# Transient Phenomena around Rotating Black Holes

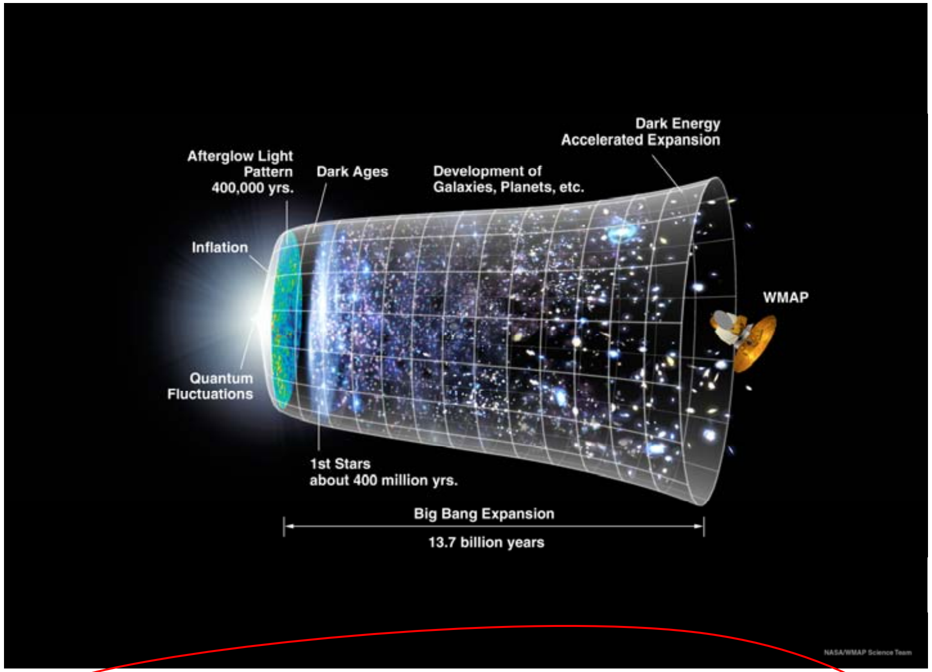
Maurice H.P.M. van Putten

OSSU08

Orleans 2008

# Gravitational Phenomenology

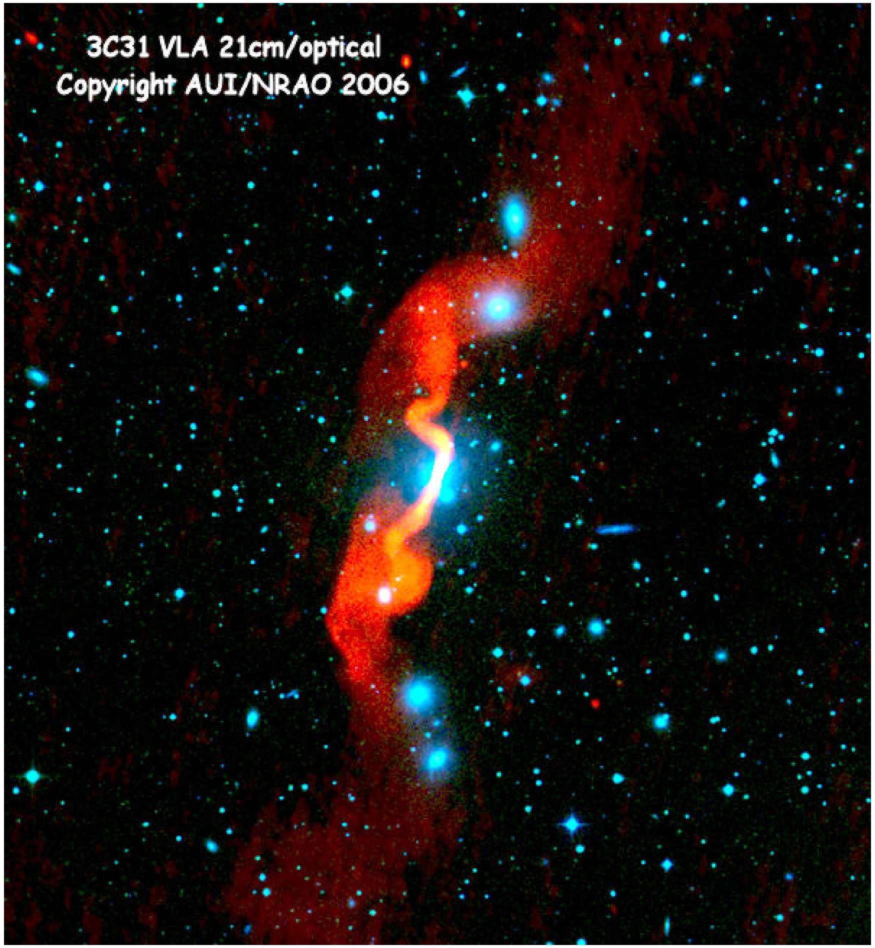
Dynamical cosmology (expansion, structure formation)



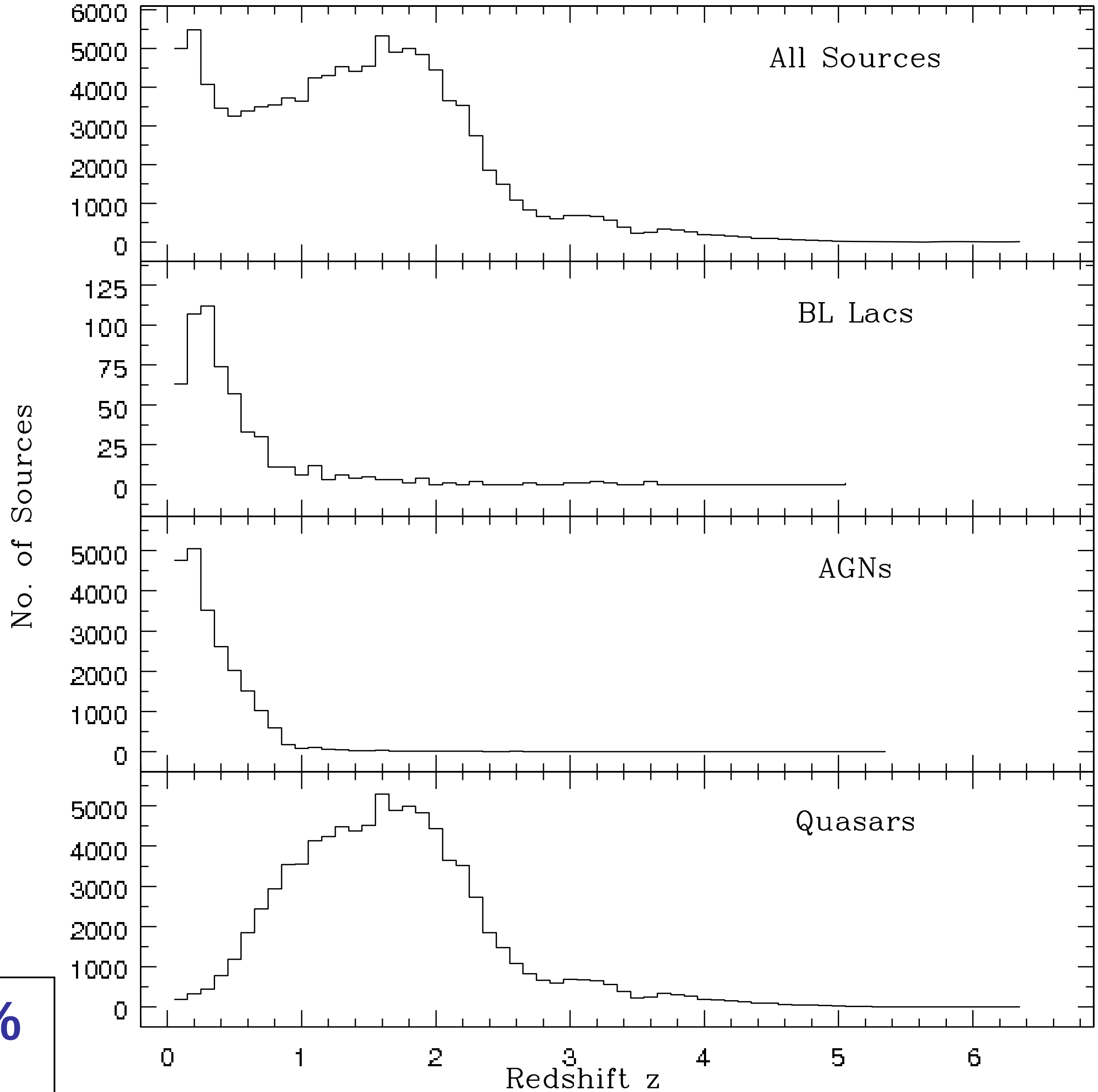

Black holes (collapse, rotating spacetimes)

Gravitational waves

# Gravity at work in AGN



# Véron-Cettty catalogue




(c)2008 van Putten

**%AGN~20-40%**

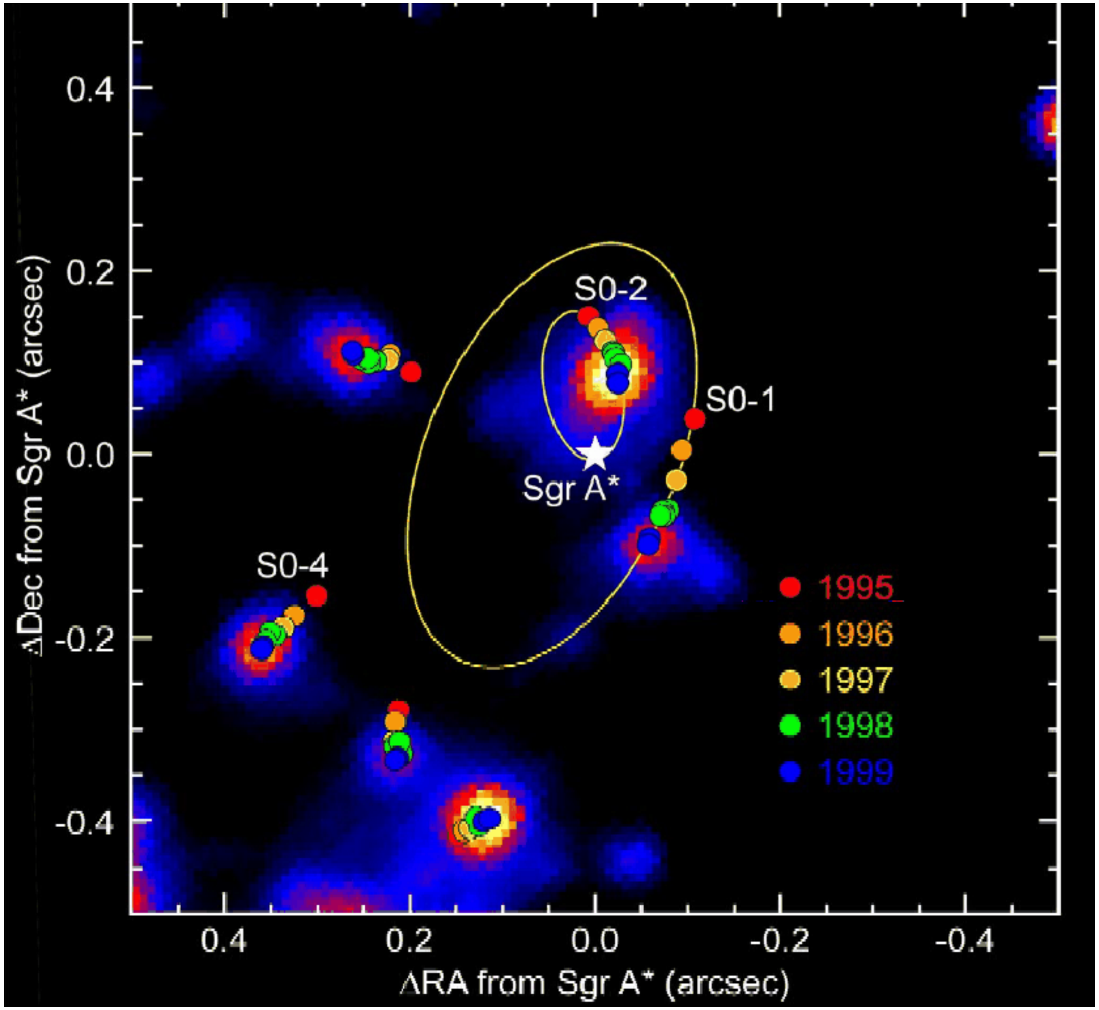
in SDSS (z<0.2)
Miller et al. 2003
Wake et al. 2004
Brinchmann et al. 2004

van Putten & Gupta, in prep. (2008)

# Phenomenology at work: Metrology on Black Holes

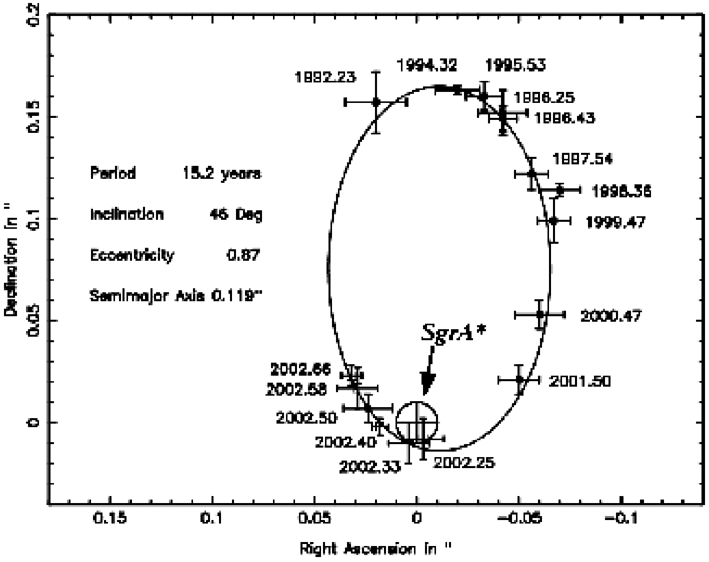
- Compactness: orbiting “test” particles (stars, accretion disks, COs)
- Frame-dragging: disk spectroscopy
- Gamma-ray bursts from rotating BHs
- Spin-down: “live” in long-duration GRBs
- Spin-energy: calorimetry on GWs

# Gravity at work in SgrA*




Ghez, A.M., Morris, M., Becklin, E.E., Tanner, A.& T. Kremenek (2000)

# Hyper-elliptic orbit of S2




$$P = 15.2\ \mathrm{yr} \qquad e = 0.87 \qquad a = 1000\ \mathrm{AU} \quad \text{pericenter radius} = 124\mathrm{AU}$$

$$-2000\ \mathrm{km/s} < v_{\parallel} < 4000\mathrm{km/s}\ \ (!)$$

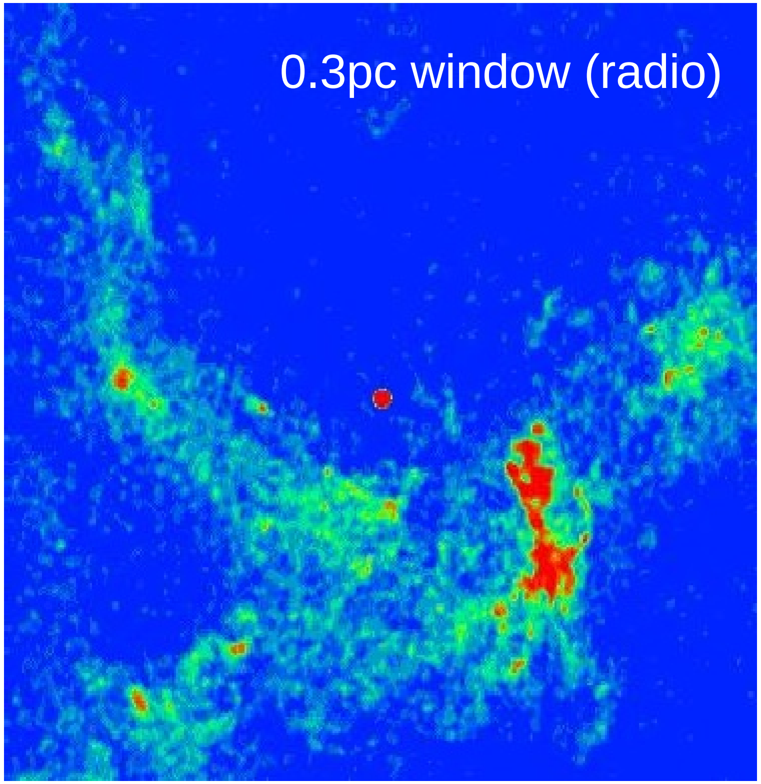
$$\Rightarrow M_{BH} = (3.7 \pm 1.5) \times 10^{6} M_{Sun}$$

