Hypernovae: GRB-supernovae as LIGO/VIRGO sources of gravitational radiation

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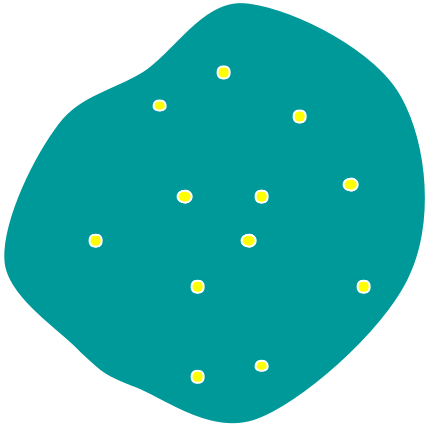
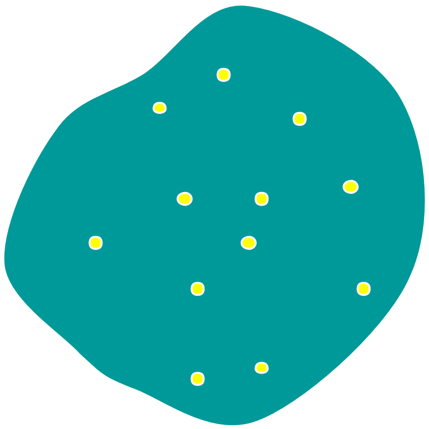
LIGO-G030269-00-R

Star-formation in a molecular cloud

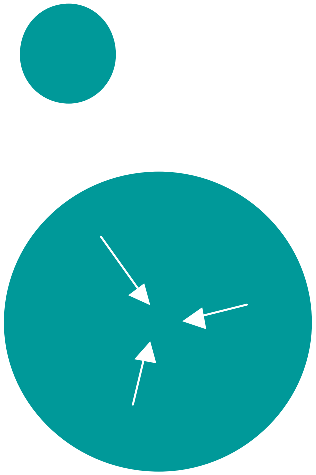


Molecular cloud

Core-collapse in a rotating massive star in a binary

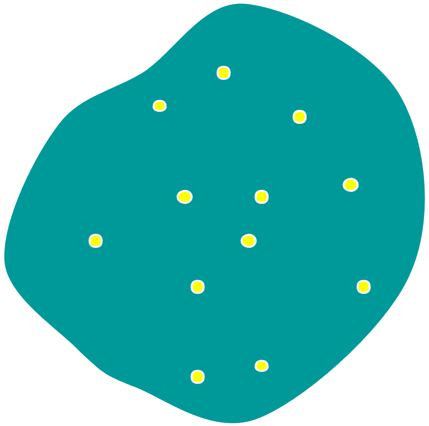


Molecular cloud

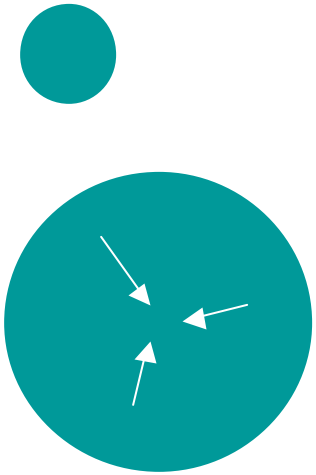


Core-collapse
(Woosley-Paczynski-Brown)

