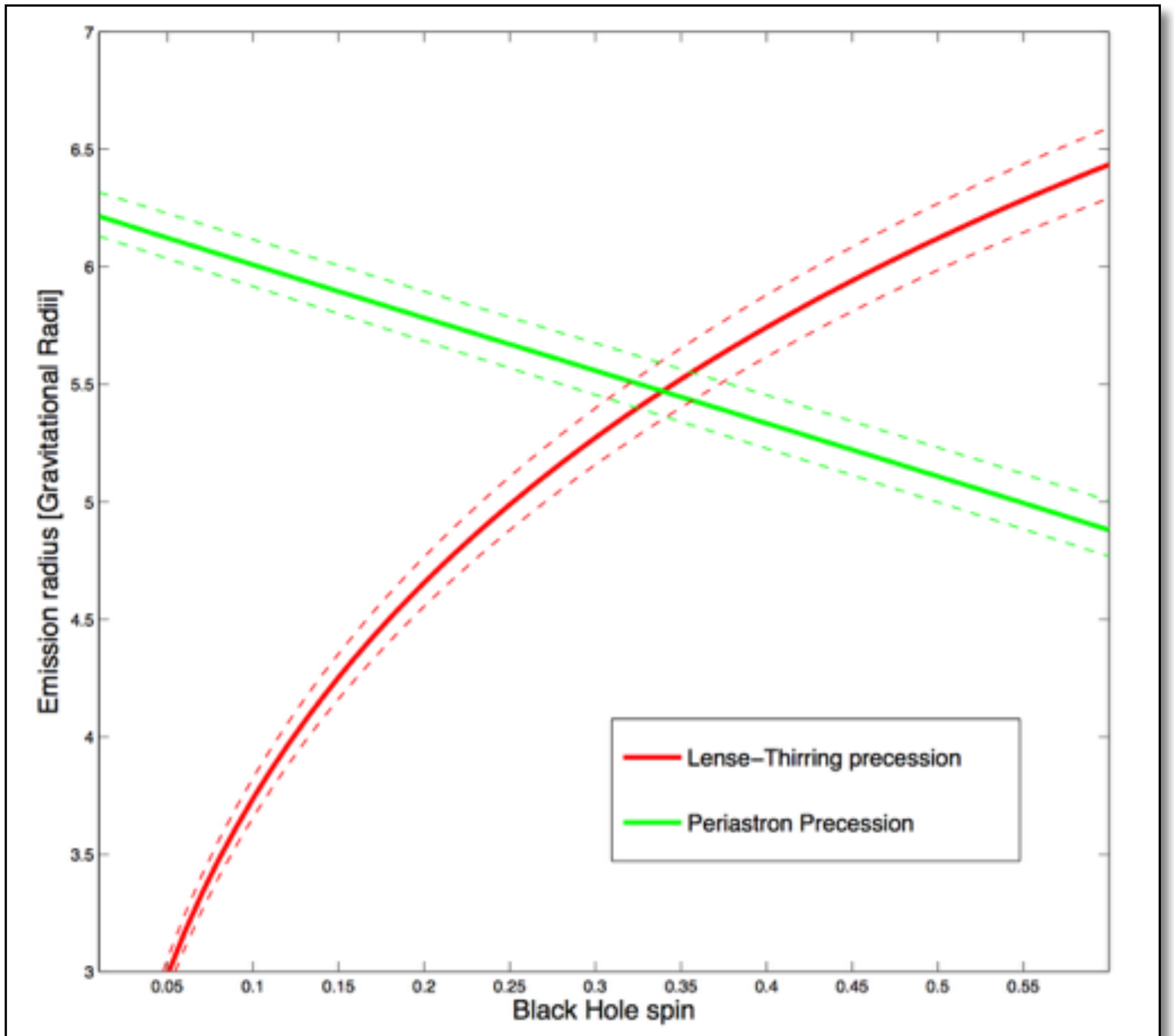
It shows simultaneous type-C and 1xHFQPO

typeC = 13.08 +- 0.08 Hz
HFQPO = 183 +/- 5 Hz



MOTTA ET AL. (2014B)

THREE EQUATIONS



Solution for

$a = 0.34 \pm 0.01$

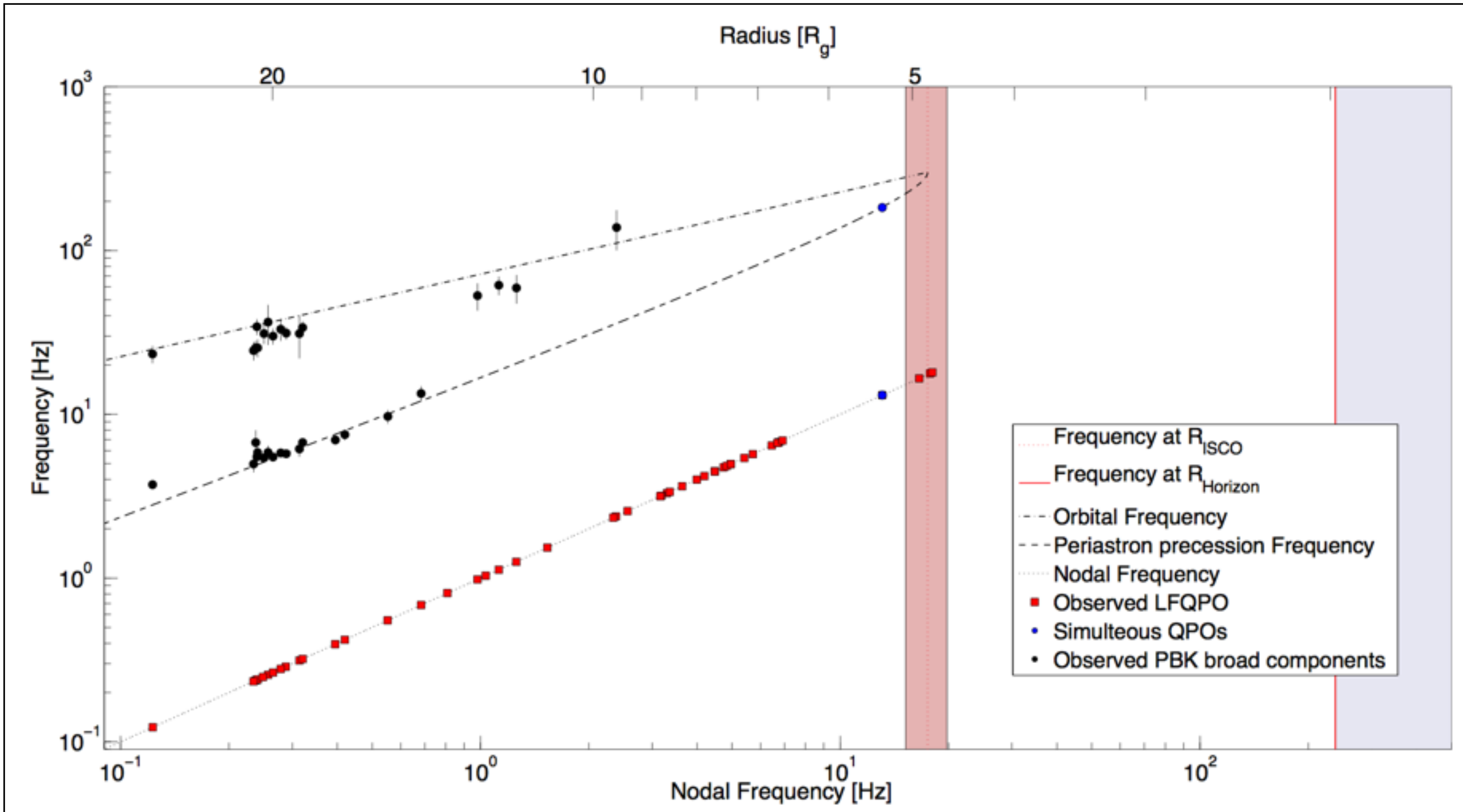
$R = 5.47 \pm 0.12\ R_g$

Dynamical mass:

$M = 9.1 \pm 0.6\ M_\odot$

MOTTA ET AL. (2014B)