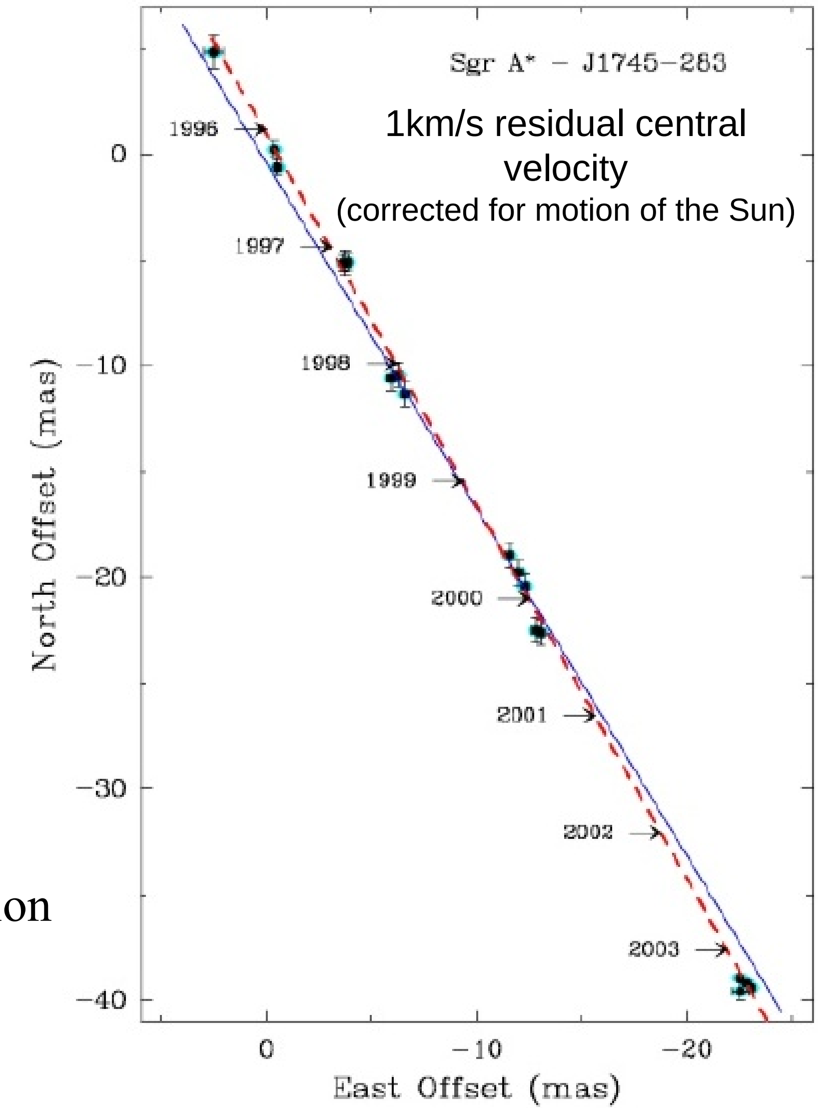
No discerneable trace of additional mass < 1pc:

$$\Rightarrow \rho \approx 3 \times 10^{6} M_{Sun} \mathrm{pc}^{-3}$$

Schödel et al. 2002
Ghez et al. 2003

# Thermal equilibrium in SgrA*




$$\left(\frac{M_{BH}}{m_{stars}} = \frac{\sigma^2[\text{stars}]}{v^2[\text{SgrA*}]}\right)_{virialized} \approx \left(\frac{1000\text{km/s}}{1\text{km/s}}\right)^2 \approx 1\,\text{Million}$$

Reid et al. (1999)
Schoedel et al. (2002)
Ghez et al. (2005); Reid et al. (2003)

# Stellar Velocity Dispersion Measurements in M87

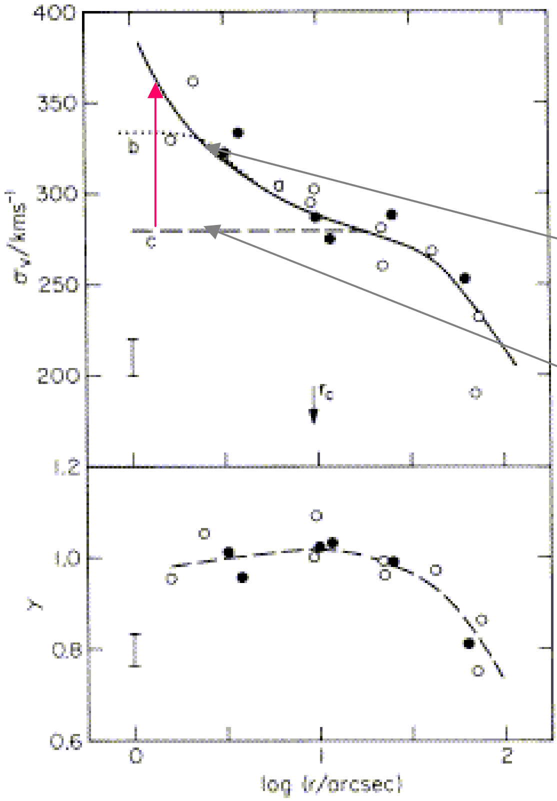



FIG. 4.—Velocity dispersions ($\sigma_v$) and the line strengths ($\gamma$) for M87. The open circles (○) are points W of the nucleus, and the filled circles (●) are E. The core radius, $r_c = 9''.6$, of the galaxy is marked. Error bars of length $2\,\sigma$ are given. Curve (*a*) is the velocity dispersion predicted by the black hole model fitted to the photometric data, (*b*) is the same model convolved with the seeing disk and slit size for the spectroscopic observations, and (*c*) is the King model that would prevail if the black hole were absent.

Sargant et al., 1978, ApJ 221:731
Young et al., 1978, ApJ 221:712

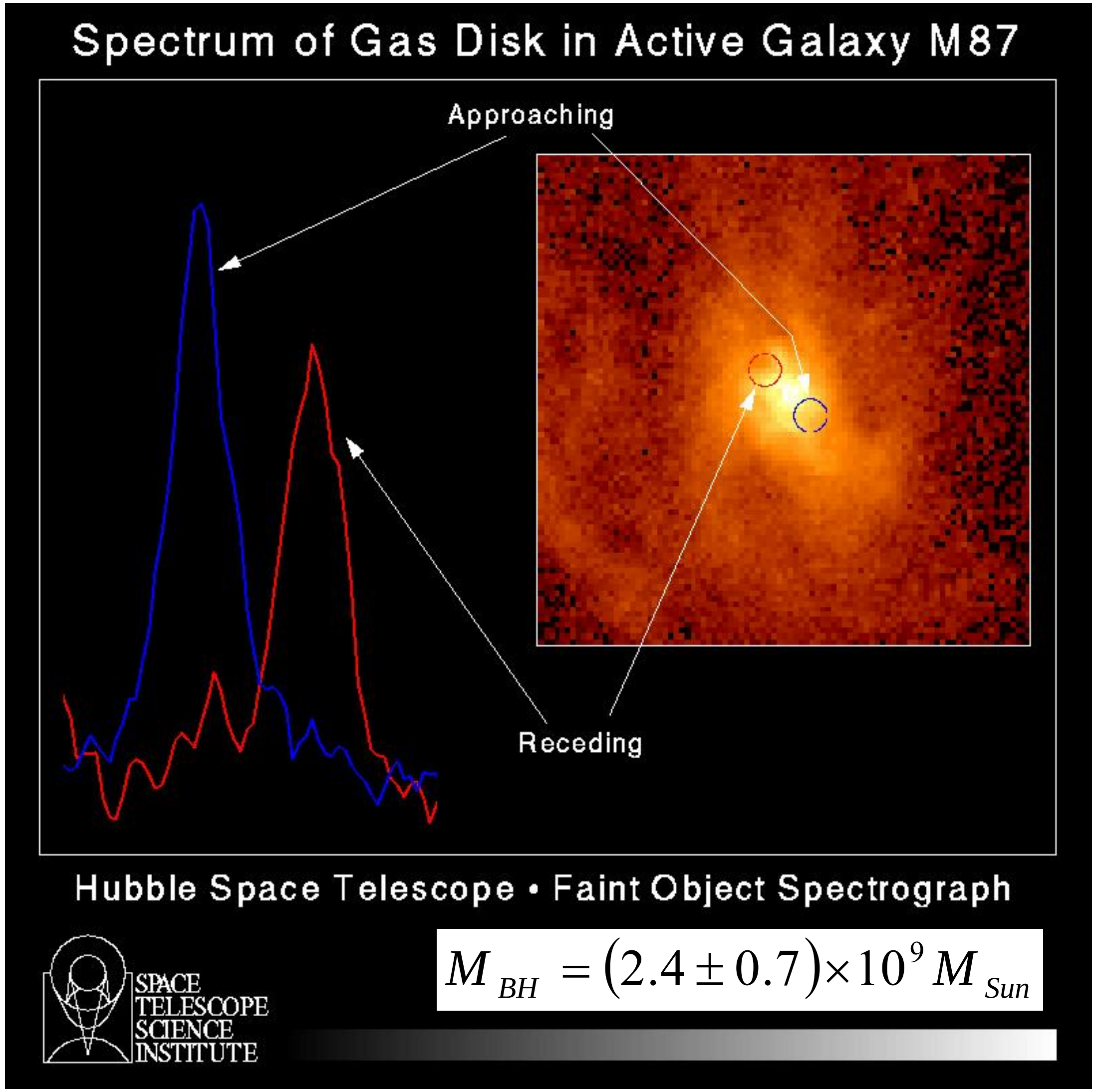
+ central BH
additional binding energy (<0) accounts for *higher* central temperatures (when virialized)

- central BH

BH mass is 3.4 billion solar masses

Van der Marel (1994)
Van der Marel et al. (1998)

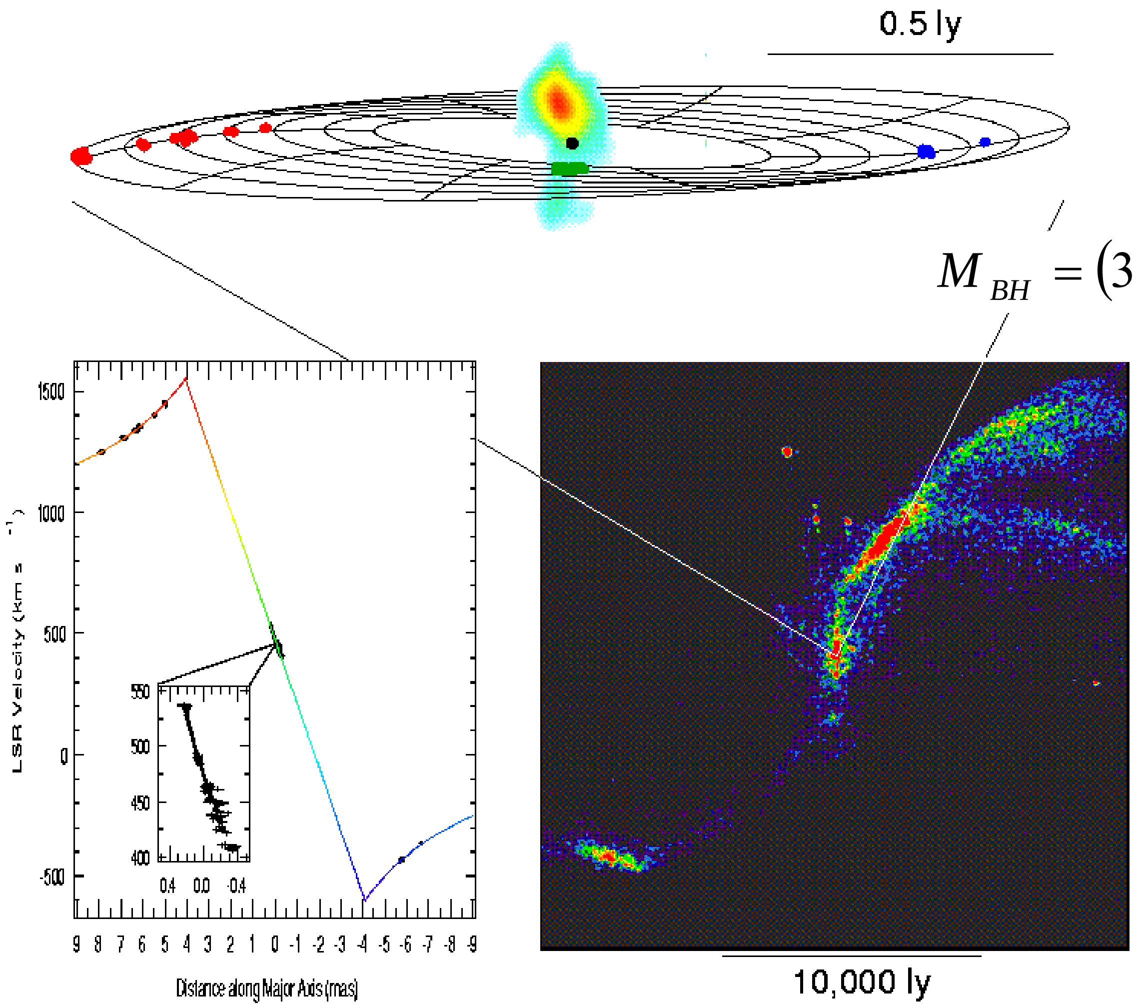
# Spectroscopy on torus of ionized gas in M87






Ford, H., et al., 1994, ApJ, 435:L27

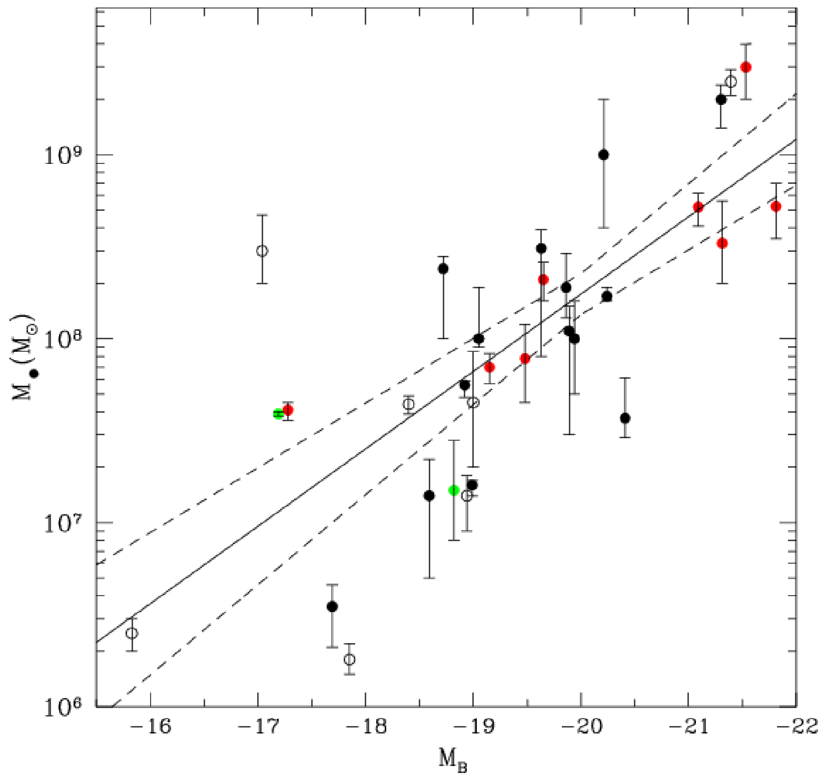
# Spectroscopy on H20-maser in disk of NGC4258

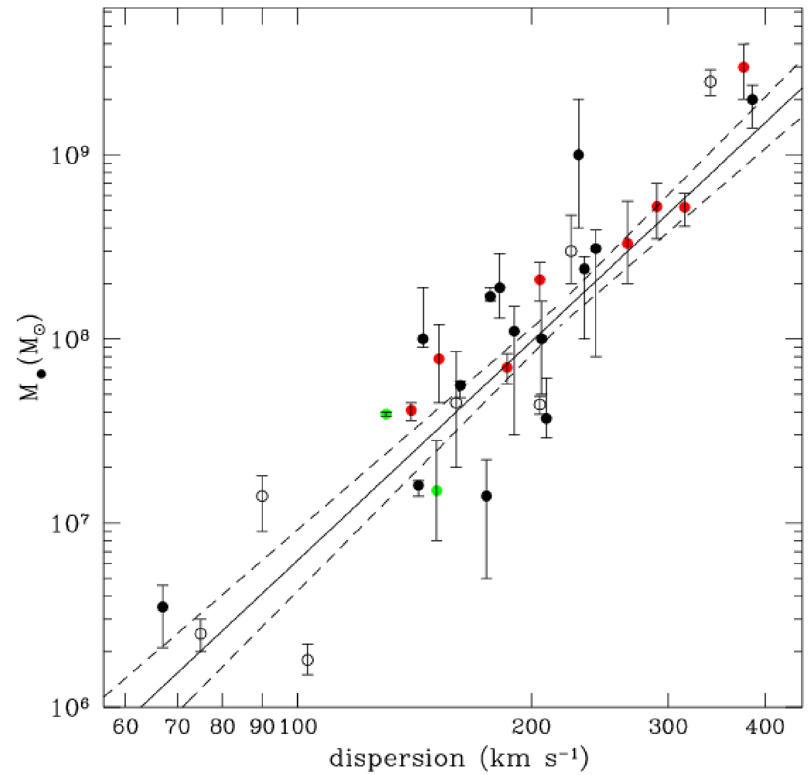



$$M_{BH} = (3.9 \pm 0.1) \times 10^7 M_{Sun}$$

Miyoshi et al.,
et al., 1995;
Hernstein et al,
1999

# Observed correlations to SMBHs




$$M_{BH} \propto L^{1.05\pm0.17}$$

$$M_{BH} \propto \sigma^{4\pm0.3}$$

Overall, the black hole mass is about 0.1% of the mass of the host galaxy

Kormendy 1993
Tremaine et al. 2002
Farrarese & Merrit 2000
Gebhardt et al. 2000

# Phenomenology at work: Metrology on Black Holes

- Compactness: orbiting “test” particles (stars, accretion disks, COs)
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# Level shifts in Circular Orbits