Active stellar nuclei

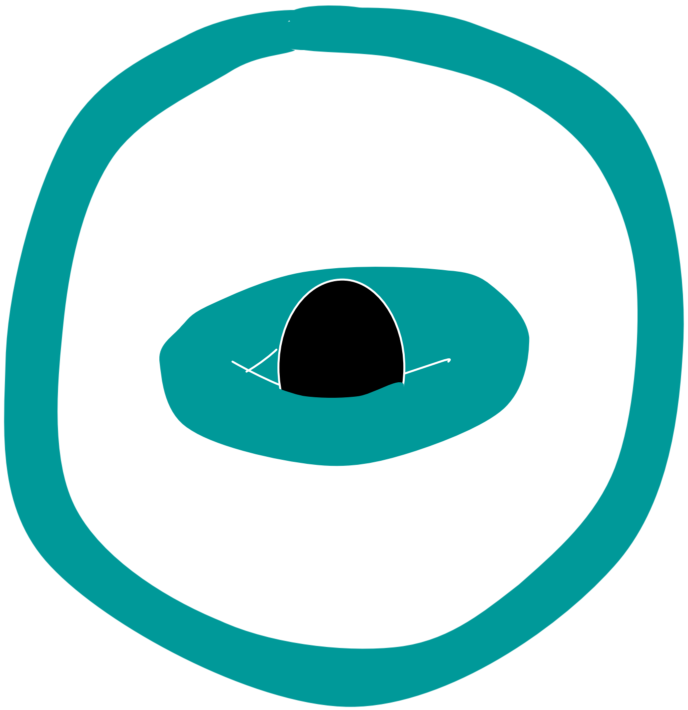


Molecular cloud

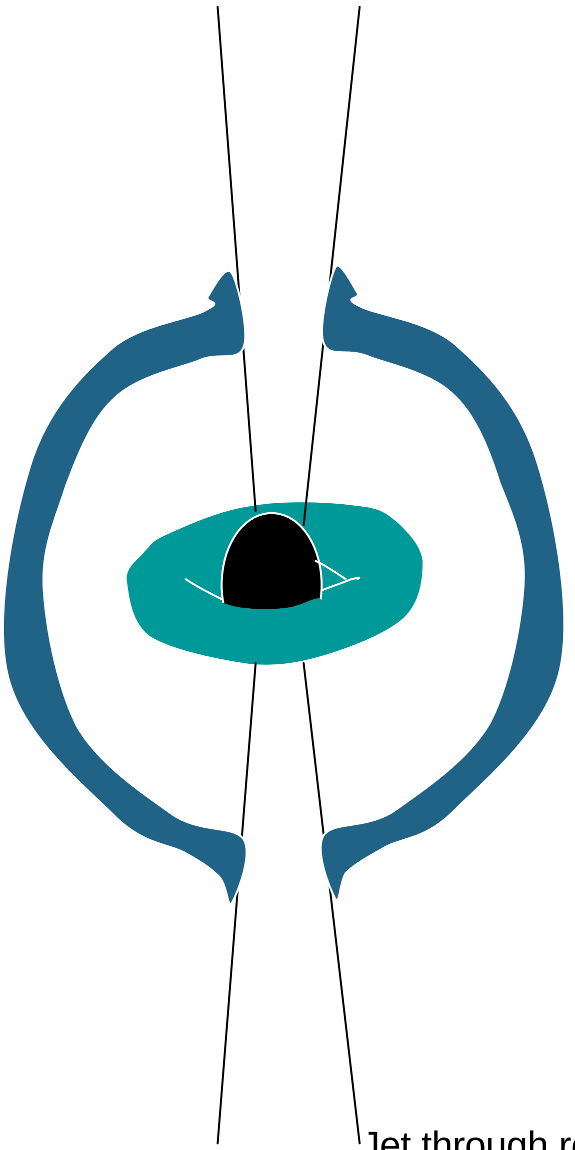


Core-collapse
(Woosley-Paczynski-Brown)