ISCO AND NOISE



QPO WIDTH

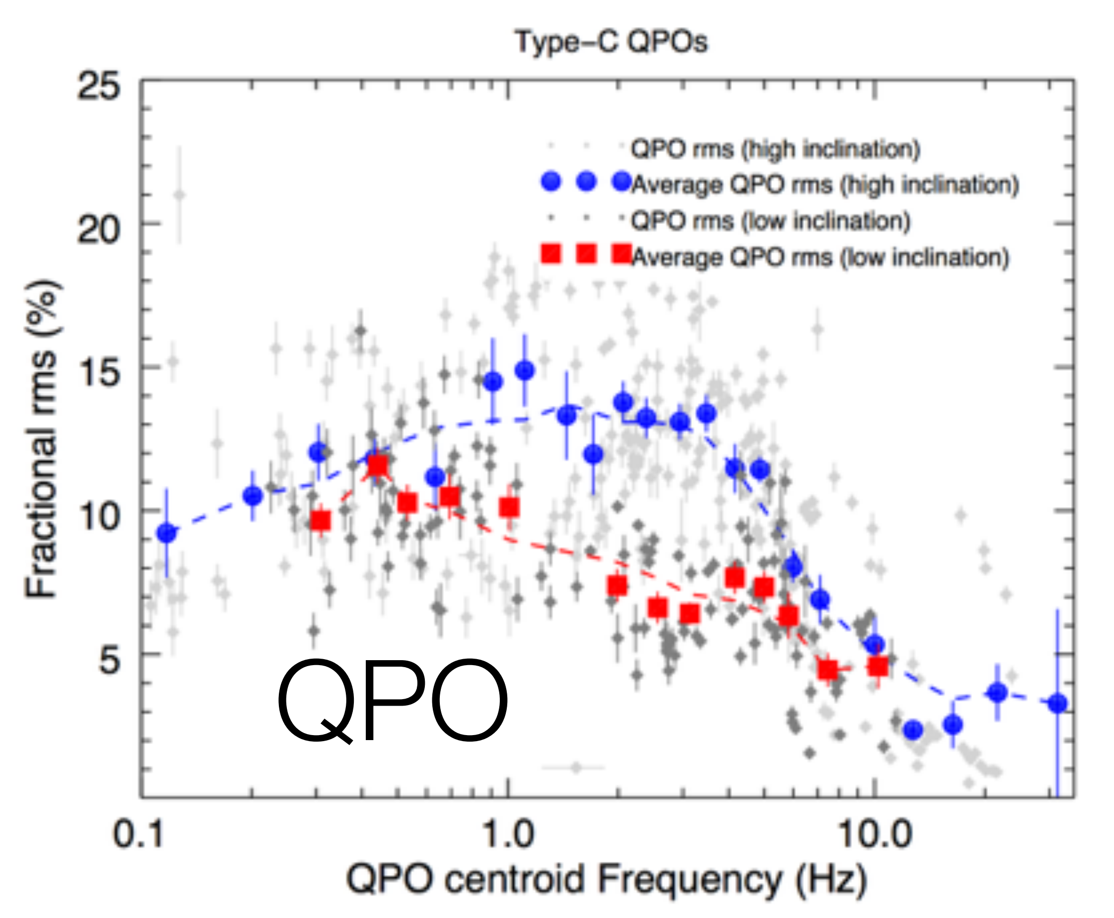
- We can jitter the radius: 5.3=5.7% is sufficient

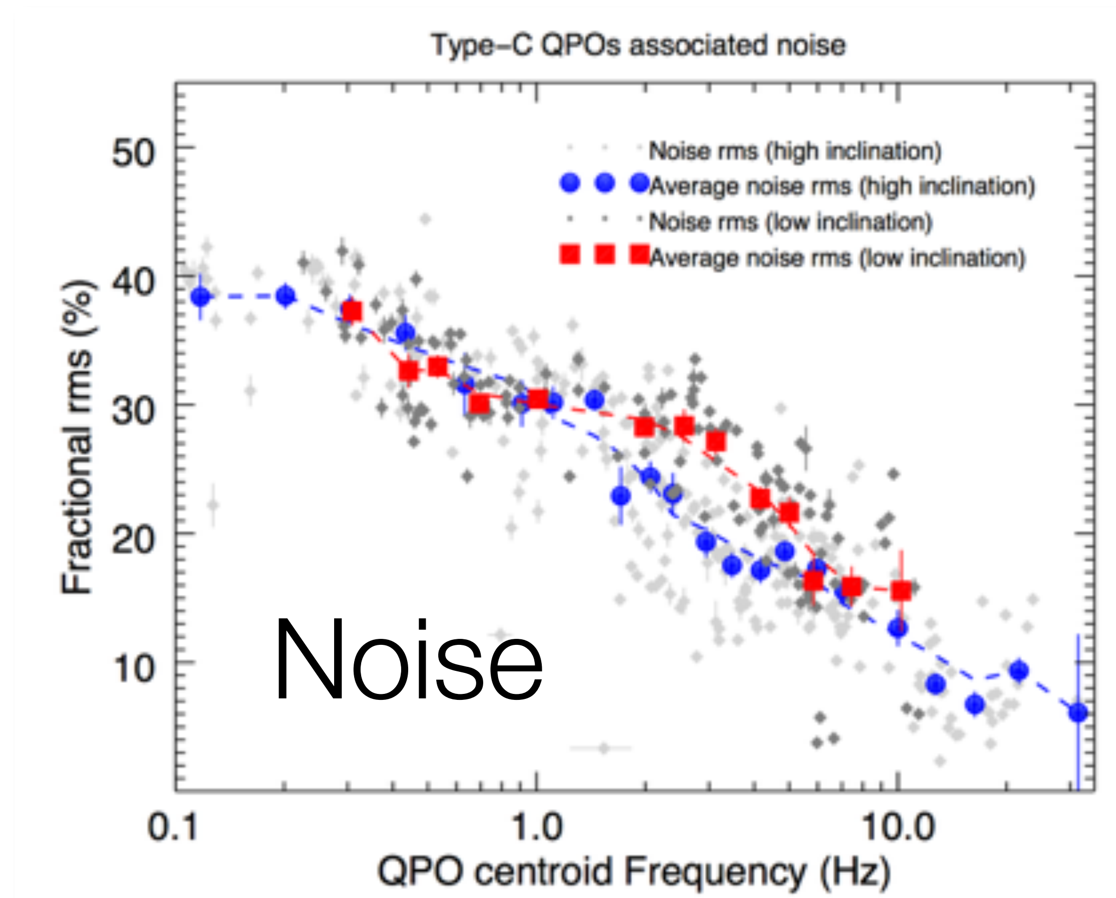
OTHER MEASUREMENTS

- Our value: a = 0.34 +/- 0.01 MOTTA ET AL. (2014B)
- Refl.+Cont: a = 0.49 (-0.20+0.13) STEINER ET AL. (2012)

INCLINATION EFFECTS

- If a relativistic effect in the disk, dependence expected





MOTTA ET AL. (2015)

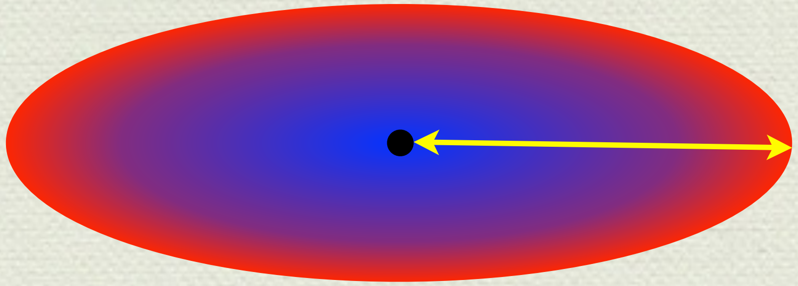
INCLINATION EFFECTS

- Type-C QPO: stronger at high inclinations: disk+GR
- Type-B QPO: stronger at low inclinations: jet
- Noise: no (weak) dependence: propagation in the disk

MOTTA ET AL. (2015)

Radii, radii, radii...

- Continuum spectra
- Broadened mission lines
- Timing features
- Compton reflection / light bending