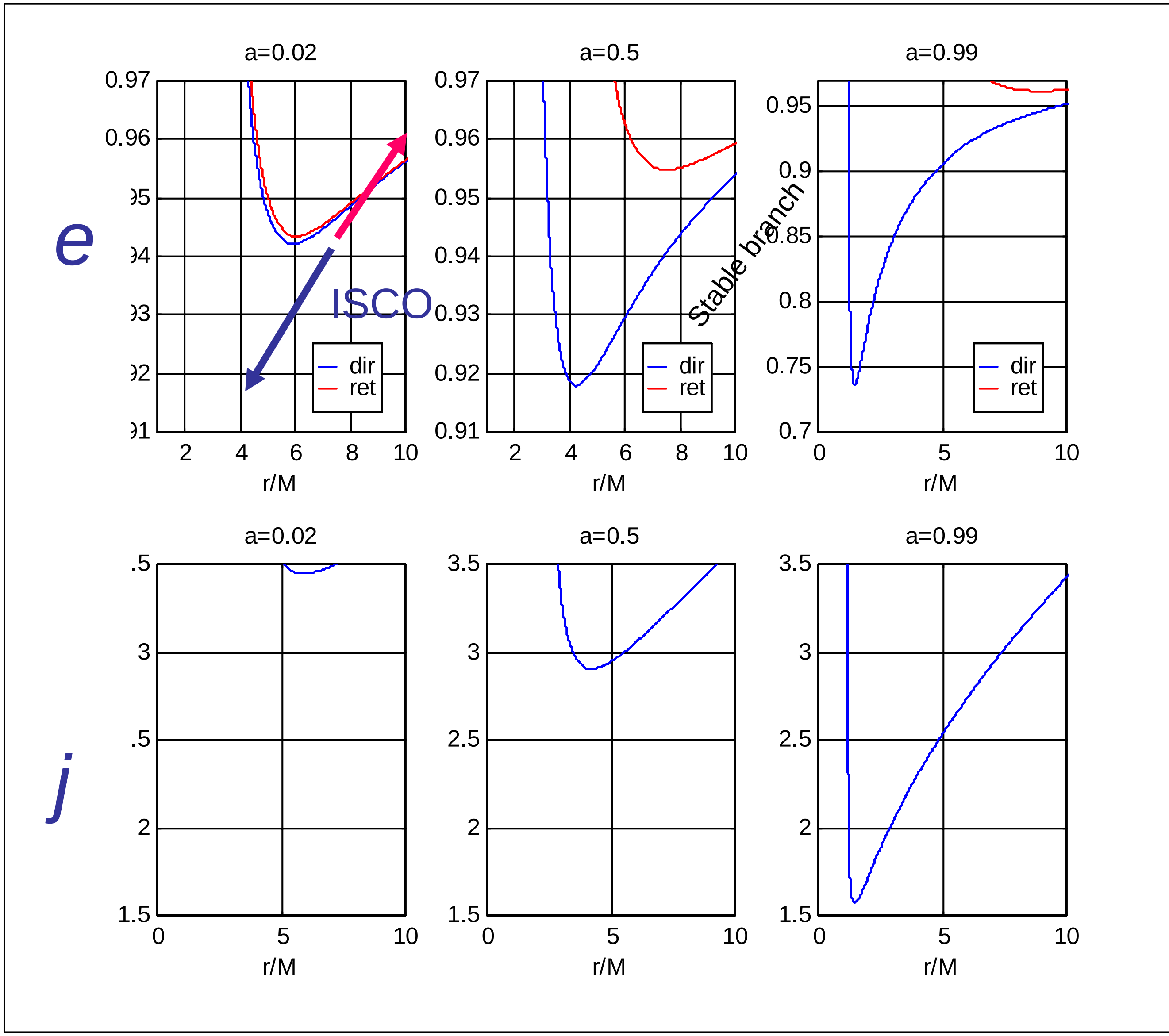
$$a : 0 \rightarrow M$$

Direct

$$e : \sqrt{\frac{8}{9}} \downarrow \frac{1}{\sqrt{3}}$$

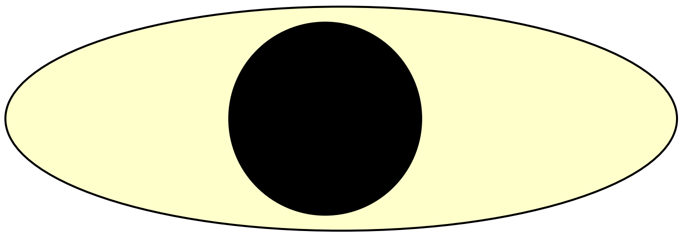
Retrograde

$$e : \sqrt{\frac{8}{9}} \uparrow \sqrt{\frac{25}{27}}$$

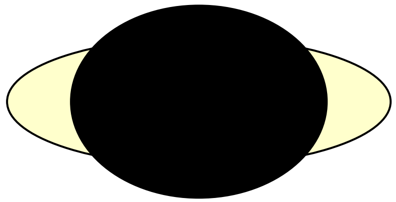



(c)2008 van Putten

Bardeen et al. 1972

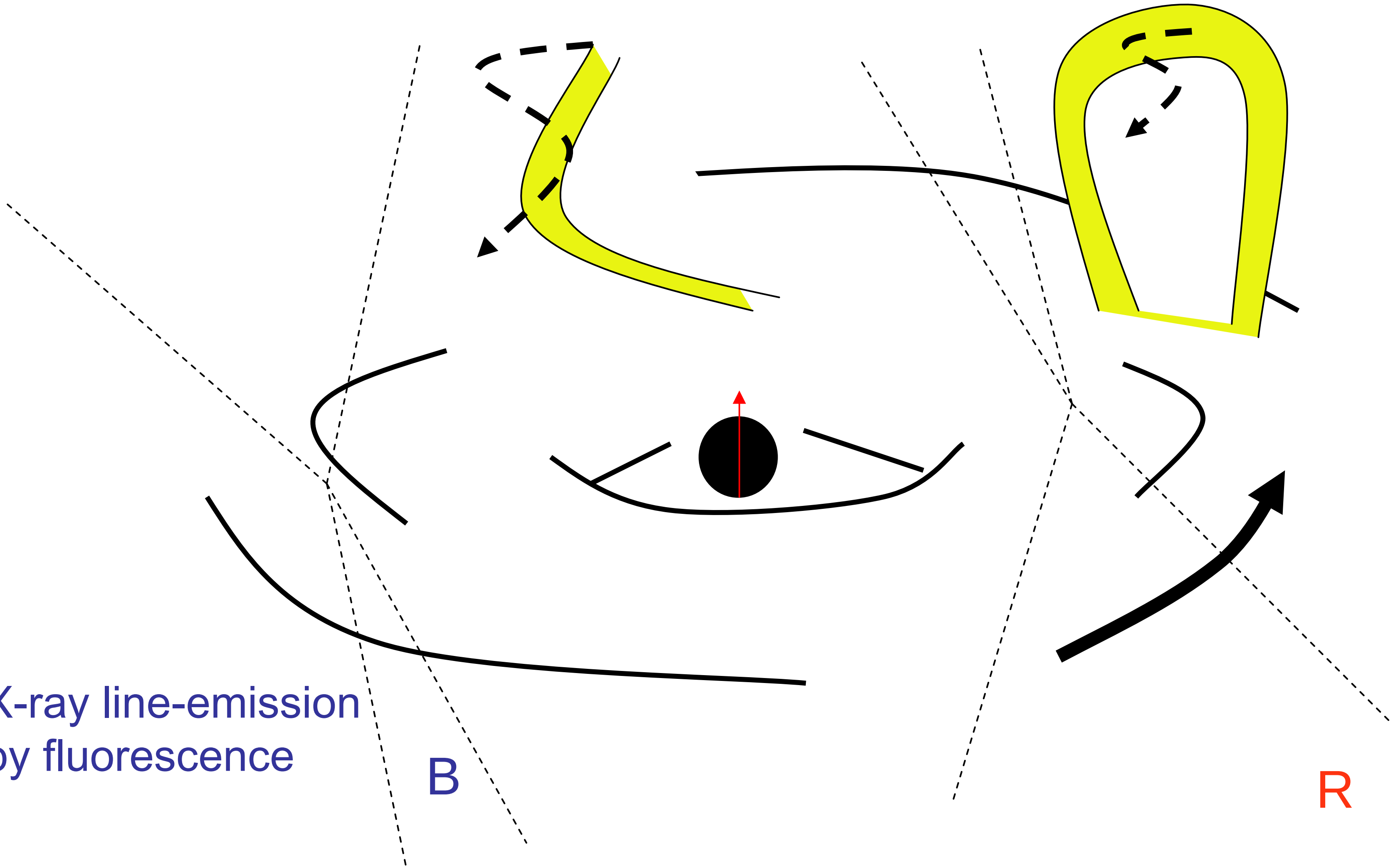


Schwarzschild metric



Kerr metric

# Magnetic Flares ("Corona Ejections") as X-ray sources

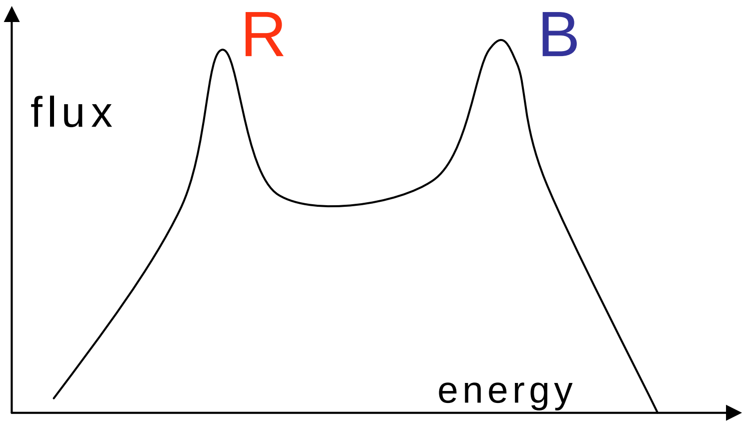



X-ray line-emission
by fluorescence

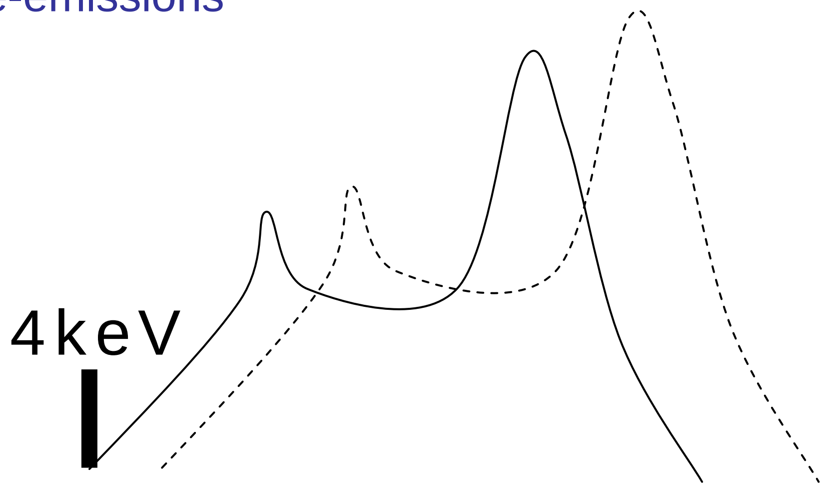


Fabian, 2005, at KerrFest

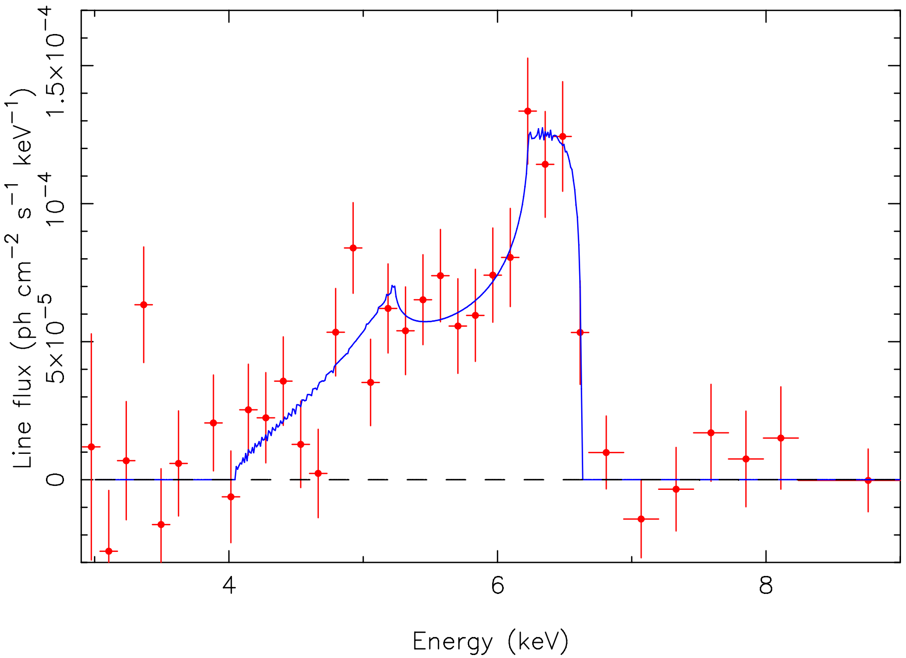
# Iron line-emissions




Newtonian




+Redshift+Doppler

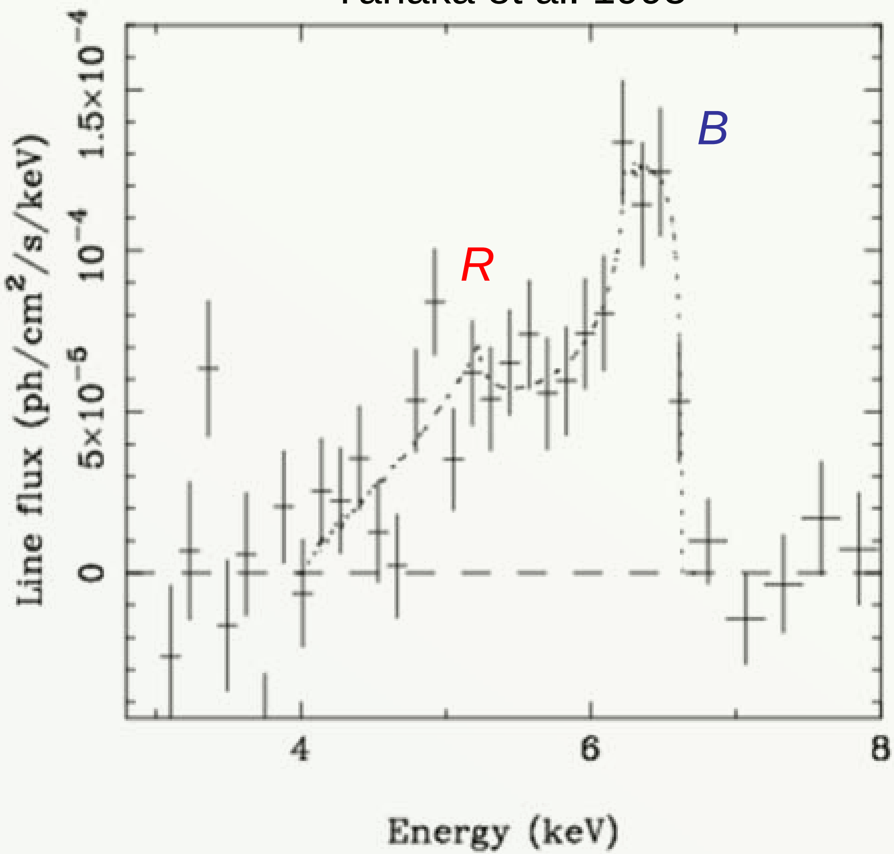



Tanaka et al. 1995

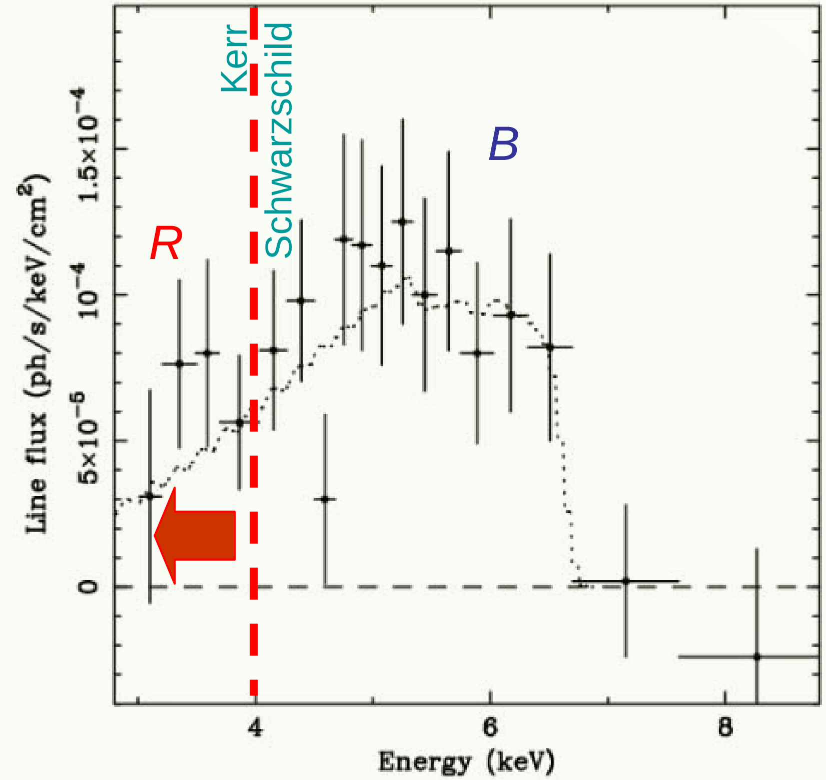
(c)2008 van Putten

After Fabian 2005 KerrFest

Tanaka et al. 1995



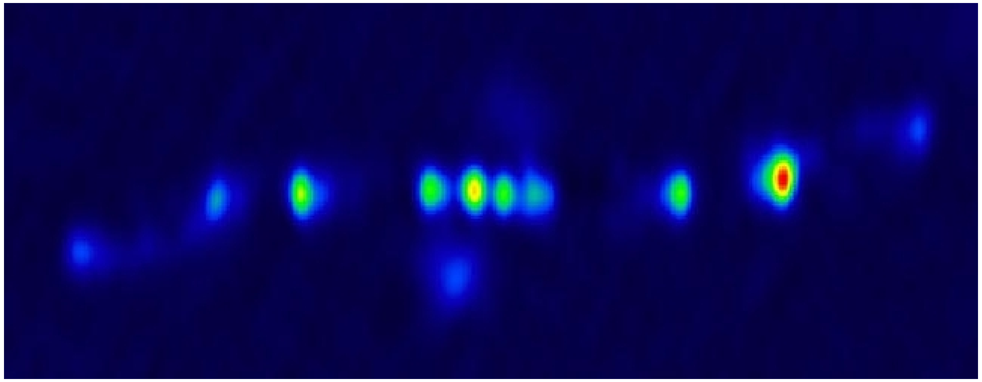

Iwasawa etal. 1996




Compact ISCO by frame-dragging

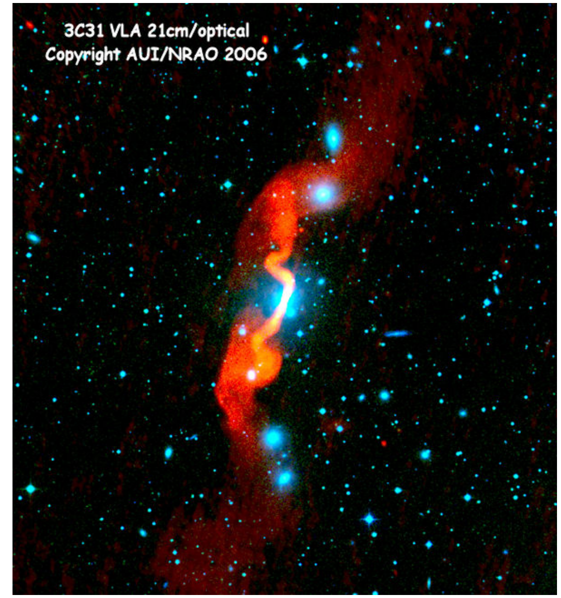
$K\alpha$ line emission in MCG-6-30-15 (Seyfert I in a <u>low</u> state) observed by ASCA

Active stellar-mass binaries



**SS433** (Mioduszewski et al., NRAO/AUI/NSF, 2004)

Active Galaxies

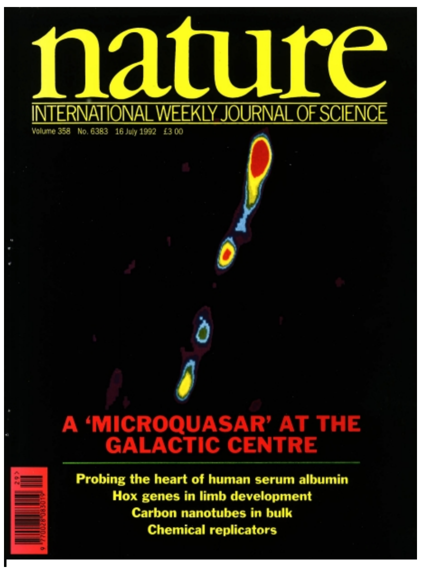



**3C31**

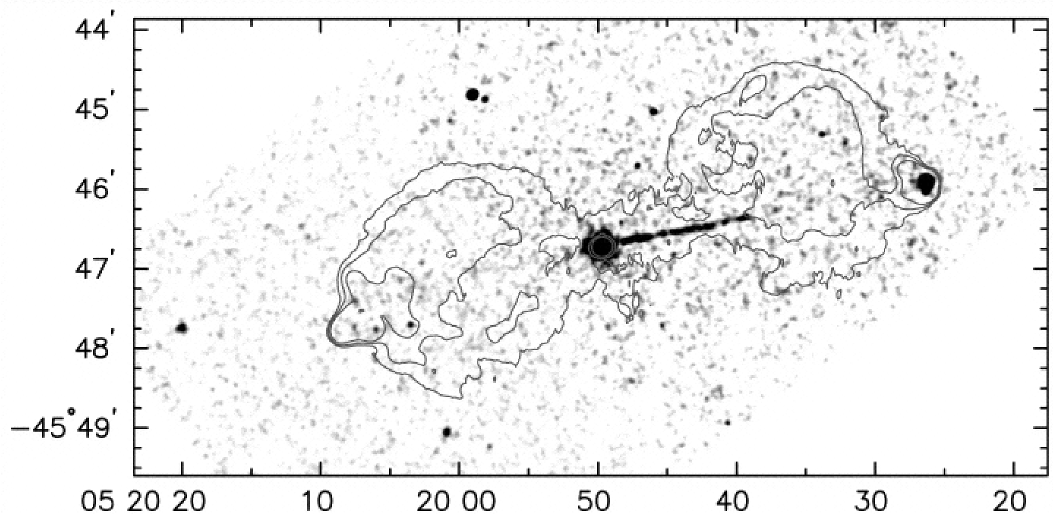
Slowly spinning BH

Rapidly spinning BH

Fanaroff-Riley I — Fanaroff-Riley II