Active nucleus *inside* remnant stellar envelope

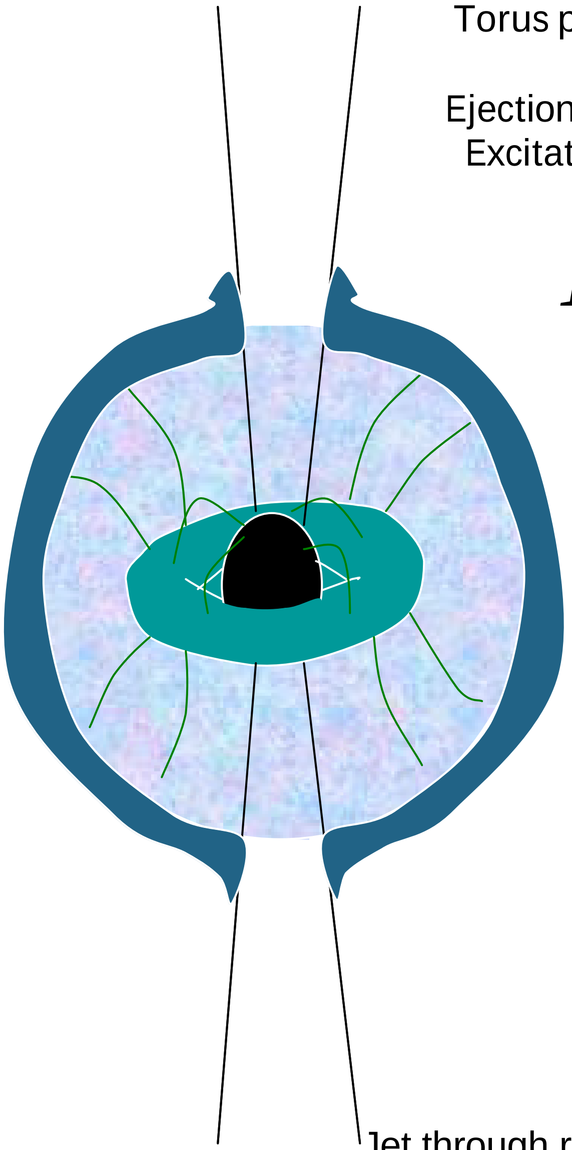


Hypernovae: GRB-supernovae from rotating black holes



Jet through remnant envelope
(McFadyen & Woosley'98)