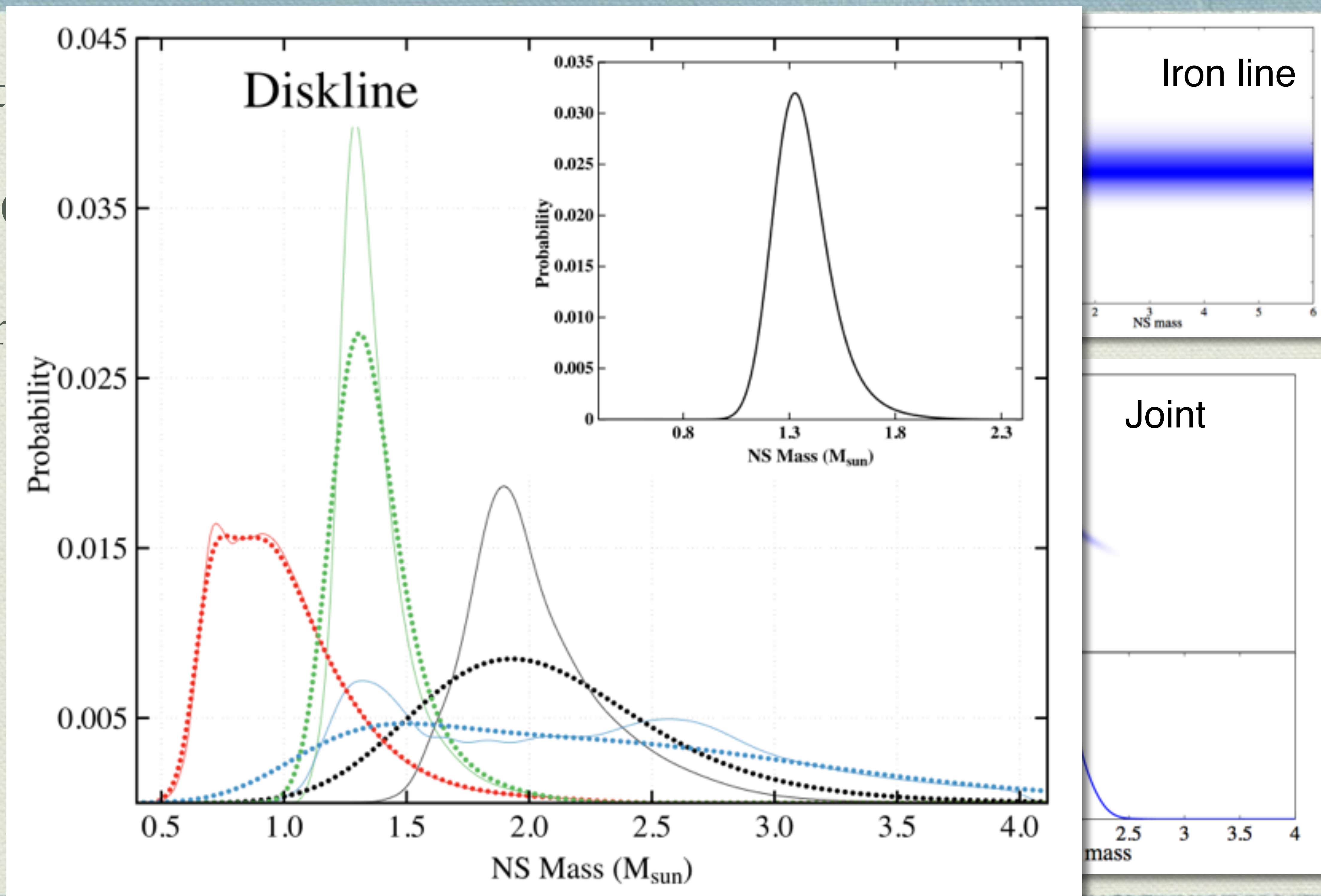


- Need a consistent picture

Timing / line attempt

Altamirano et al. (2009), Sanna et al. (2014)

- Neut
- kHz (
- No m



COMPARISON OF METHODS

	Continuum	Fe-Line	QPO
Instrument calibration			
Distance			
Inclination			
Detailed model			
Absorption			

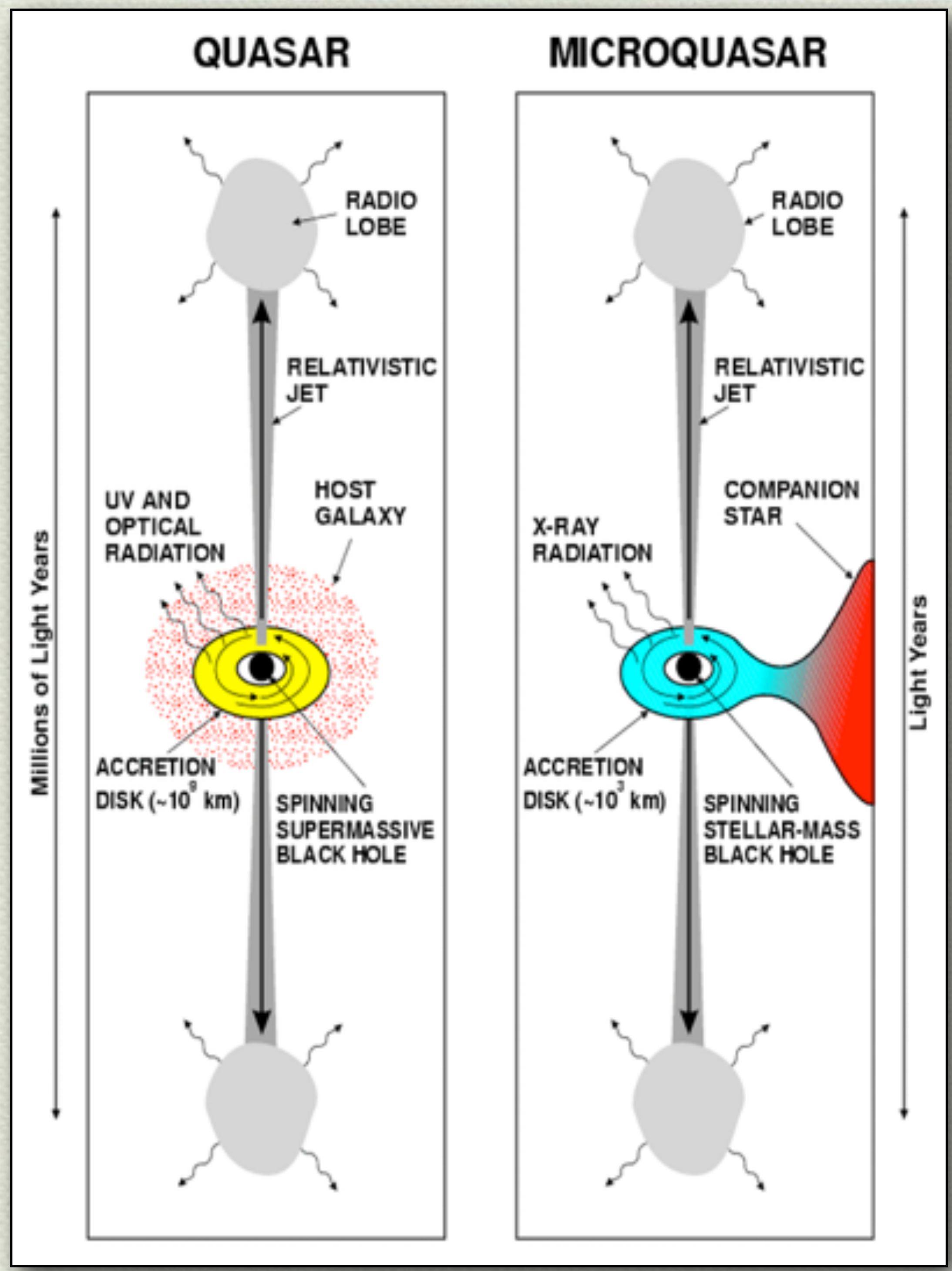
GR: physics

Production mechanism

Few detections

The AGN connection

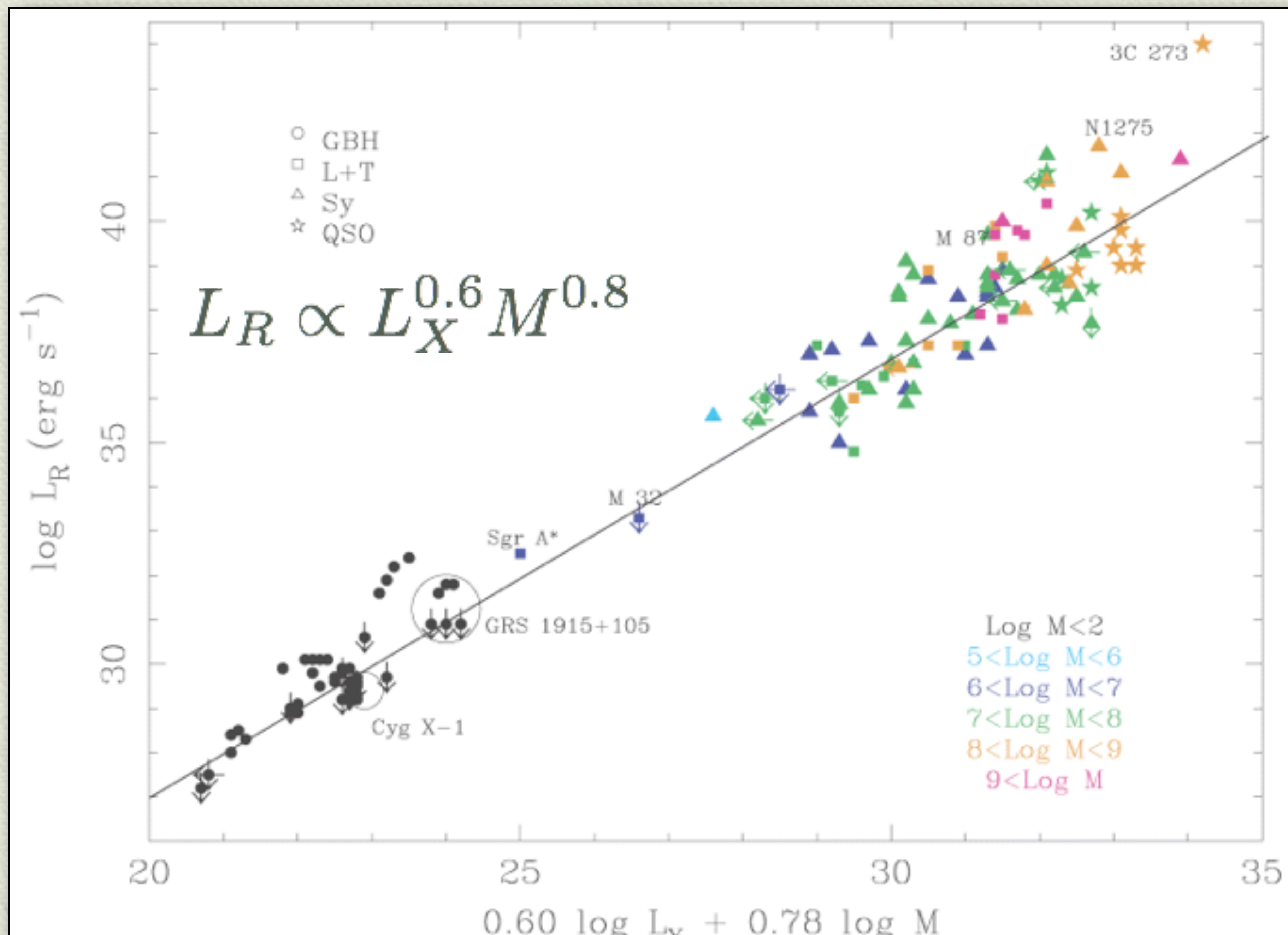
- Must be similar
- Accretion/ejection
- Different time scales
- Scaling
- Many more systems