**GRS 1915+105**
Mirabel & Rodriguez (1994)




**Pic A** (Wilson 2000)

(c)2008 van Putten

# Phenomenology at work: Metrology on Black Holes

- compactness: orbiting “test” particles (stars, accretion disks, COs)
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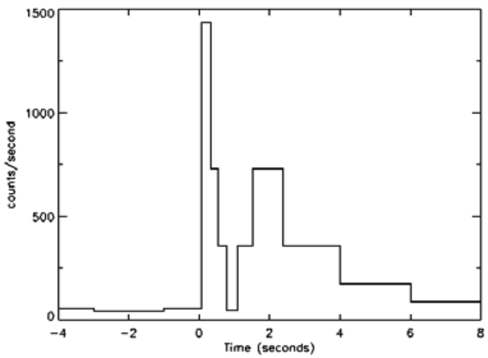
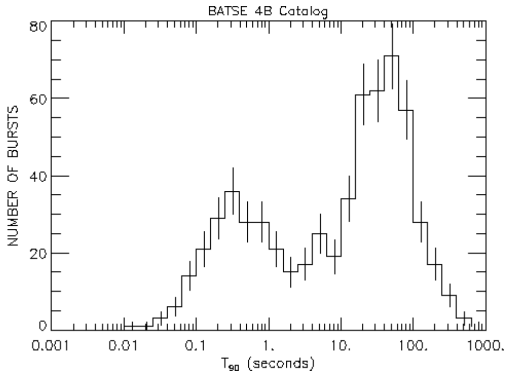
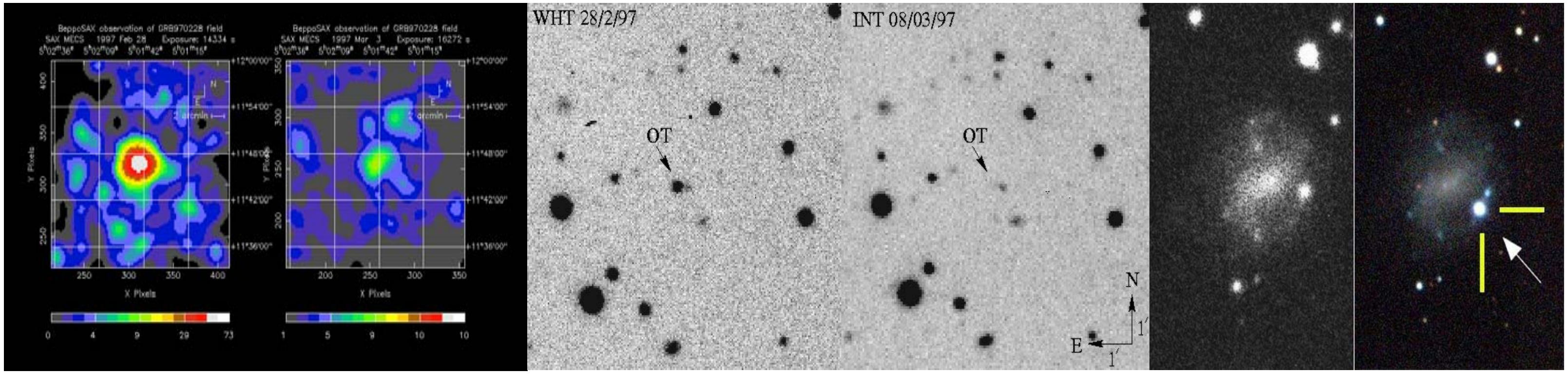
# A brief history of GRBs



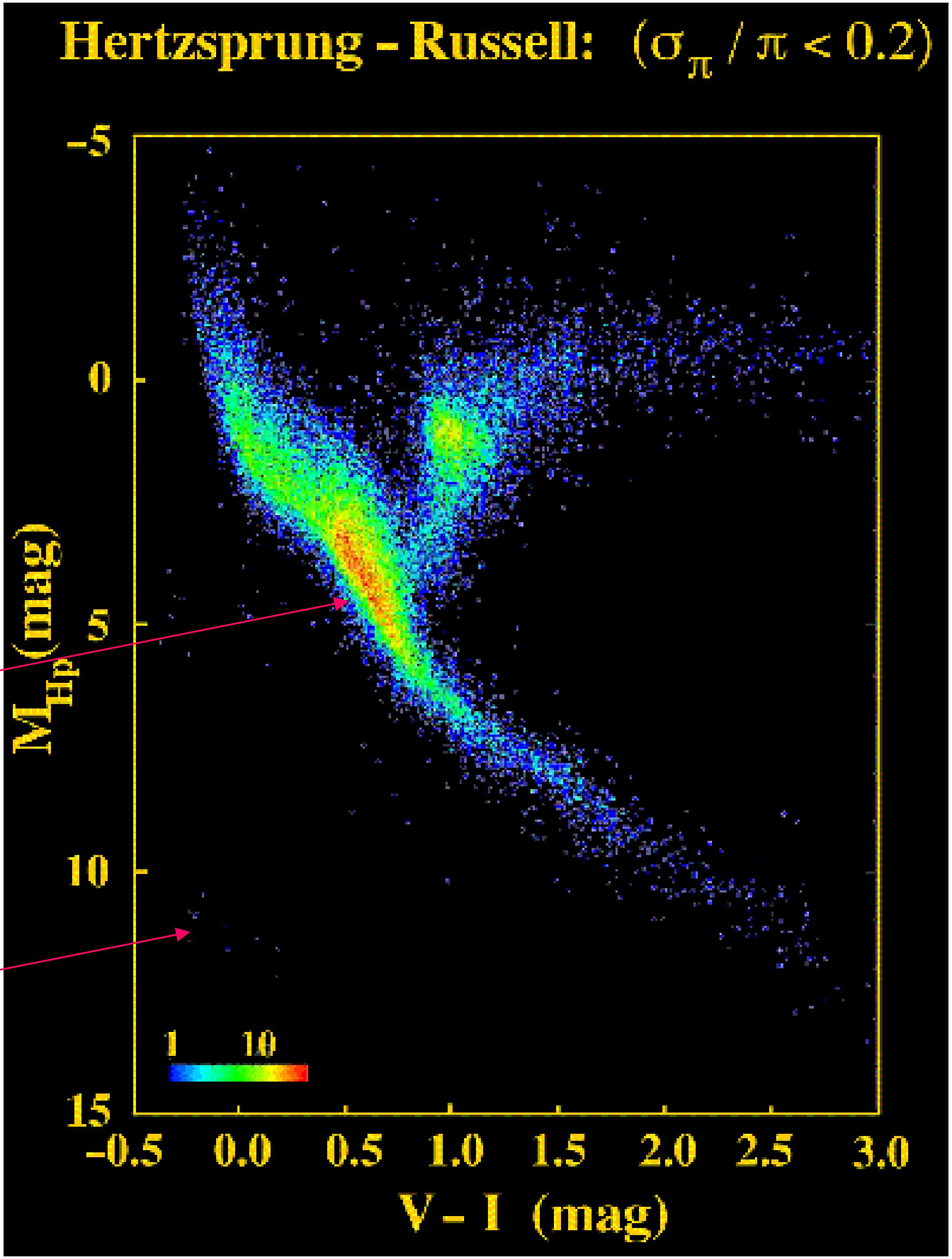




Discovery by Vela/Konus, catalogued by BATSE, localized by Beppo-Sax

HETE-II, Swift and now GLAST (June 11 2008)

$$T_{MS} = 13\left(\frac{M}{M_{sun}}\right)^{-5/2} \text{Gyr}$$

white dwarfs

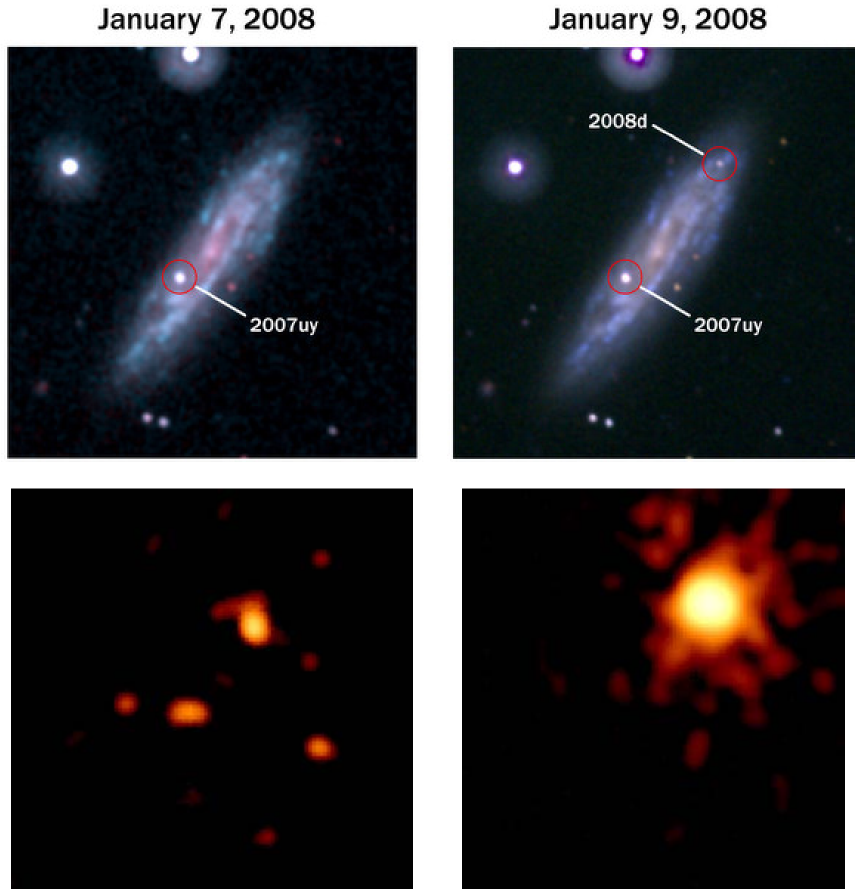



Hipparcos satellite

# 1987A (Type II): formation of HDM (neutrinos > 10 MeV)

# SN2008d (Type Ib): X-ray flash at break-out

SN2008d



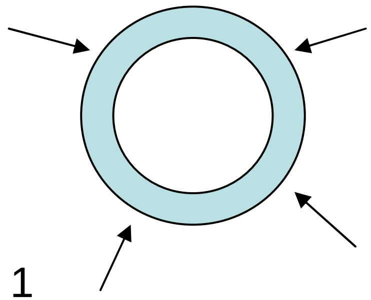

Soderberg et al. (2008), Malesani et al. (2008), Modjaz et al. (2008)

Type Ia [exploding WD] ~ 50%
- both in spirals and in ellipticals
- Light curves are "normalizable" (Phillips)
- intermediate mass progenitors
- in binaries?

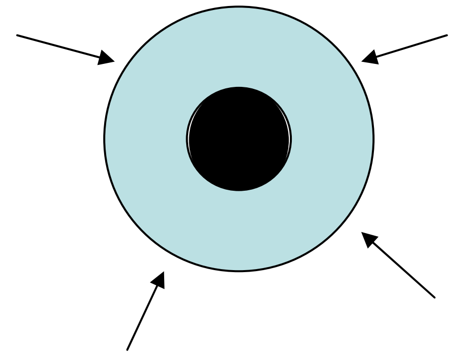
Type II [H-envelope retaining] ~40%
- primarily in spirals
- some in binaries (SN1993J)
- massive progenitors

Type Ib/c [with/without He] ~10%
- primarily in spirals
- massive progenitors
- in compact binaries?