Hypernovae: GRB-supernovae from rotating black holes

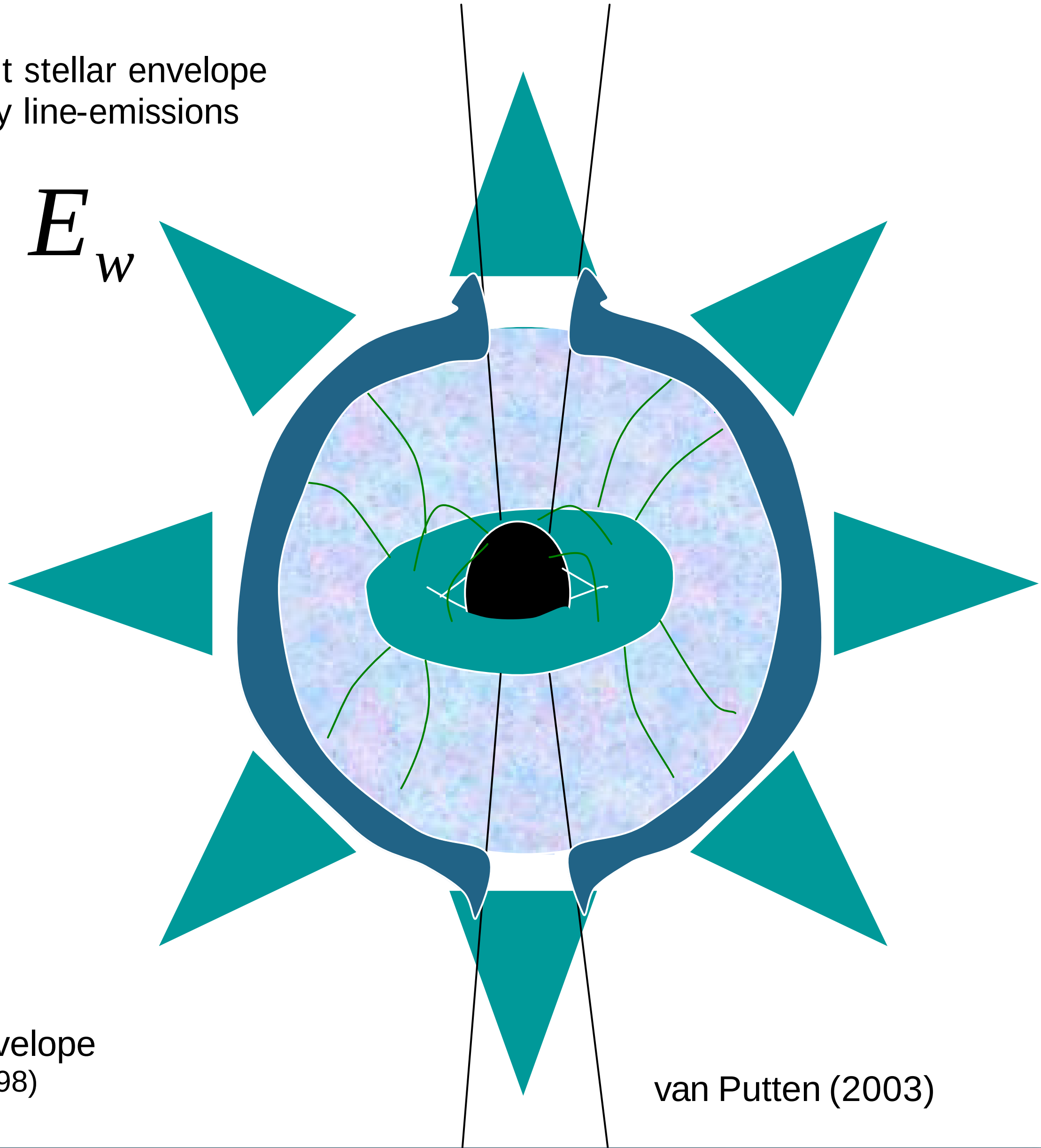


Torus produces winds & radiation:

Ejection of remnant stellar envelope
Excitation of X-ray line-emissions

$$E_r \cong E_w$$

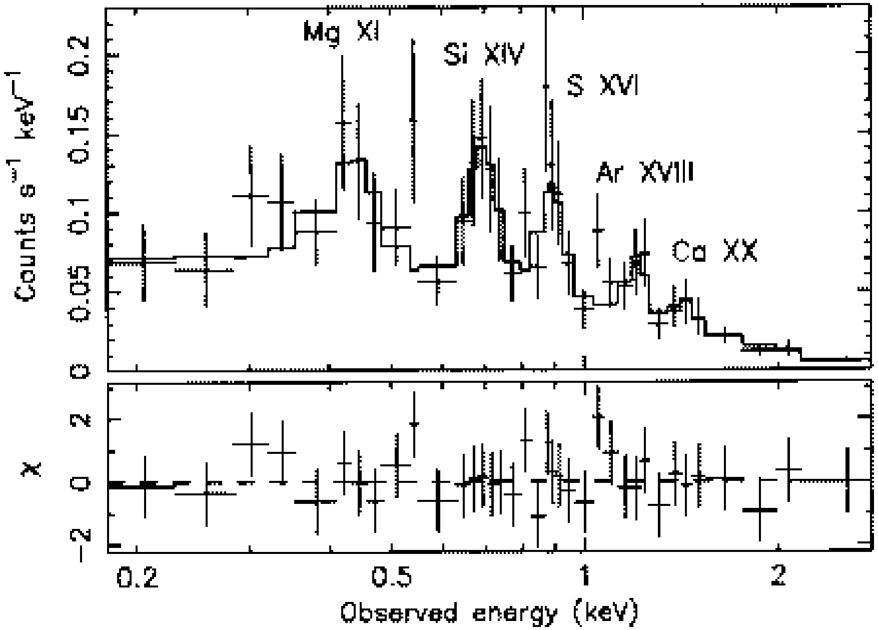
Jet through remnant envelope
(McFadyen & Woosley'98)