The fundamental plane

- L_R is not a good measure
- Power of jet?
- Mass accretion rate?

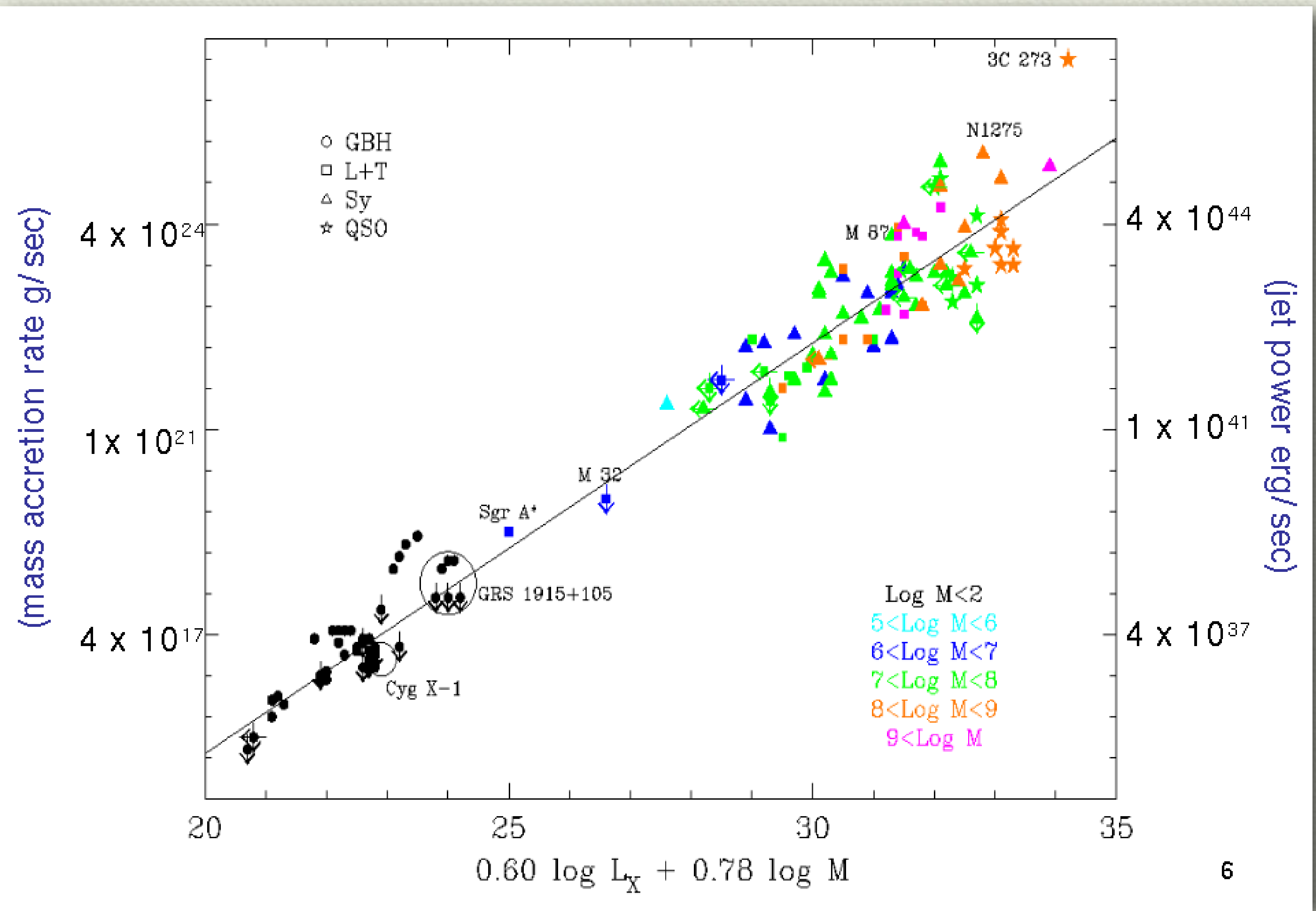
Merloni, Heinz & Di Matteo (2003)