# Formation of Kerr BH in core-collapse

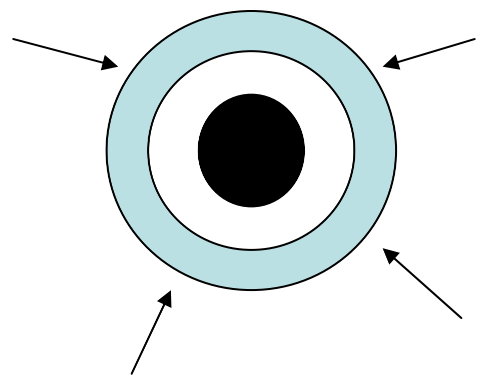


*Open torus* $Jc/G/M2 > 1$
(highly unstable: Duez, Shapiro & Yo, 2004, gr-qc/0401076)



*Rotating BH* by matter accreted from $r>r^*$ (when kick velocity is small)

*Torus around BH* by infall of matter from $r>r^*$ stalled against angular momentum barrier





van Putten, 2004, ApJ, 611, L81

# Radiation from Kerr black holes

Rotational energy per unit mass

$$E_{spin} = \frac{1}{2}\Omega_H^2 I f_s^{\,2} \qquad f_s = \frac{\cos(\lambda/2)}{\cos(\lambda/4)} \qquad (\sin\lambda = a/M)$$

(Van Putten 1999)

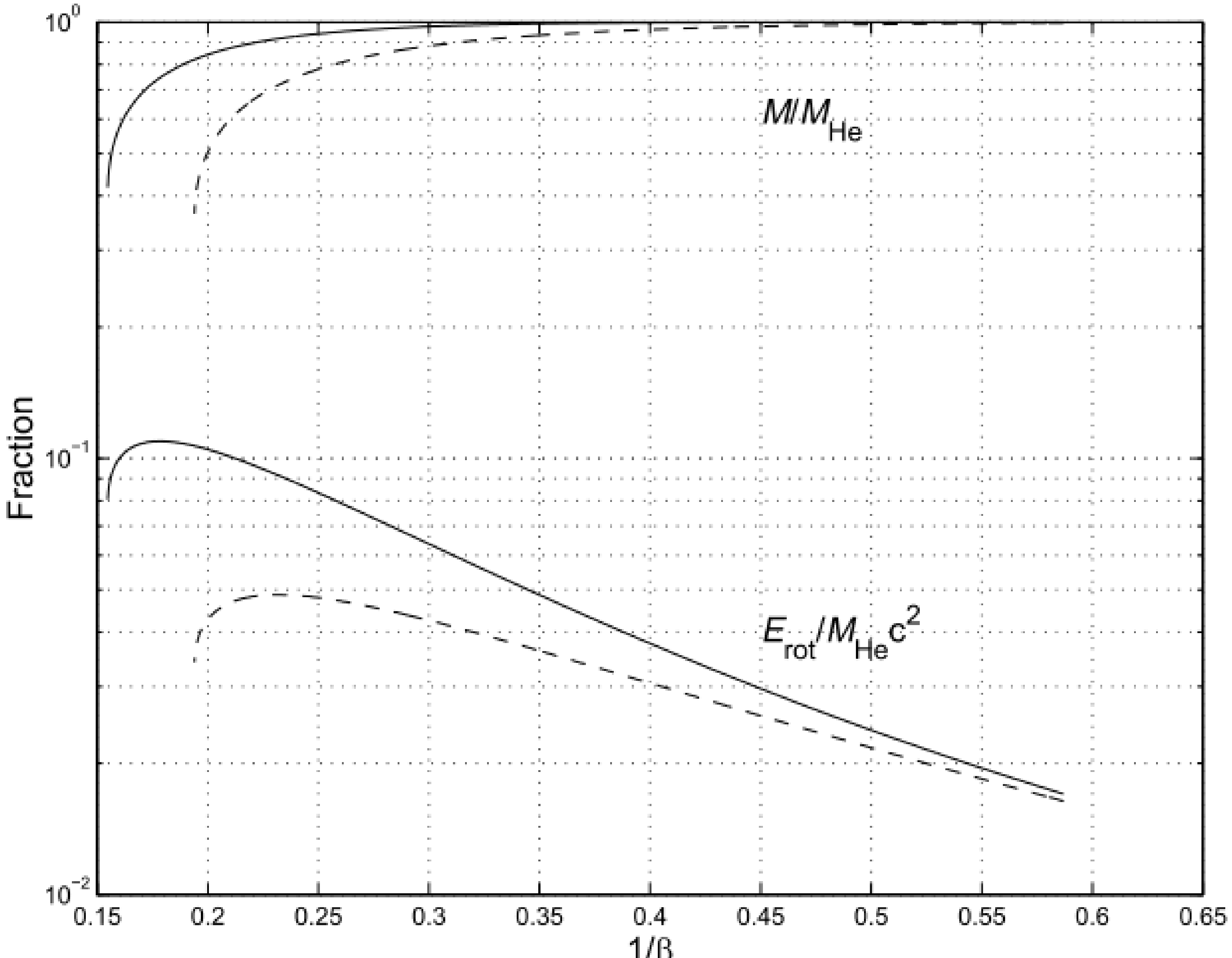
$$\Rightarrow$$

$$E_{spin} \le 4\times 10^{54}\left(\frac{M}{7M_{sun}}\right)\mathrm{erg}$$

BHs tend to radiate in accord with the Rayleigh criterion

$$a_p \ge 2M > M \ge a_H$$

# BH mass and angular momentum distributions in CC-SNe

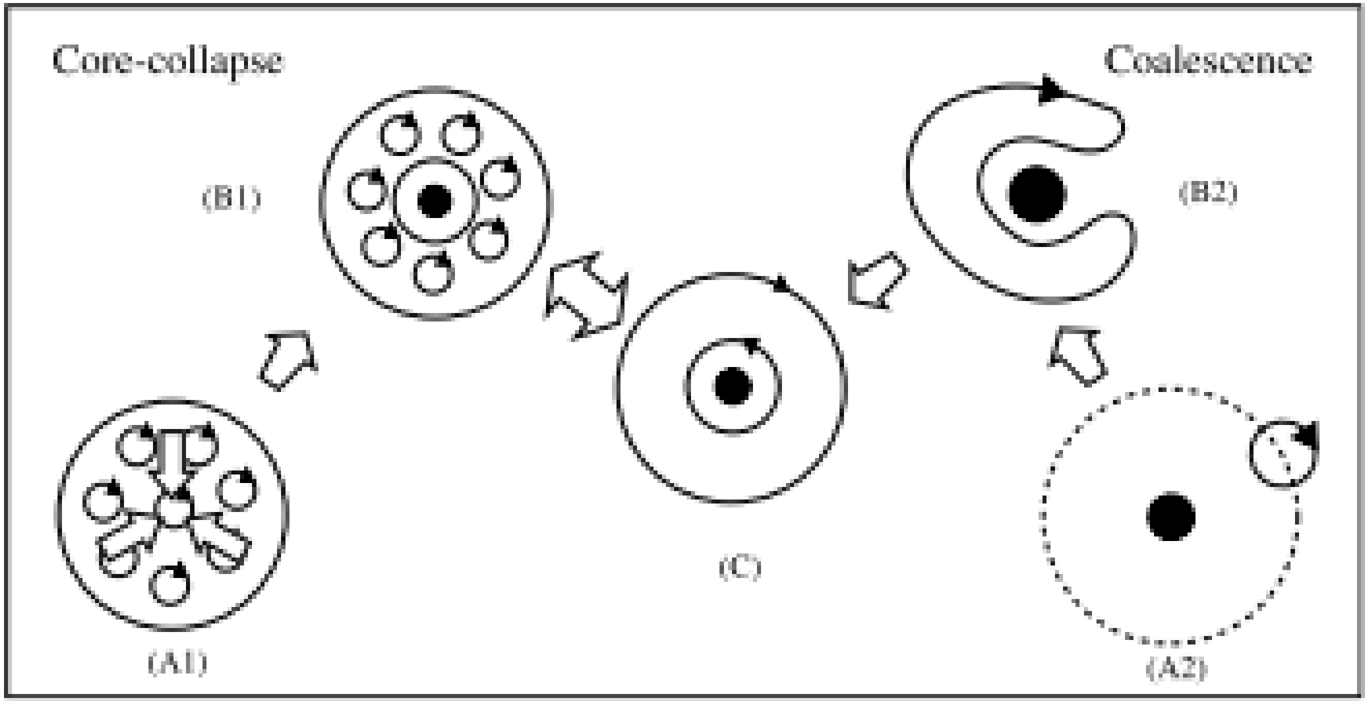



(Binary) period



Van Putten (2004)

# Black hole spin interactions with HDM



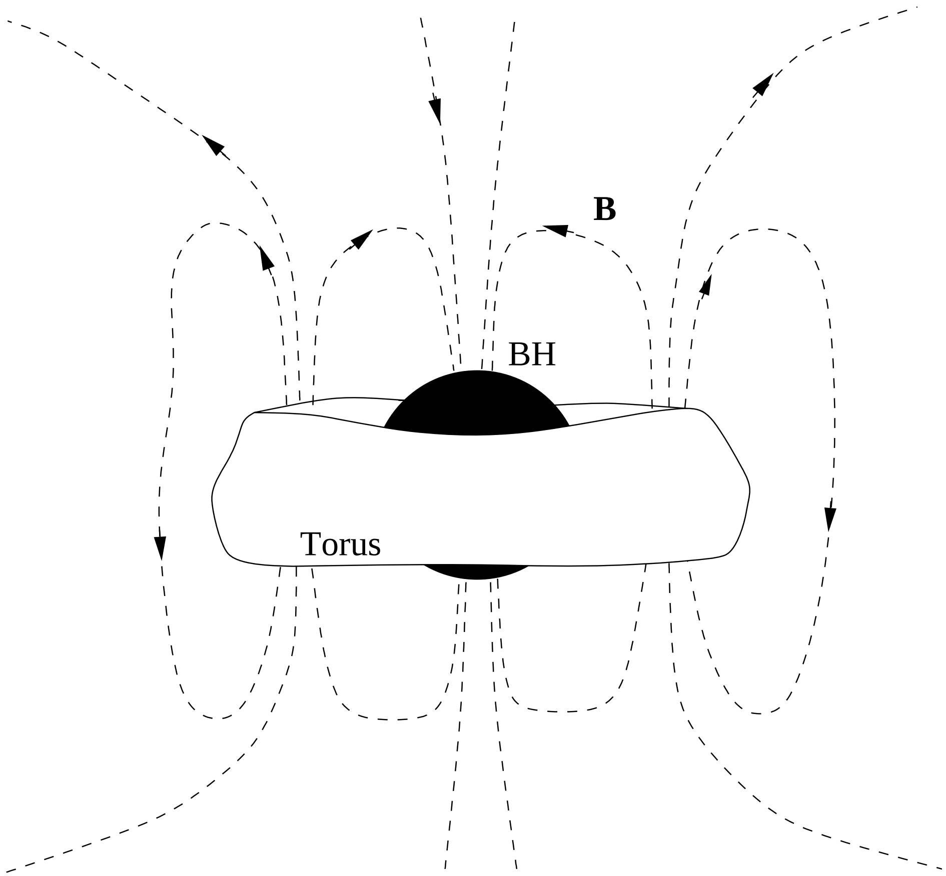

GRB030329/SN2003dh

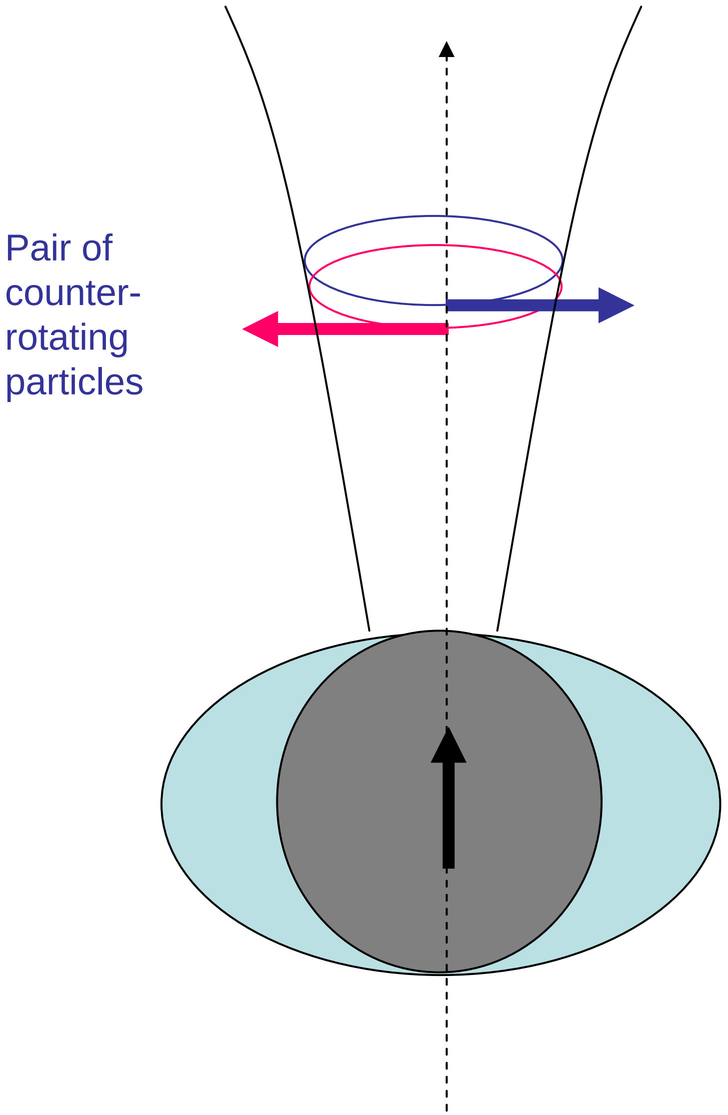
GRB060614

A common inner engine to long GRBs from CC-SNe and mergers


Van Putten Science 1999
Van Putten & Ostriker ApJ L 2001
van Putten & Levinson ApJ 2003

# Non-thermal emissions along open magnetic flux-tubes






van Putten 2000 PRL
van Putten, Il. Nuov. Cim. 2005

# Frame-dragging couples to angular momentum

Ab initio (perturbative)

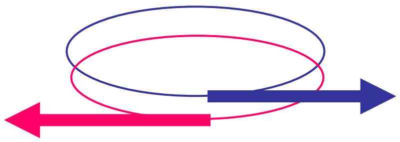
Grey-body factor

$$\frac{d^2N}{dEdt} = \frac{1}{2\pi}\frac{\Gamma}{e^{2\pi(E-V_F)/g_H}+1}$$

Fermi-level of the horizon surface

$$V_F = \nu\Omega_H, \quad \nu = \pm eA_\varphi$$

Modified Hawking radiation



$$J_\pm = g_{\varphi t}u^t + g_{\varphi\varphi}u^\varphi = \gamma g_{\varphi\varphi}(\Omega_\pm - \omega)$$

$$[J] = \gamma g_{\varphi\varphi}[\Omega - \omega] = \gamma g_{\varphi\varphi}[\Omega]_-^+$$

$$E \equiv \frac{1}{2}[E]_\pm = \omega J \qquad (J = \pm eA_\varphi)$$

Level splitting picture



van Putten 2000 PRL
van Putten, Il. Nuov. Cim. 2005

# Energetic coupling of angular momentum to Riemann curvature

$$F_c = \frac{1}{2} {}^* R_{abcd} J^a u^b u^d$$

L. Blanchet, this meeting

$$J = \pm e A_\varphi$$

"Unfortunately, in practical situations it is so weak that nobody has ever found any significant application for it." Thorne, Price & McDonald (1986) p156

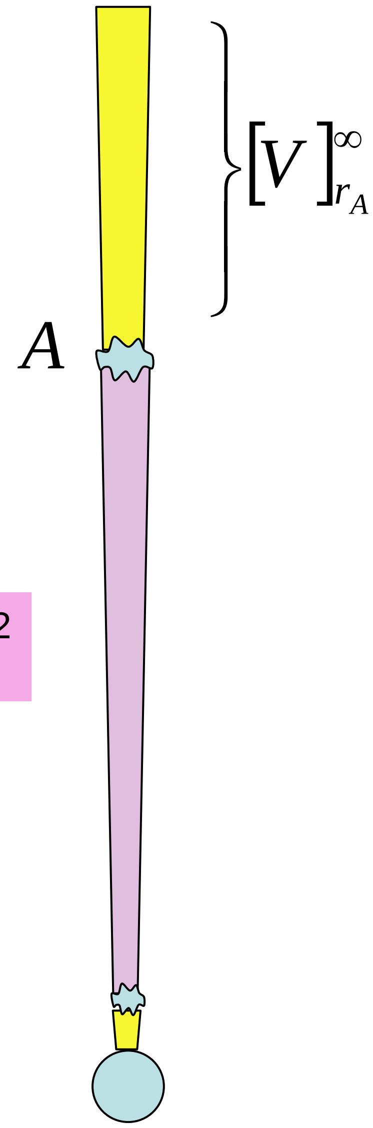
$$E = \int_r^\infty J \times \mathrm{Riemann}\ ds = \omega J$$

van Putten, Il. Nuov. Cim. 2005

cm2 cm-2

# Relativistic capillary motion

Linear accelerator
(below pair-creation)




Force-free section bounded by 2 Alfven surfaces

supermassive BH

$$E \approx 2\times 10^{18}\left(\frac{M_H}{10^9 M_{Sun}}\right)\left(\frac{B}{10^4\,\mathrm{G}}\right)\left(\frac{\theta_H}{0.15}\right)^2 \mathrm{eV}$$

Applications to UHECRs
(pick-up of ions in UV env.)