The fundamental plane

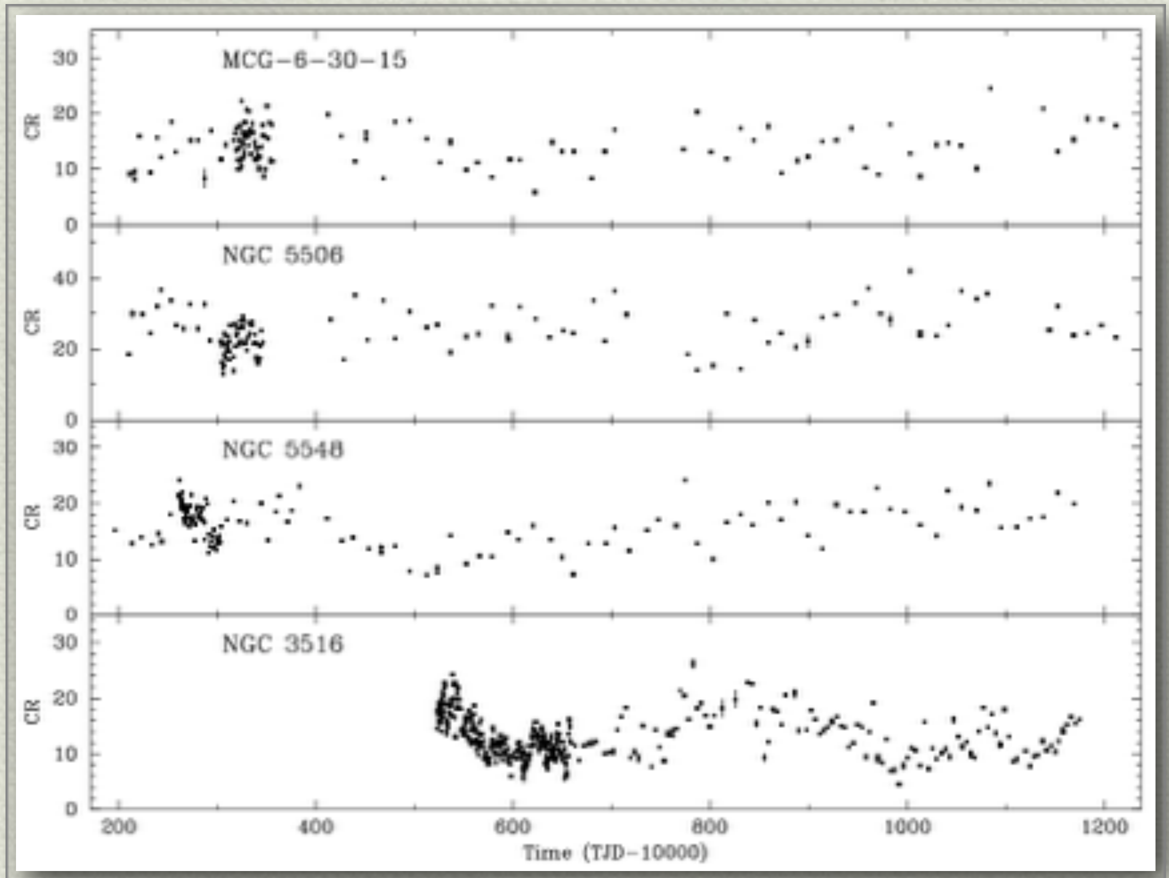
- Recalibrated

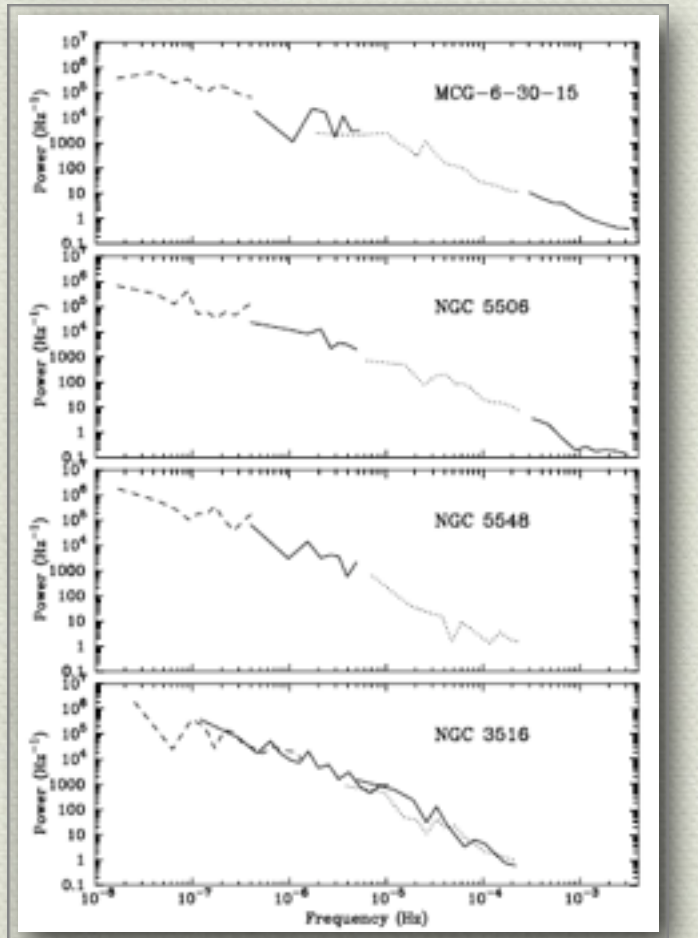
Fender (2009)



AGN timing

- Difficult techniques
- Important for AGN studies
- Analysis then timing

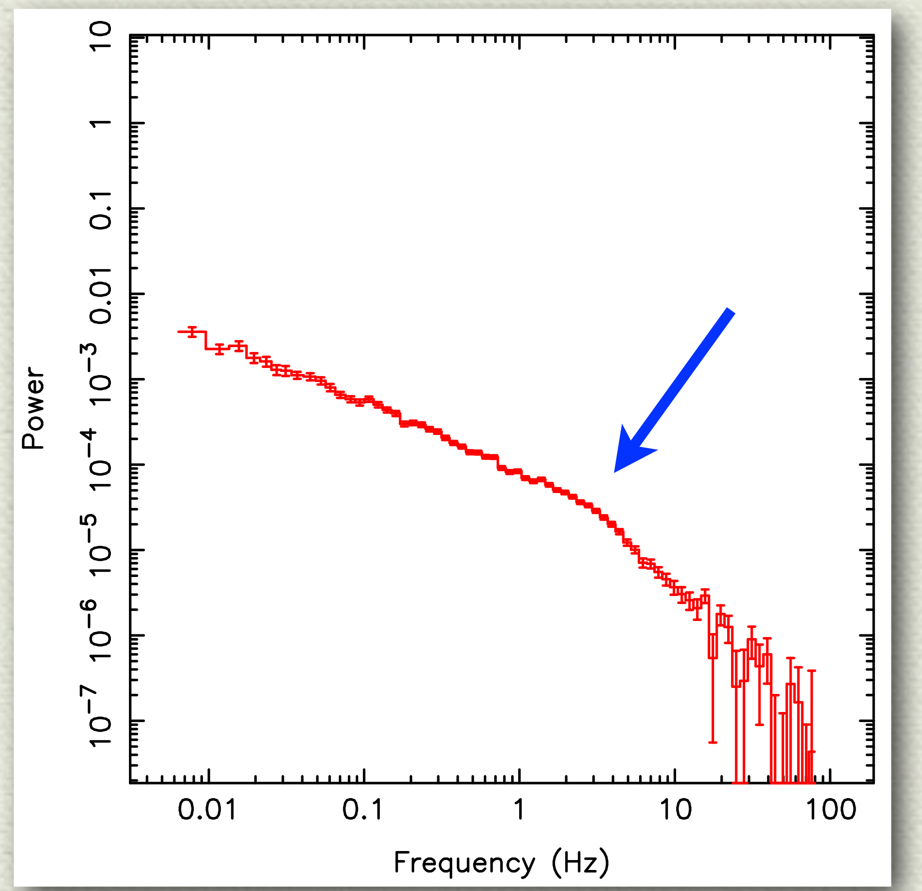




Timing plane

McHardy et al. (2006)

- AGN power spectra
- All soft-state?
- Break: mass scaling?
- Does not work with AGN



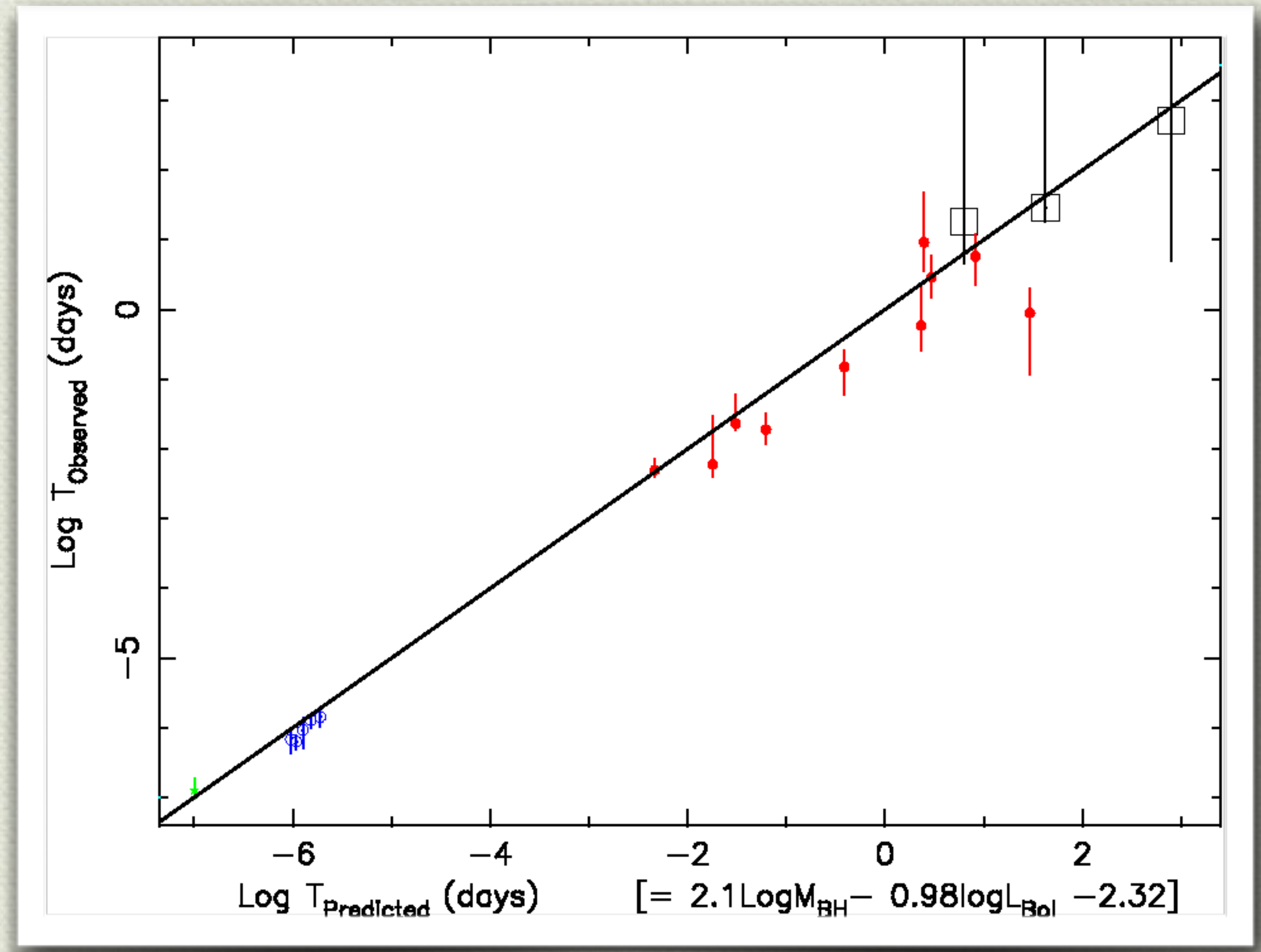
- Dependence on both M and $\dot{M}$?

Timing plane

McHardy et al. (2006)

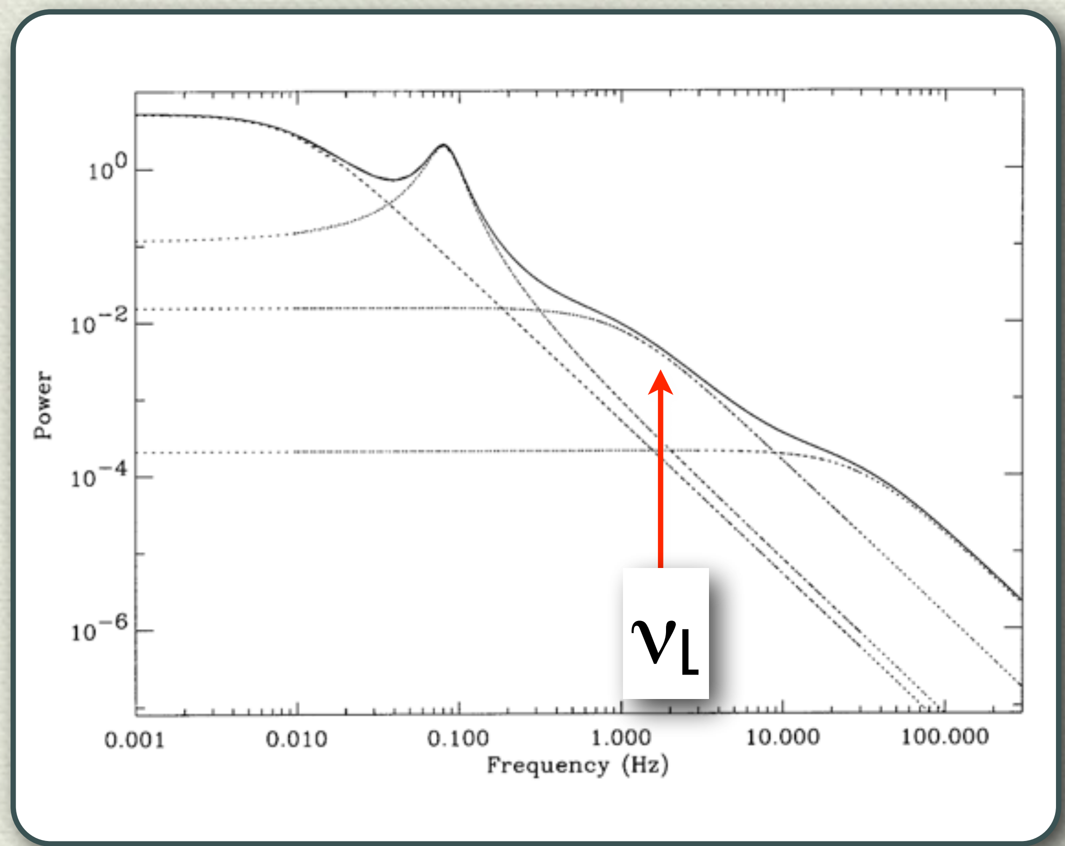
- Best fit: $T \propto M^{2.1} L_{Bol}^{-0.98}$
- Radiatively efficient (sot state)
- Therefore $L_{bol} \Leftrightarrow \dot{M}$

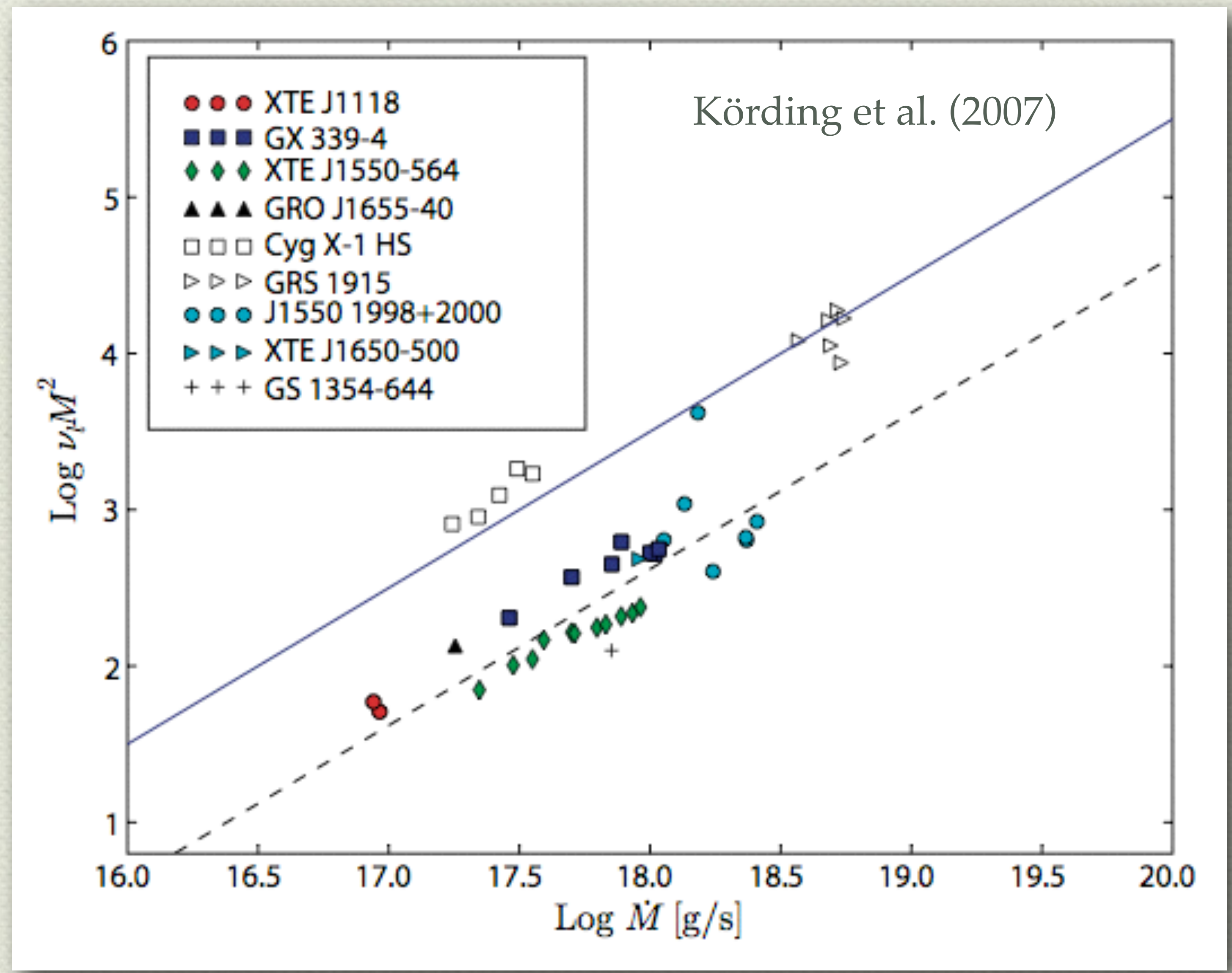
$$T \propto \frac{M}{\dot{m}/\dot{m}_{Edd}}$$