stellar mass BH

$$E \approx 3\times 10^{22}\left(\frac{M_H}{7 M_{Sun}}\right)\left(\frac{B}{10^{16}\,\mathrm{G}}\right)\left(\frac{\theta_H}{0.15}\right)^2 \mathrm{eV}$$

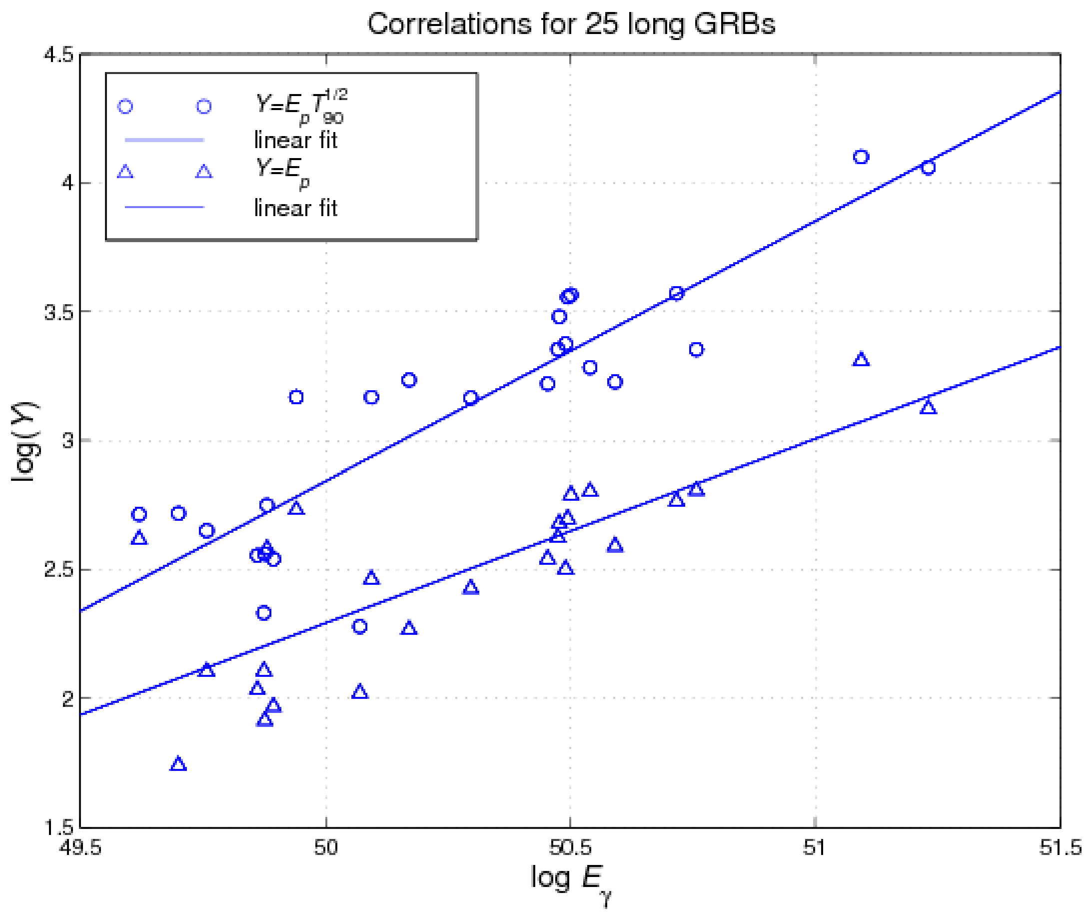
van Putten et al., PRD (2004)

$$\begin{cases} E_p = c_1 E & \left(E = \omega J, \quad J = eA_\varphi\right) \\ E_\gamma = c_2 L T_{90} & \left(L = \Omega_F^2 A_\varphi^2, \text{Goldreich \& Julian 1969; Blandford \& Znajek 1977, Thorne et al. 1987}\right) \end{cases}$$

$$c_2 \propto c_1, \quad \omega, \Omega_F \sim \Omega_H \rightarrow E_p T_{90}^{1/2} = ek E_\gamma^{1/2} \quad \left(k = 2c_1 c_2^{-1/2}\right)$$

$$\begin{cases} E_p \propto E_\gamma^{0.7} & \text{(Ghirlanda et al. 2004)} \\ c_1 \propto E_p^{3/2} & \text{(Eichler \& Juntof - Hutter 2005)} \end{cases} \; ; \quad k \propto E_\gamma^{21/40} \cong E_\gamma^{1/2} \Rightarrow \boxed{E_p T_{90}^{1/2} \propto E_\gamma}$$

*HETE-II and Swift data*




*Pearson coefficients*:
Circles: 0.85
Triangles: 0.76

van Putten, 2008, subm.

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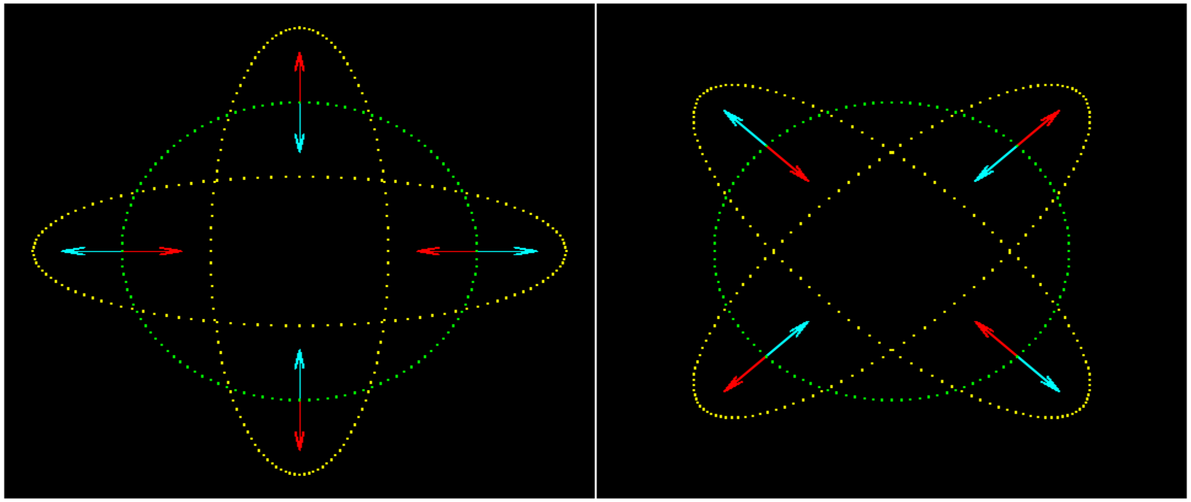
# Gravity at work: Gravitational radiation

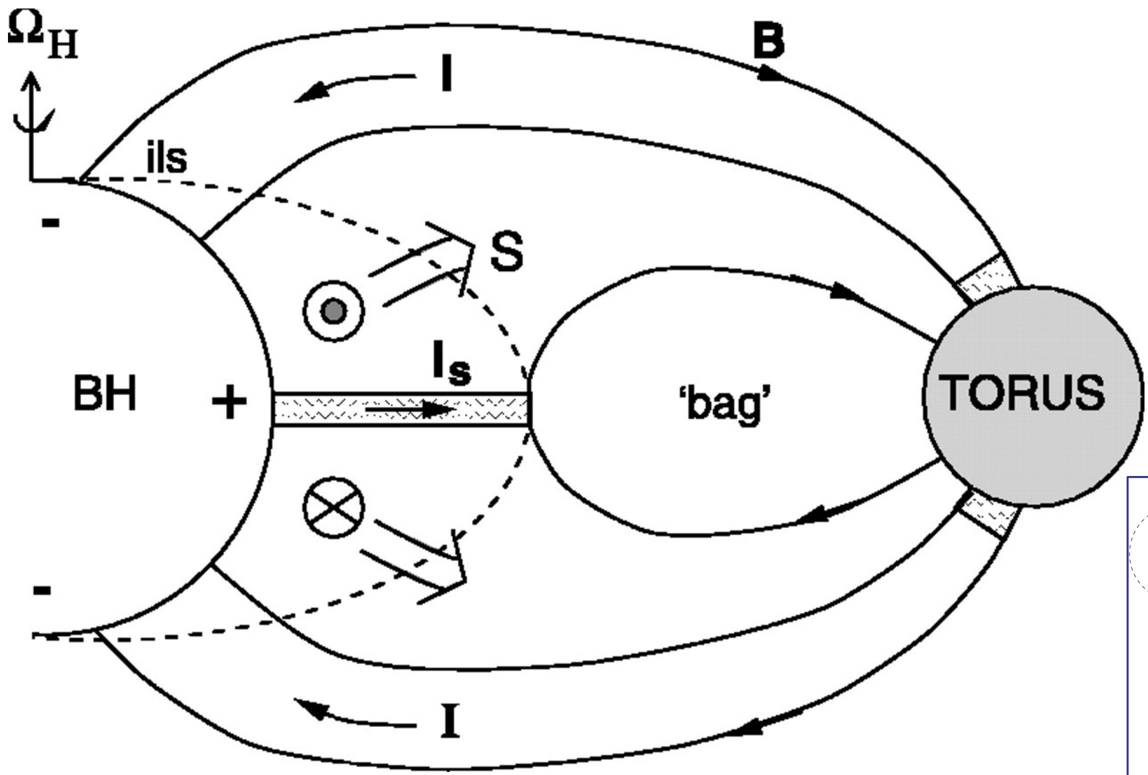


http://carina.astro.cf.ac.uk/groups/relativity/research/part4.html

$$L_{GW} = 0.15\% \text{ of } L_{sun} (3.8 \times 10^{33} \text{ erg/s})$$

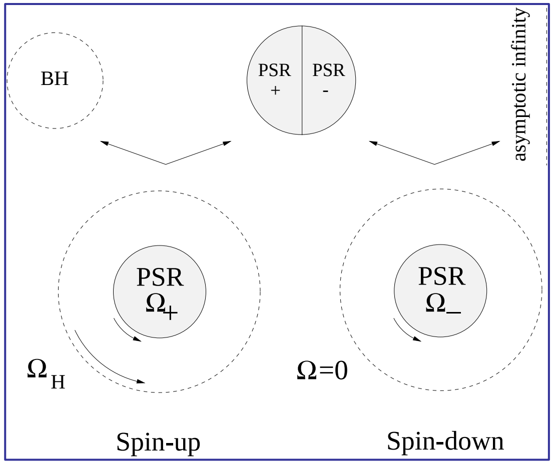
in Hulse-Taylor binary NS

# Spin-connection between black hole and surrounding matter




Luminous torus in suspended accretion

Duration: lifetime of rapid spin of BH




Equivalence to pulsar magnetospheres when viewed in poloidal topology



van Putten Science, 1999, 284, 115
van Putten & Ostriker ApJL 2001
van Putten & Levinson ApJ 2003

# Complete spin-down of a Kerr black hole in suspended accretion

$$\text{Position of the ISCO (rel. } M\text{)}: z = 3 + Z_2 - ((3 - Z_1)(3 + Z_1 + 2Z_2))^{\frac{1}{2}}$$

$$Z_1 = 1 + (1 - a^2)^{\frac{1}{3}}((1+a)^{\frac{1}{3}} + (1-a)^{\frac{1}{3}}), \quad Z_2 = (3a^2 + Z_2^1)^{\frac{1}{2}};$$

$$\text{Specific energy and angular momentum at ISCO}: e = \sqrt{1 - \frac{2}{3z}} \quad l = \frac{2}{\sqrt{3}}\left[1 + 2(3z-2)^{\frac{1}{2}}\right]:$$

$$2/\sqrt{3} \le l \le 2\sqrt{3} \quad \left(a = M, z = 1; a = 0, z = 6\right)$$

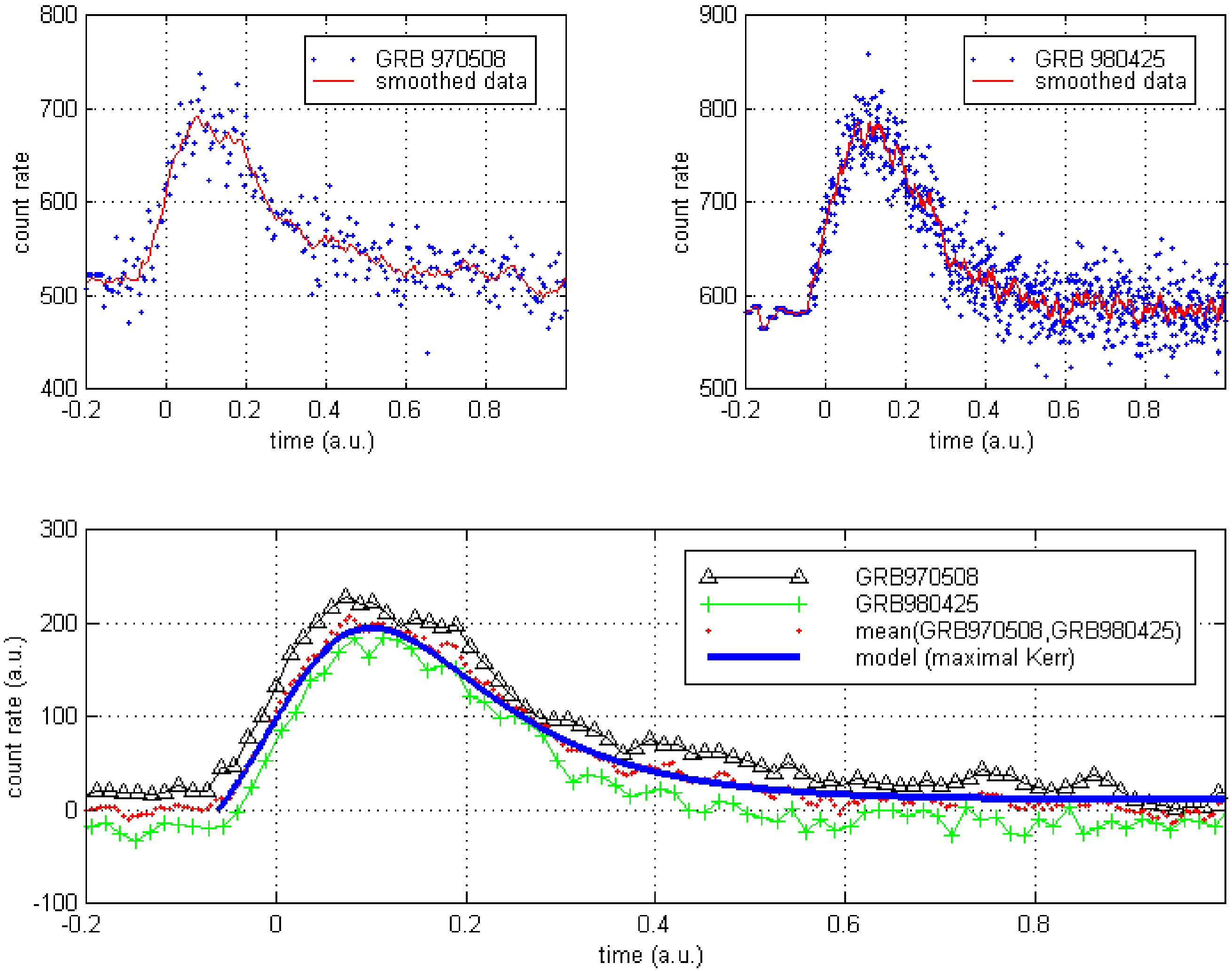
Bardeen et al.1972

$$\Omega_T = \frac{1}{M}\frac{1}{z^{\frac{3}{2}} + a}, \quad \Omega_H = \frac{\tan(\lambda/2)}{2M} \Rightarrow \eta = \frac{\Omega_T}{\Omega_H} = \left[\frac{1}{2}\left(z^{\frac{3}{2}} + a\right)\tan\left(\lambda/2\right)\right]^{-1}$$

Van Putten 1999

$$\Rightarrow \quad \begin{cases} \dfrac{dM}{dt} = -e\left(1-\eta\right)\eta\Omega_H^2 \\ \dfrac{dJ}{dt} = -e\left(1-\eta\right)\Omega_H \end{cases}$$

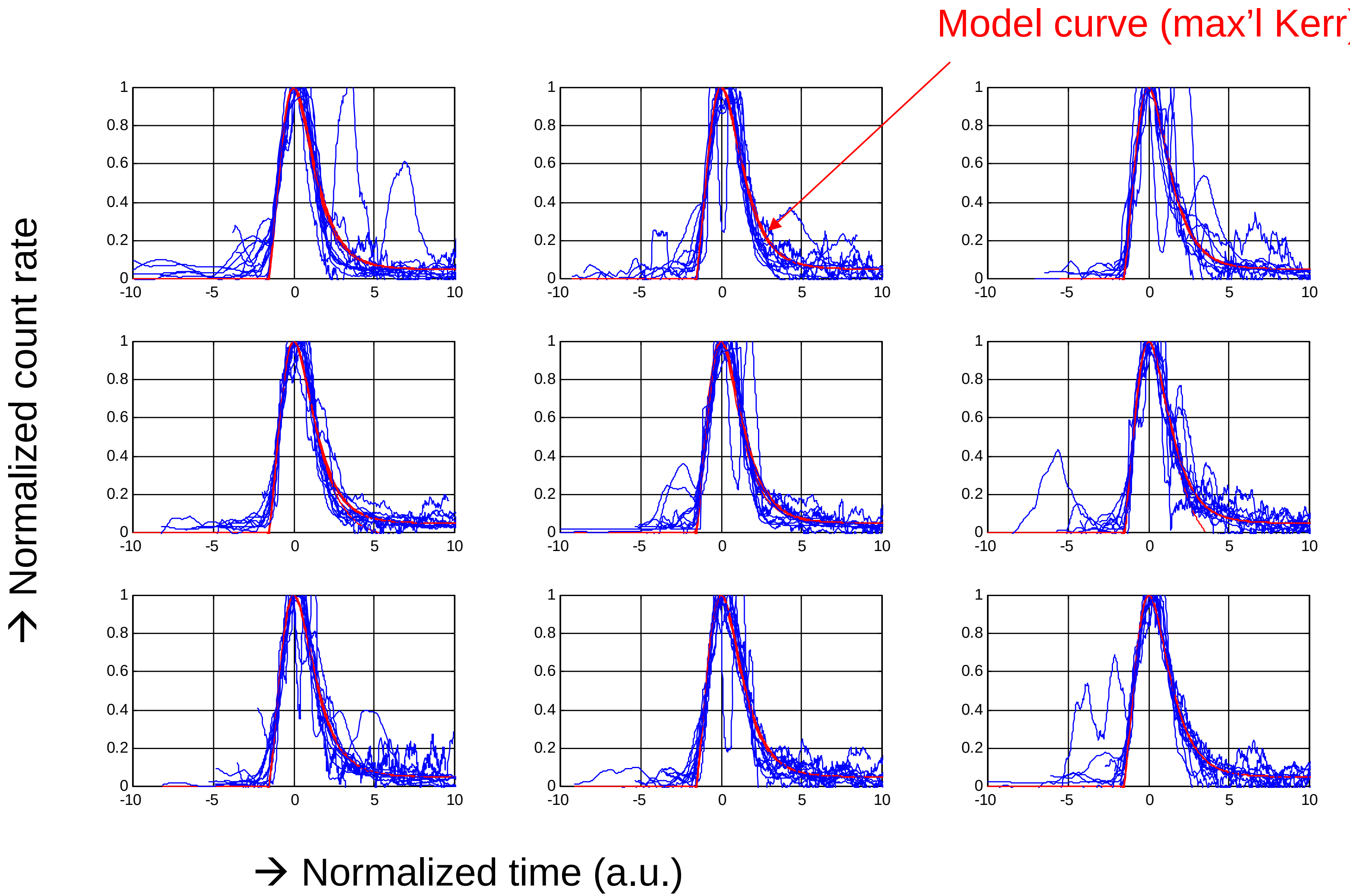
Van Putten, subm.