Timing correlation

- Remember lecture 4
- Upper line is McHardy

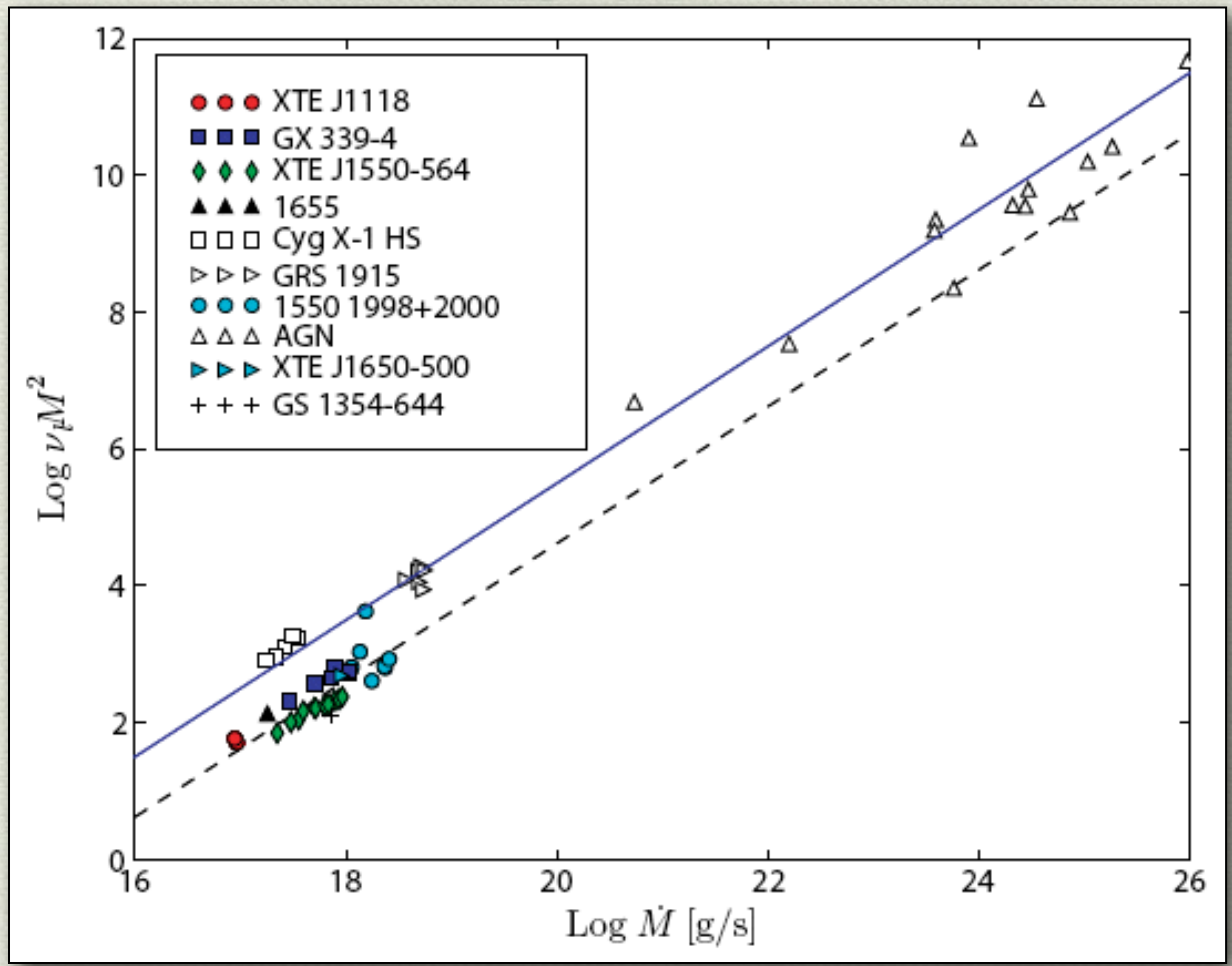




Timing correlation

- AGN extension

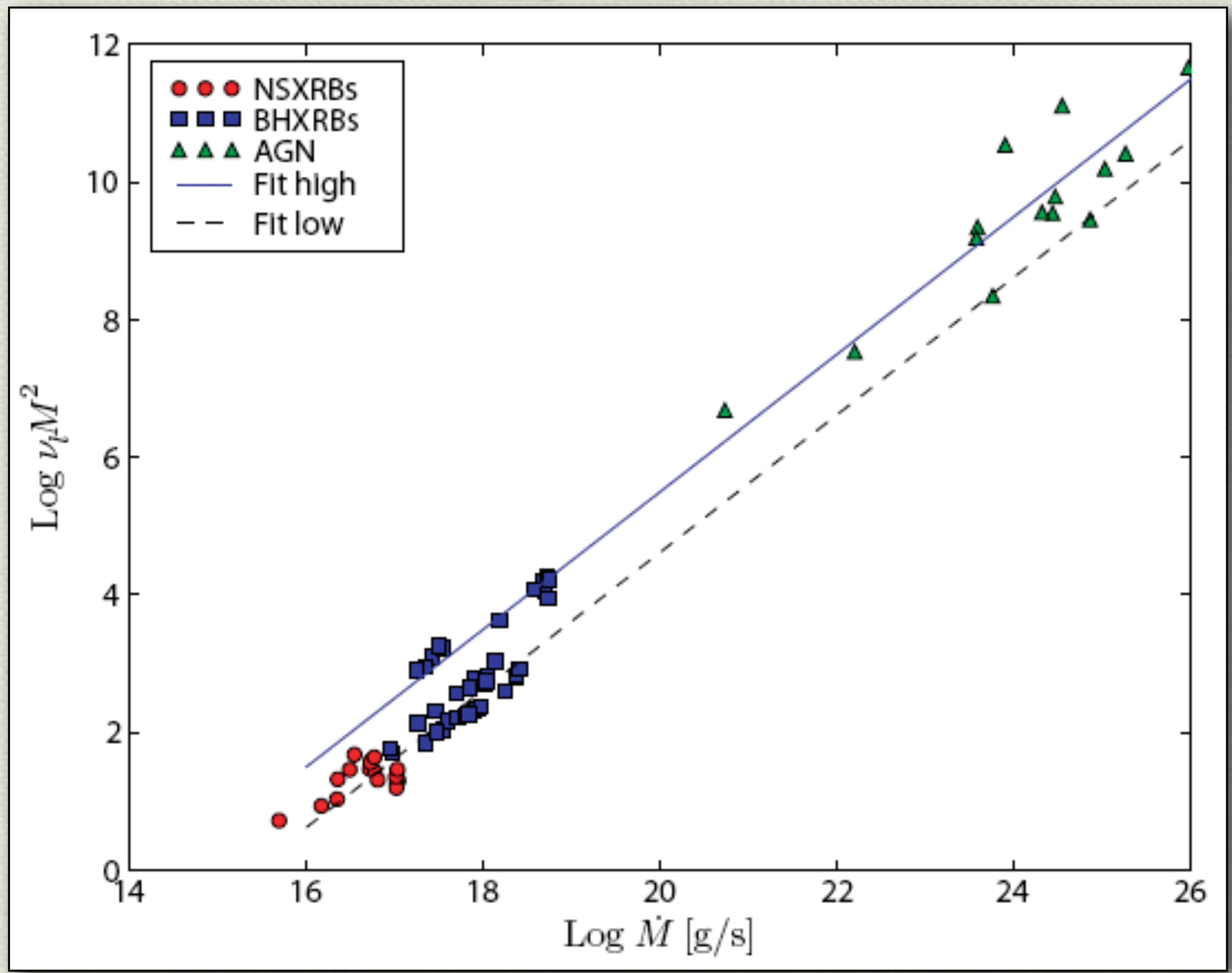
Körding et al. (2007)



Timing correlation

- NS extension

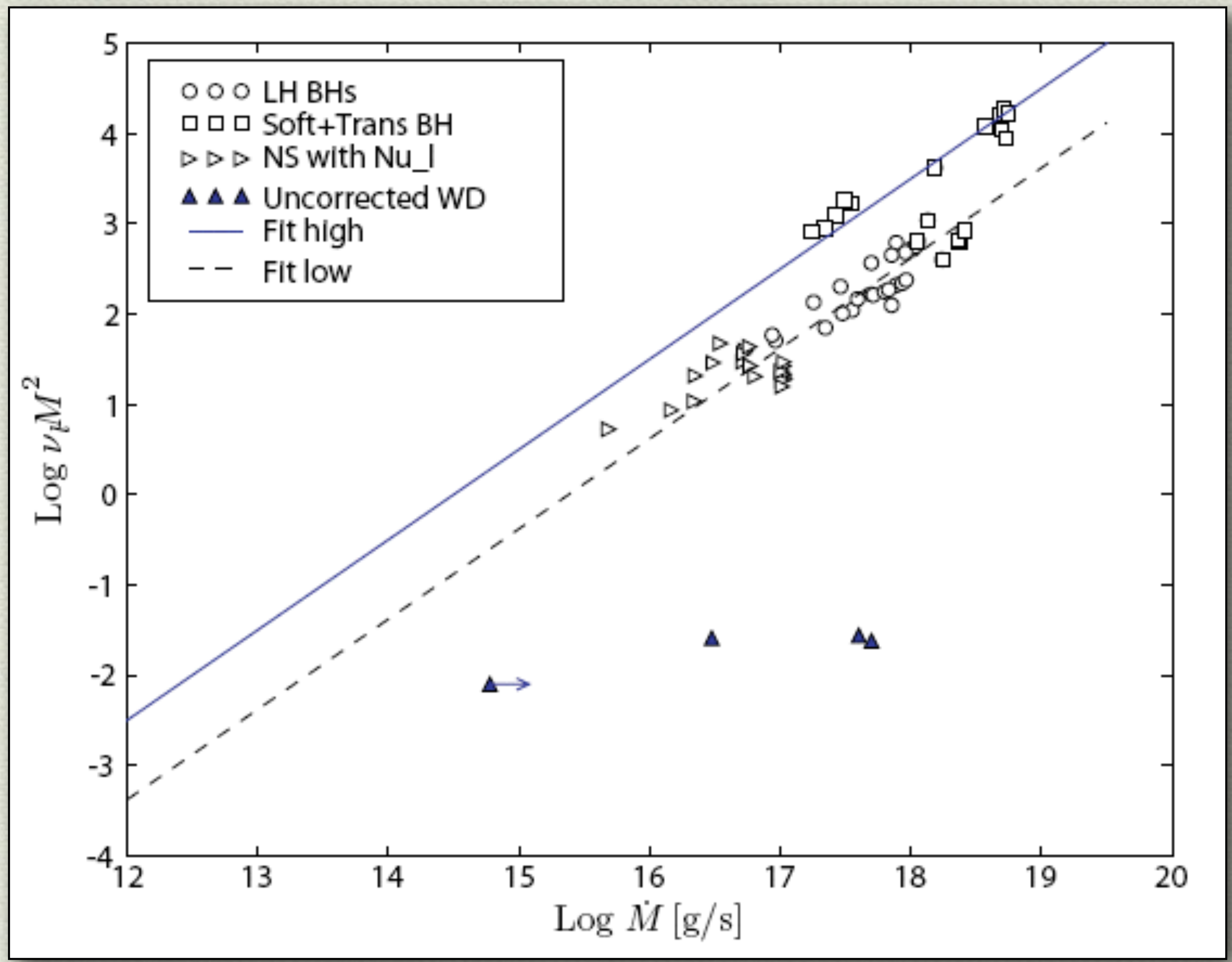
Körding et al. (2007)



Timing correlation

- WD extension?
- No
- Emission not in X
- Large radius?

Körding et al. (2007)

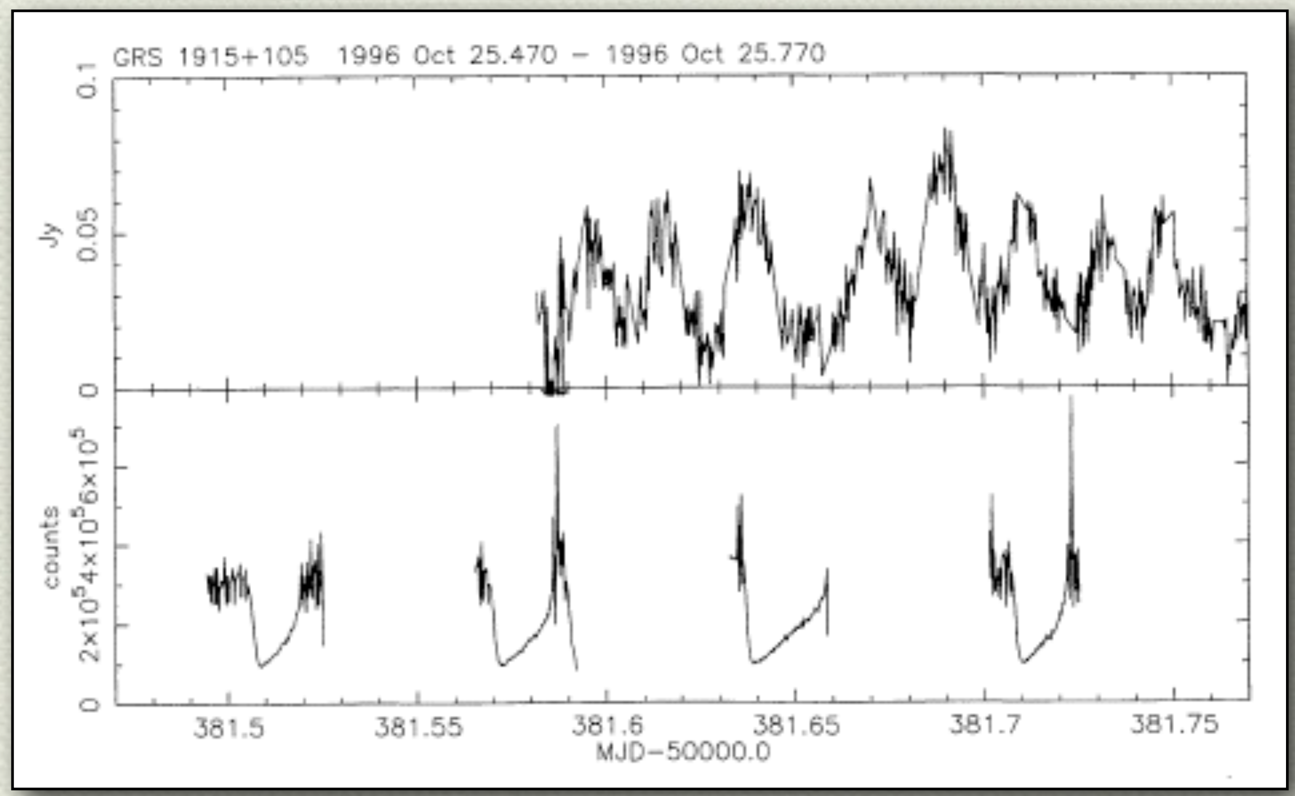


Accretion / ejection?

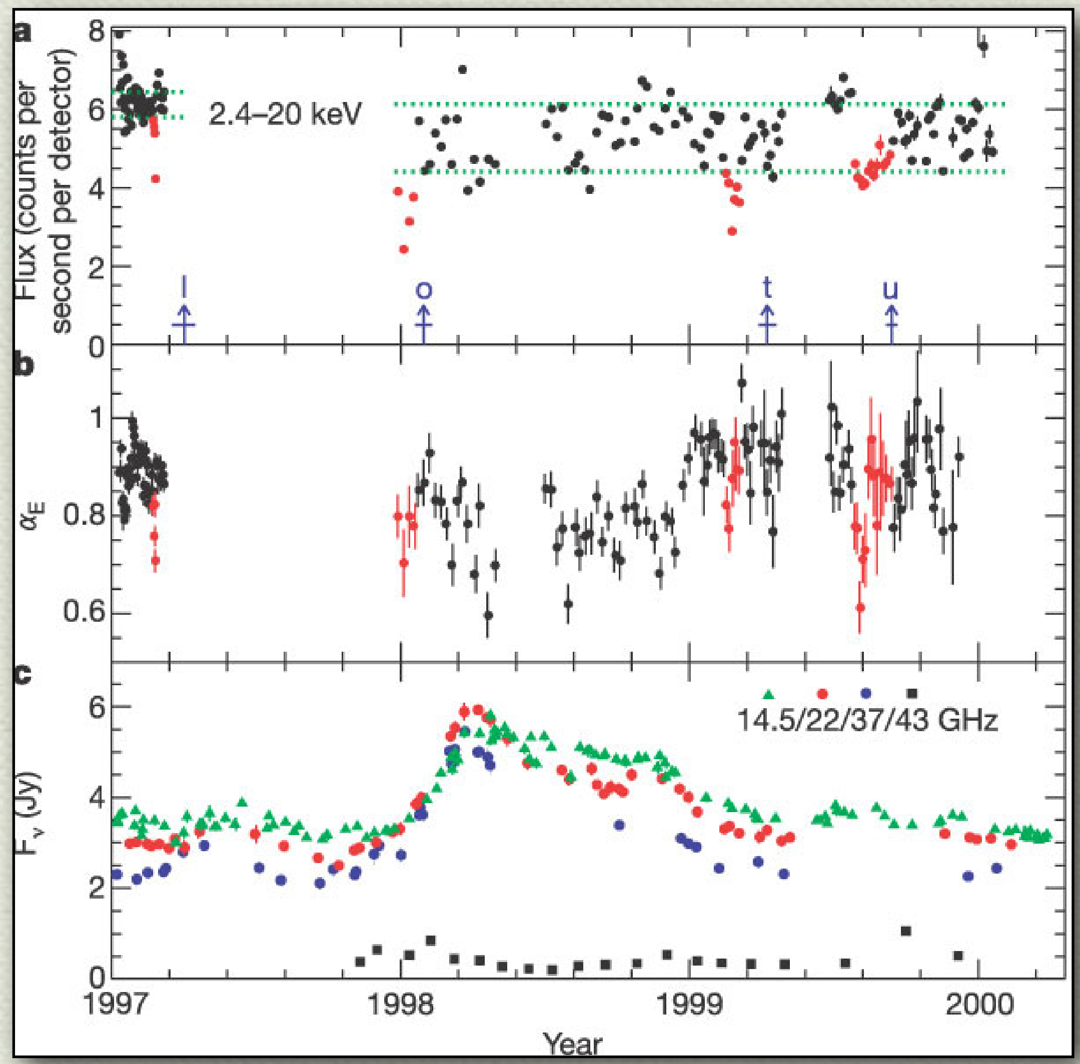
- Like GRS 1915+105?

Marscher et al. (2002)

GRS 1915+105



3C 120



AGN QPOs

- Only one serious case: RE J1034+396.

Gierlinski et al. (2008)

- P = 3,730 +/- 130 s
- Q > 16
- A HFQPO?