→ Normalized count rate

→ Normalized time (a.u.)

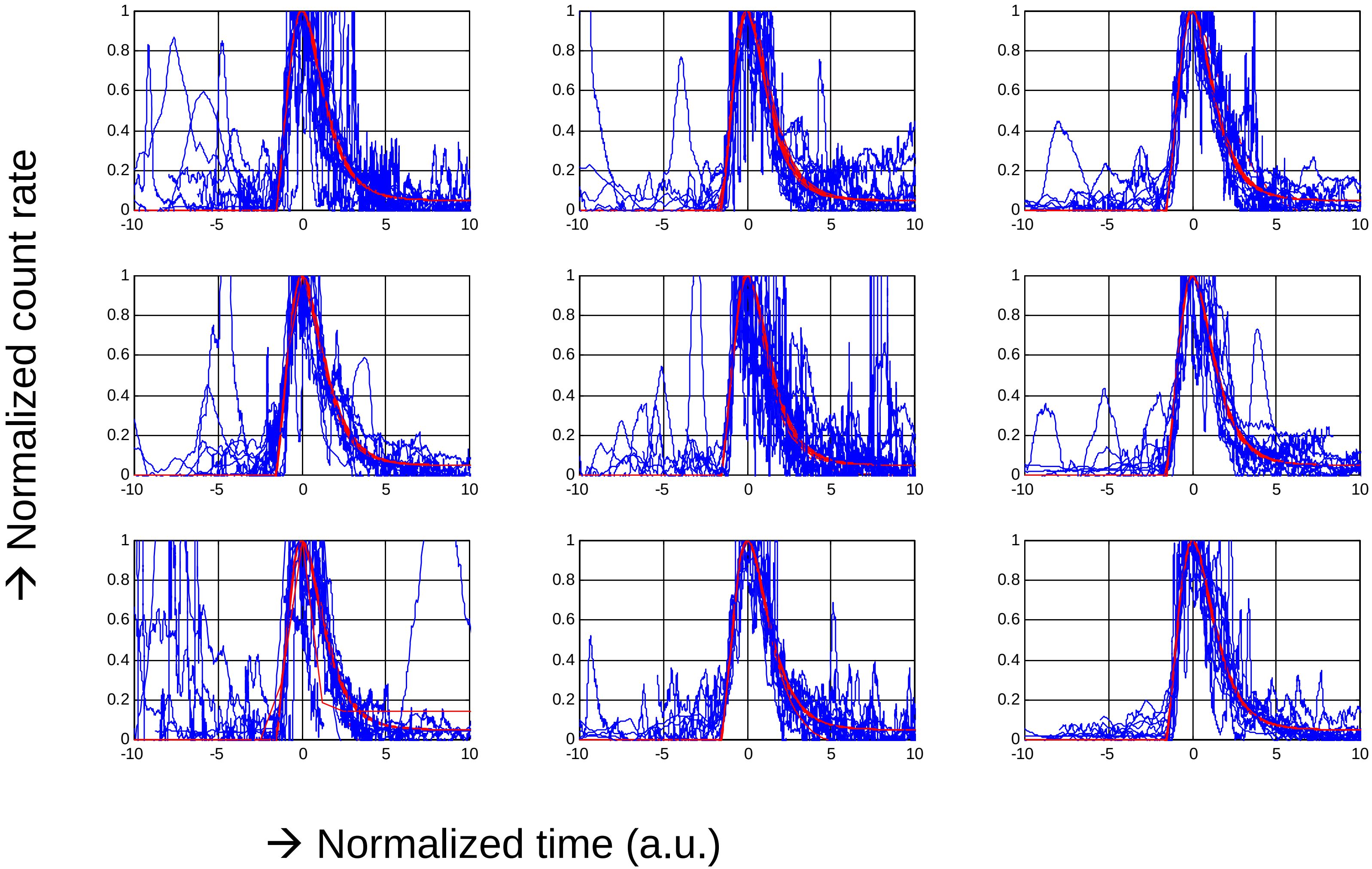
# 2 s < T90 < 20 s






van Putten & Gupta, 2008, in prep.

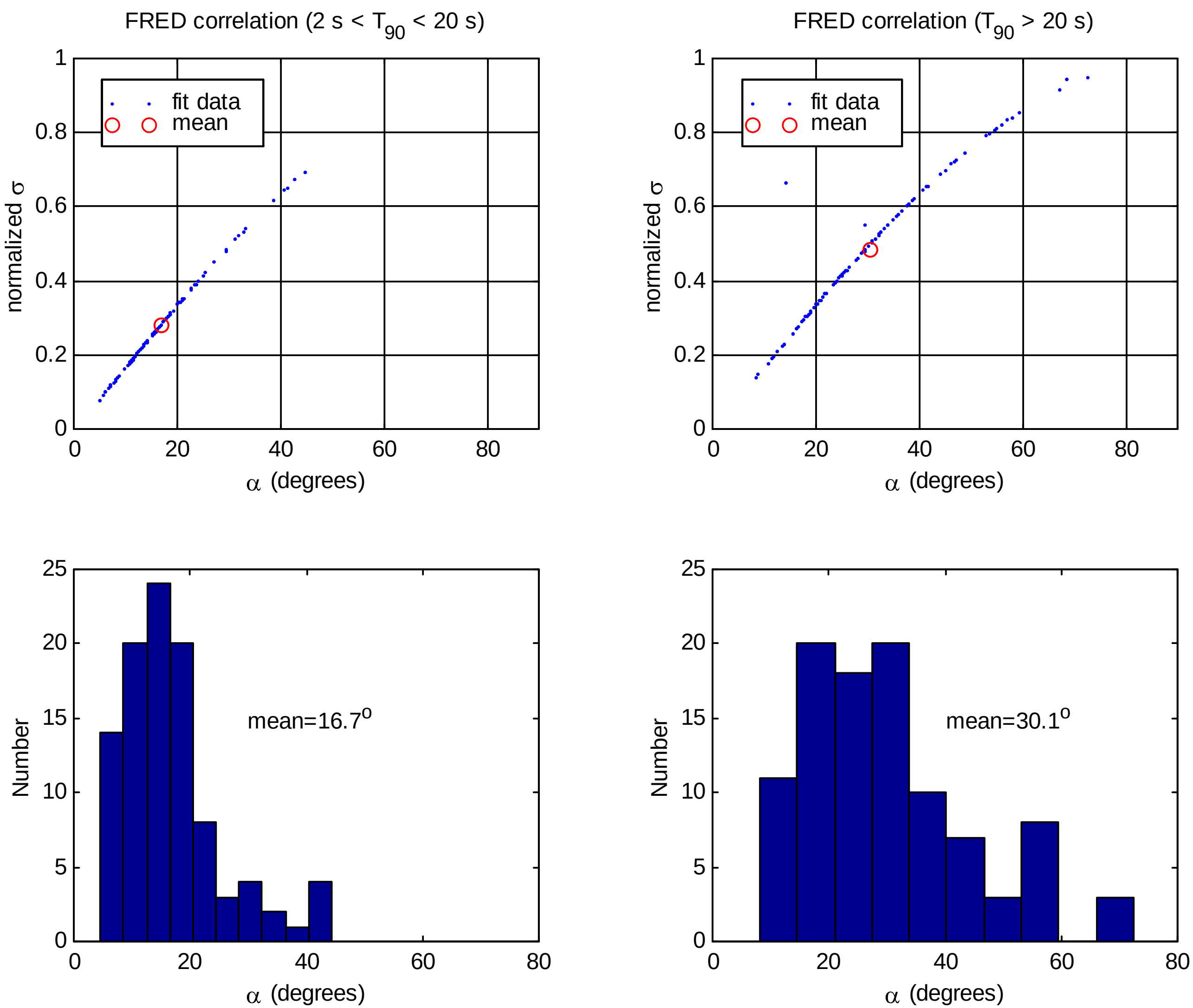
# T90 > 20 s




(c)2008 van Putten

van Putten & Gupta, 2008, in prep.

# Pearson coefficient = $\cos\alpha$

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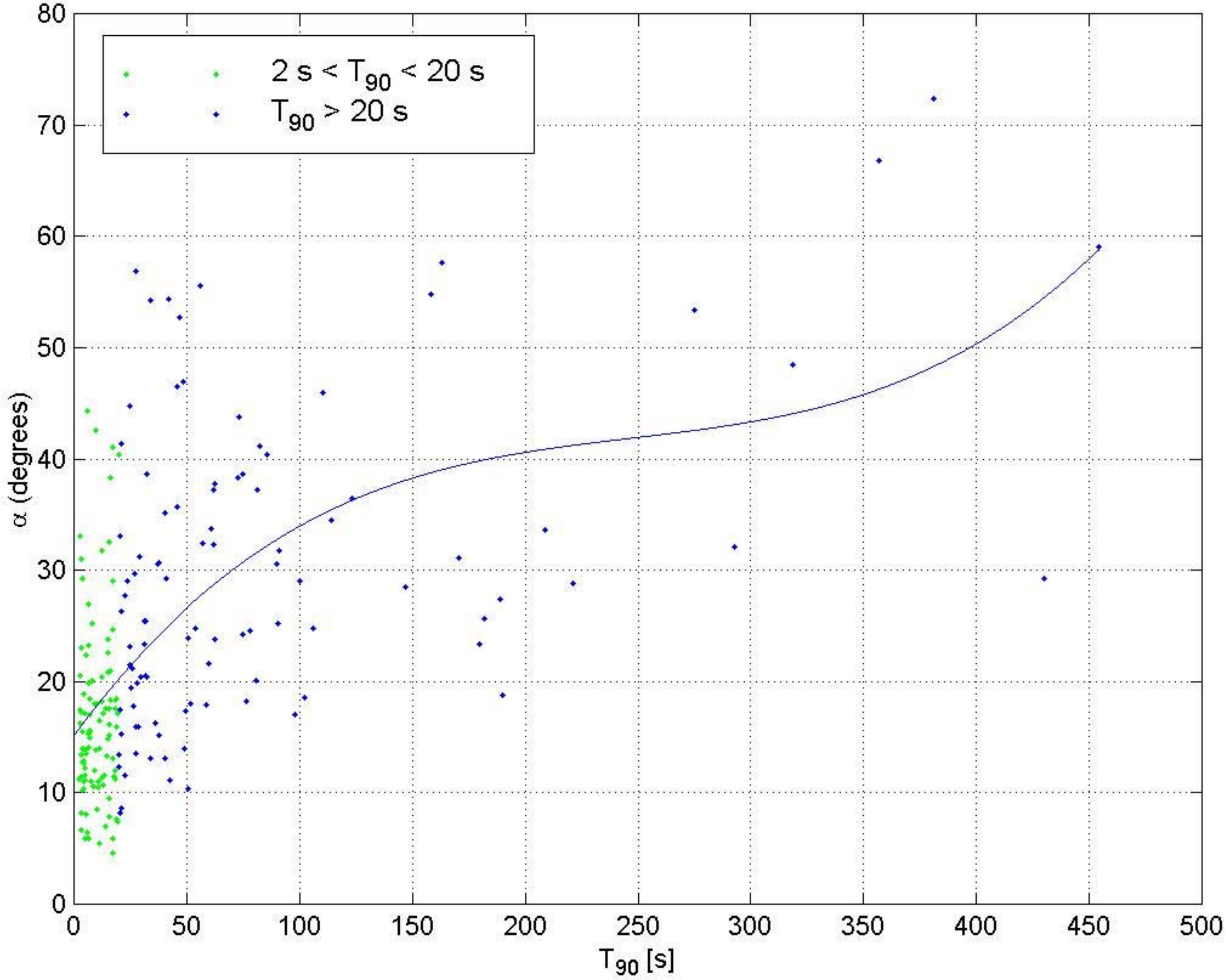
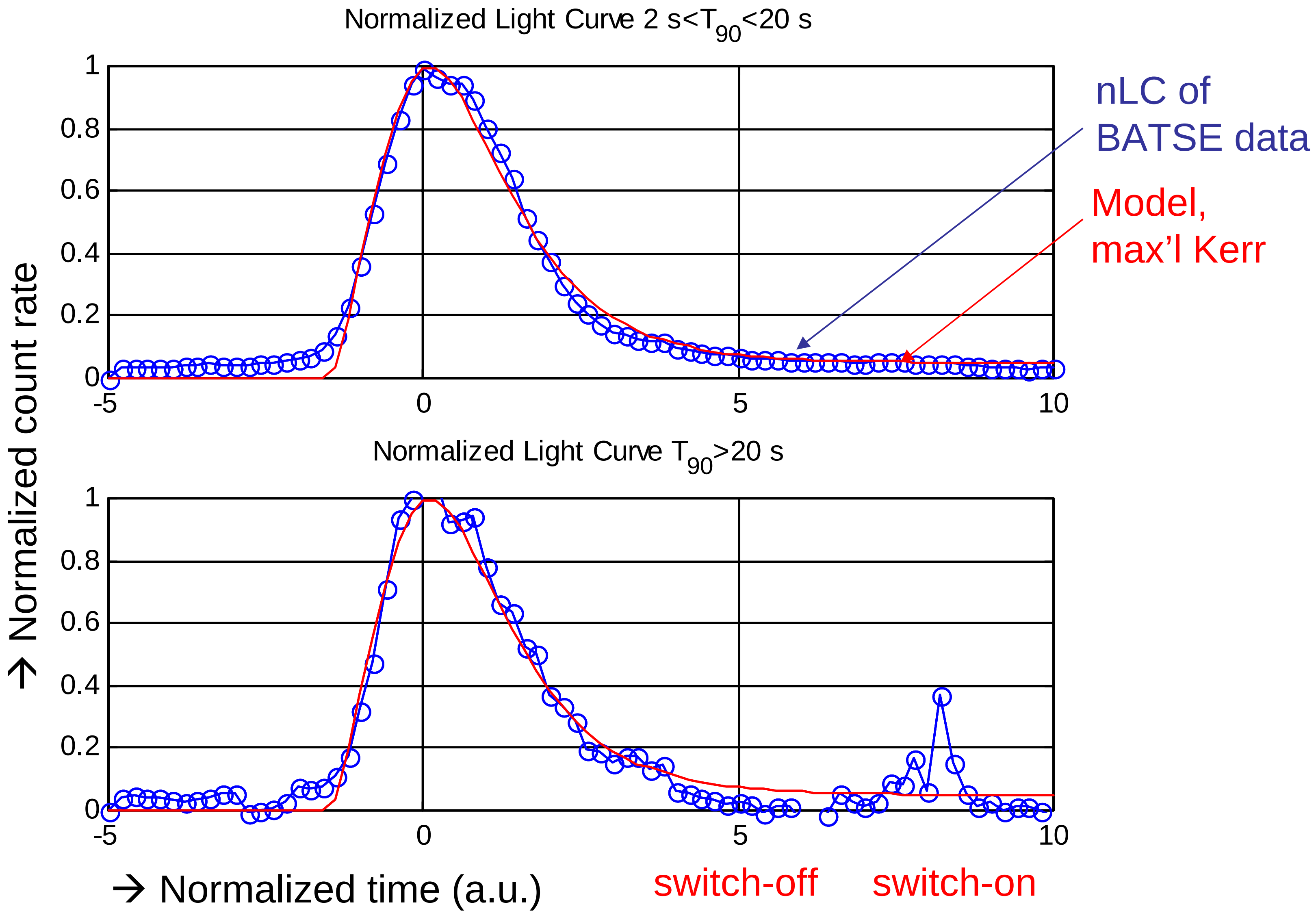
van Putten & Gupta, 2008, in prep.

# Pearson coefficient = $\cos\alpha$






van Putten & Gupta, 2008, in prep.




(c)2008 van Putten

van Putten & Gupta, 2008, in prep.

# Phenomenology at work: Metrology on Black Holes

- compactness: orbiting “test” particles (stars, accretion disks, COs)
- Frame-dragging: disk spectroscopy
- Gamma-ray bursts from rotating BHs
- Spin-down: “live” in long-duration GRBs
- Spin-energy: calorimetry on GWs

# Tori are naturally non-axisymmetric

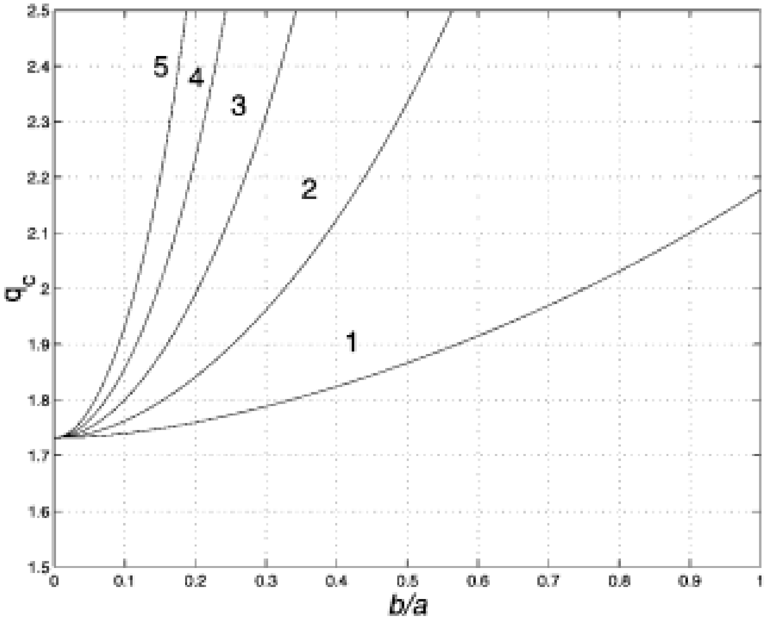
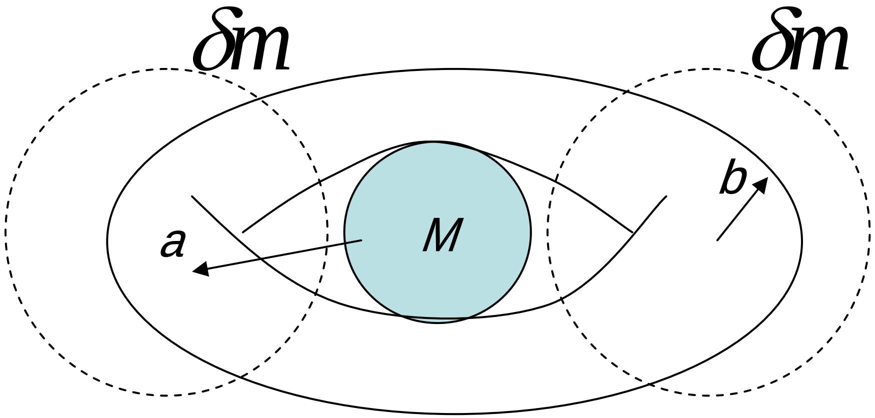



FIG. 2.—Diagram showing the neutral stability curves for buckling modes in a torus of incompressible fluid, as an extension of the Papaloizou-Pringle instability to large ratios of minor-to-major radius $b/a$. Curves of critical rotation index $q_c$ are labeled with azimuthal quantum numbers $m = 1, 2, \ldots,$ where instability sets in above and stability sets in below. Of particular interest is the range $q \leq 2$, where the $m = 0$ mode is Rayleigh-stable. For $q = 2$, the torus is unstable for $b/a < 0.7385$ ($m = 1$), 0.3225 ($m = 2$) and, asymptotically, for $b/a \simeq 0.56/m$ ($m \geq 3$).

*GWs,*
*MeV neutrinos,*
*magnetic winds*




$m$=2

## Critical slenderness creates $m$=2 instability



van Putten 2002

# Equations of suspended accretion

$$\tau_+ = \tau_- + \tau_{gw}$$

Balance of torque

$$\Omega_+ \tau_+ = \Omega_- \tau_- + \Omega \tau_{gw} + P_{mhd}$$

Balance of power

$$P_{mhd} \cong A_r^2 (\Omega_+ - \Omega_-)^2$$

Largely into MeV-neutrinos

$$\Omega \cong \frac{1}{2} (\Omega_+ + \Omega_-)$$

Mean angular velocity of torus



van Putten 2001, van Putten & Ostriker 2001, van Putten & Levinson 2005

# Suspended accretion state

## Evolution

Active over its lifetime of rapid spin (minutes)

Viscous spin-down: most of the spin-energy is dissipated unseen in the horizon

## Radiation

Receives most of the black hole luminosity

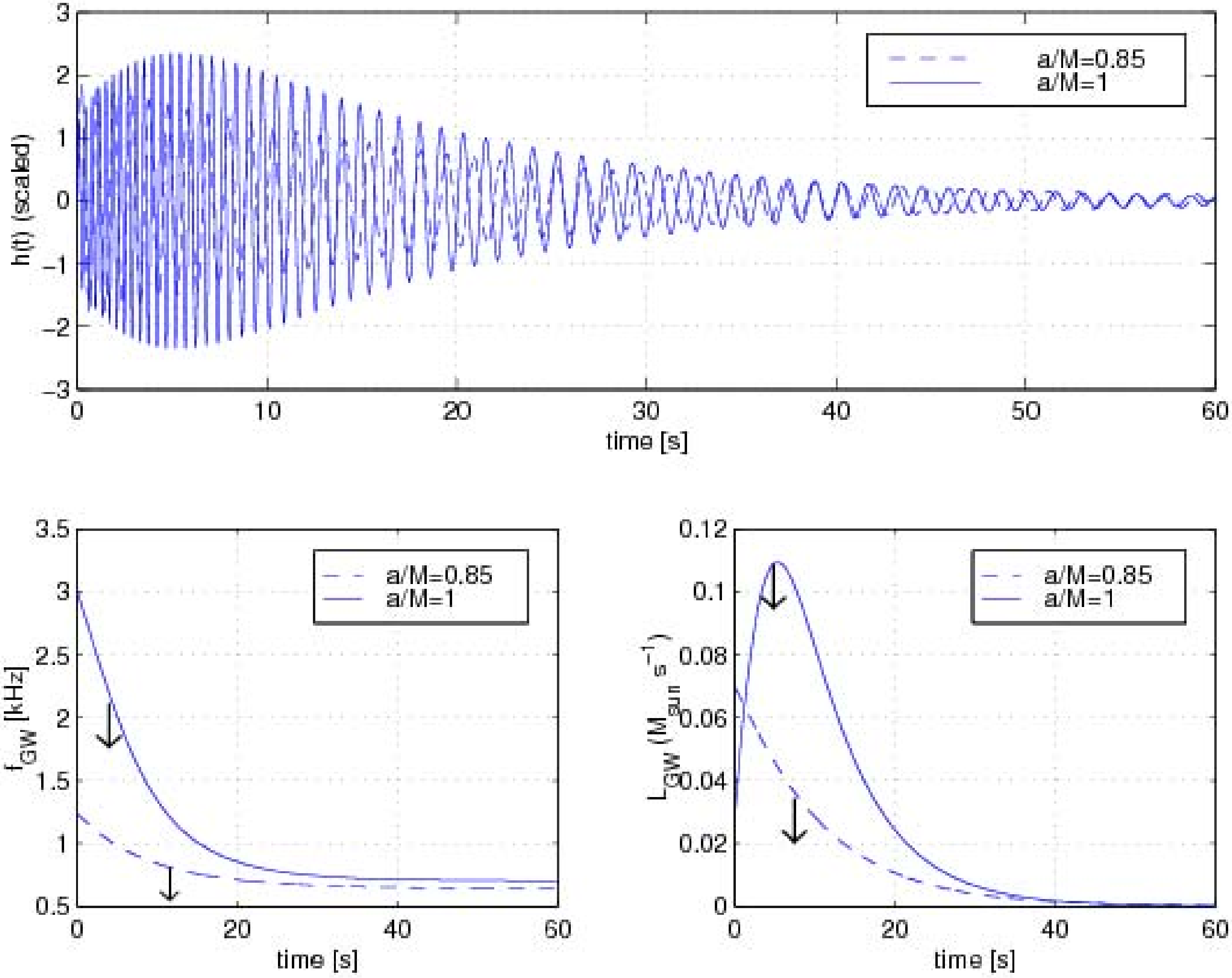
Is mostly luminous in GWs (subdominant emissions in MeV and winds)

GWs are mostly in low-frequency quadrupole emissions

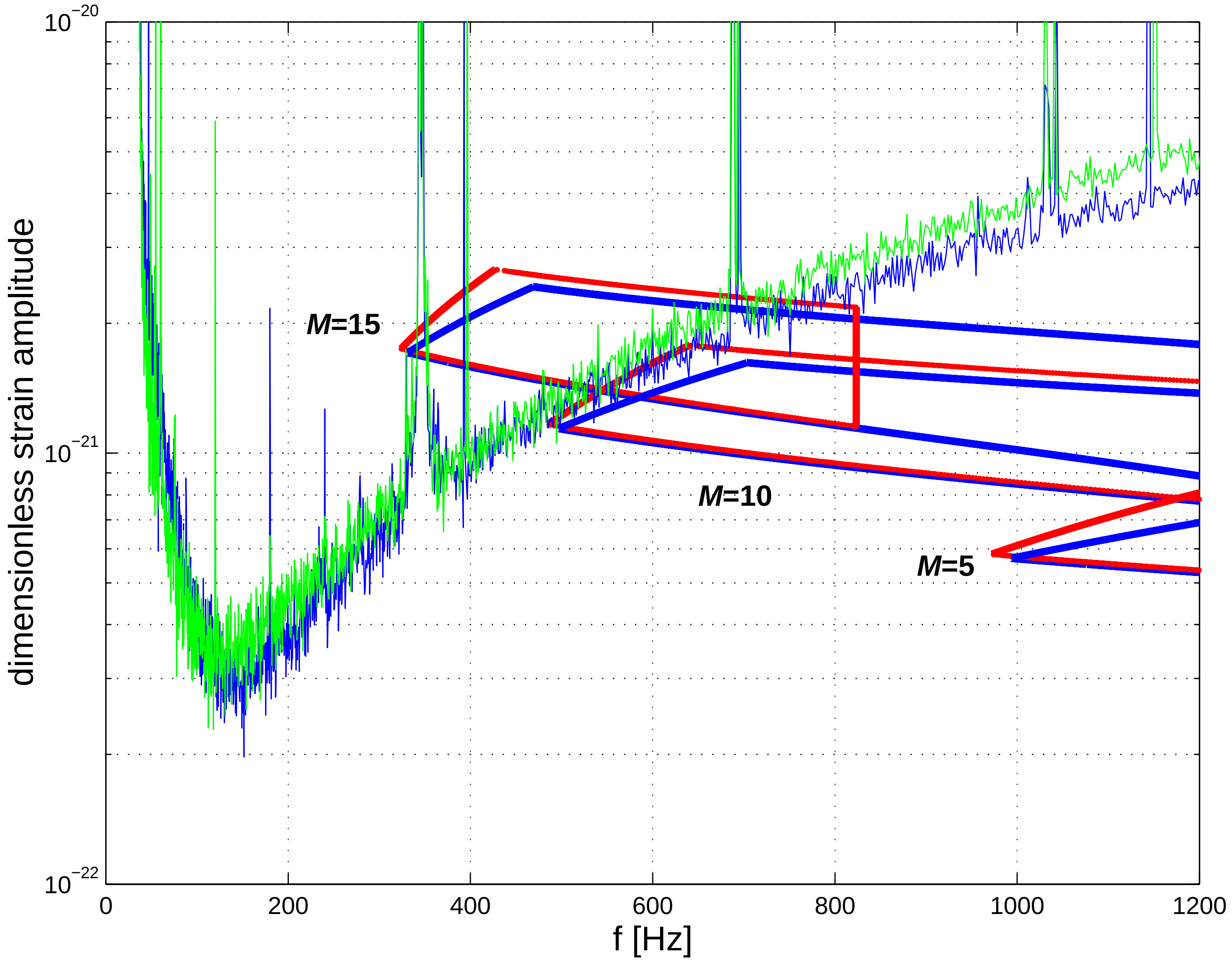


Van Putten 2001 et seq.

# Wave-form of long-duration burst




van Putten 2008, subm.



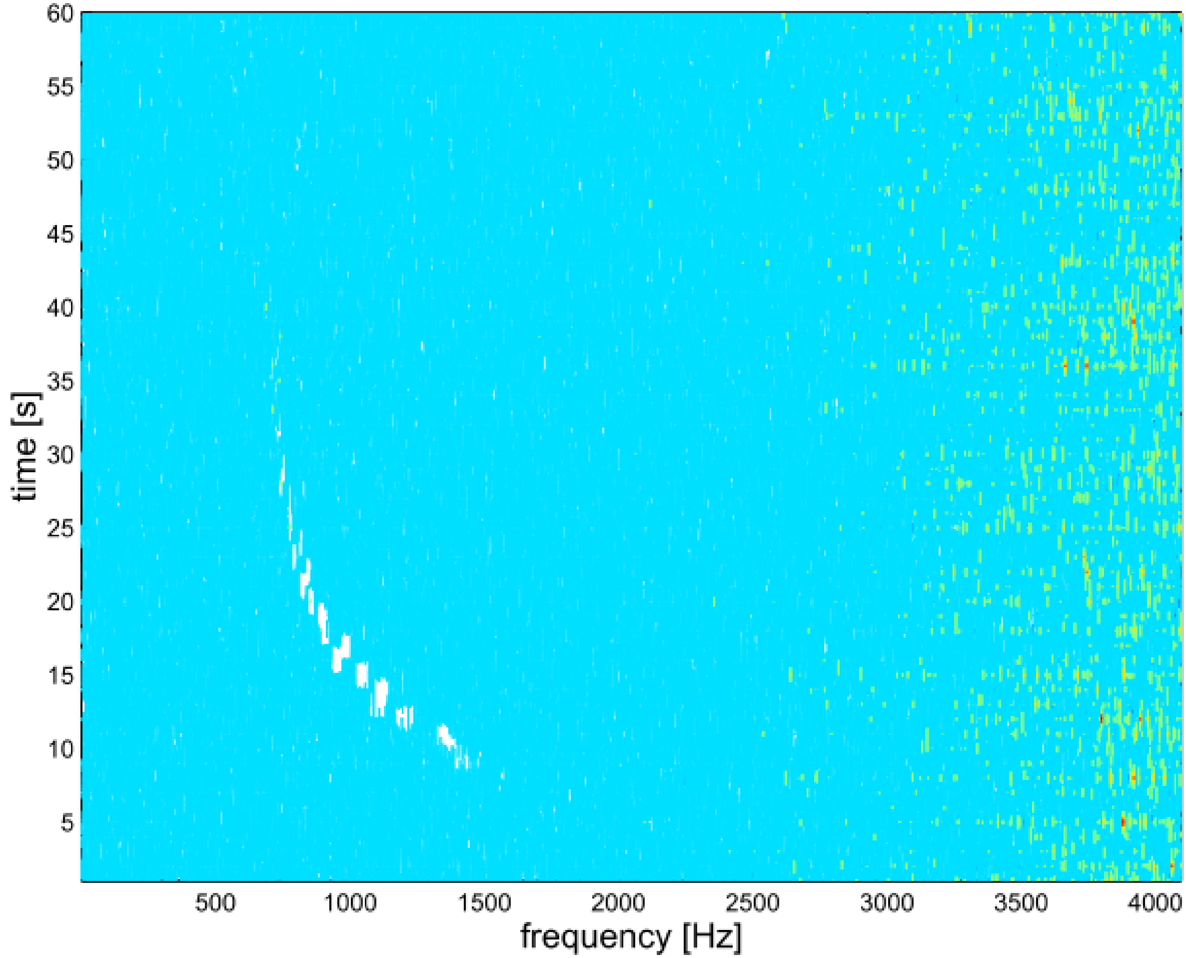



van Putten, 2008, subm.

# Time-frequency trajectory

(GRB030329/SN2003dh or GRB060614)

The sound of a long-duration GRB




$$M_{BH} \leq 5.9\, f_{gw}^{-1} M_{Sun}$$

$$S / N = \sqrt{N_w}\sigma_h / \sigma_{sn} = 1.5 \quad (1\,\mathrm{s\ segments, 16kHz})$$



Finnskyview_hst.jpg

# Conclusions

Metrology on spacetime around rotating BHs

spectroscopy on stars, accretion disks

Evidence for rotating BHs in long-duration GRBs

Correlation between peak energy, T90 and true energy in gamma-rays
Evidence for viscous spin-down of Kerr BHs in suspended accretion
Prediction long-duration bursts in GWs with negative chirp

New opportunities for high-frequency GWs (> 200 Hz)

Advanced LIGO/Virgo (4 km)
Very long armlength detector: ILC-GWD (40 km)?