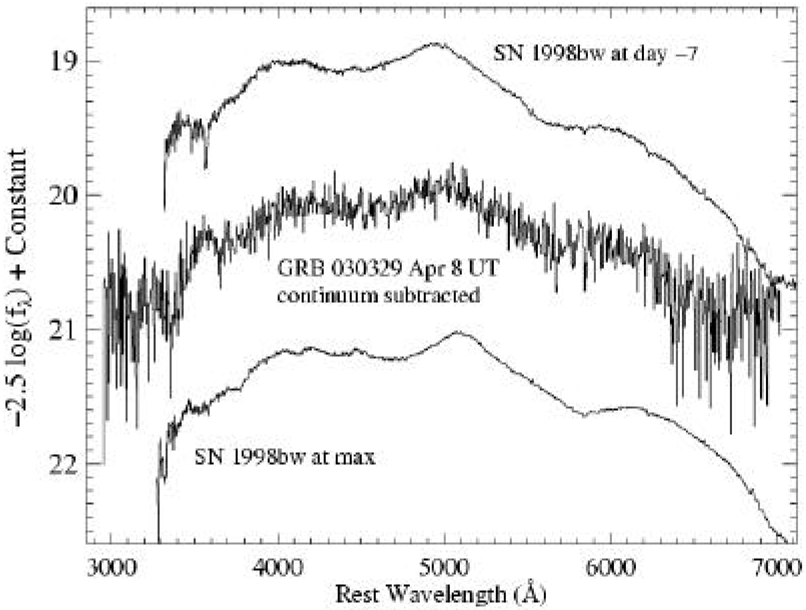


van Putten (2003)

GRB-SNe in 011211 and 030329

GRB 011211 (z=2.41) Reeves et al. '02





$E_r \cong 4\times10^{52}$ (G. Ghisellini 2002)

Stanek, K., et al., 2003 astro-ph/0304173

Outline

1. Quantitative phenomenology of GRB-supernovae
2. A causal spin-connection in active stellar nuclei
3. Durations of tens of seconds of long bursts
4. Calorimetry on radiation energies
5. Observational opportunities for Adv LIGO/VIRGO
6. Conclusions

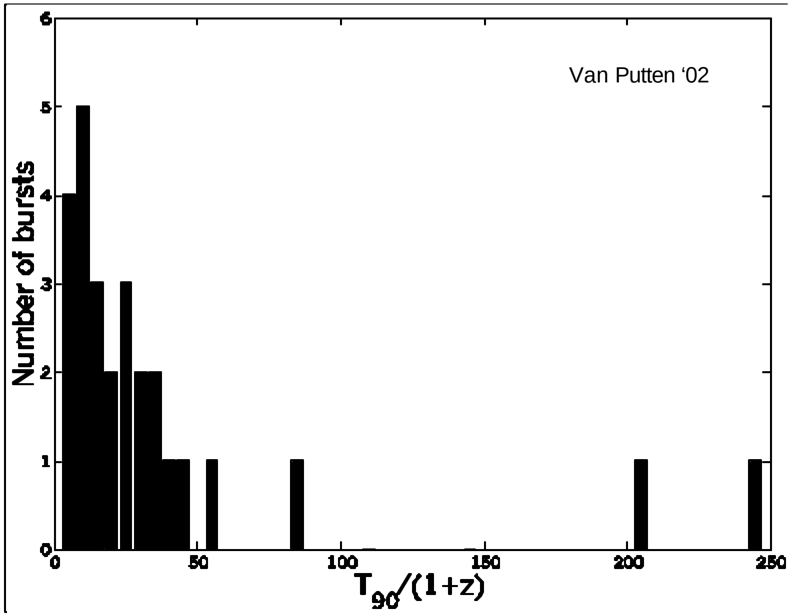
GRBs with redshifts (33) and opening angles (16)

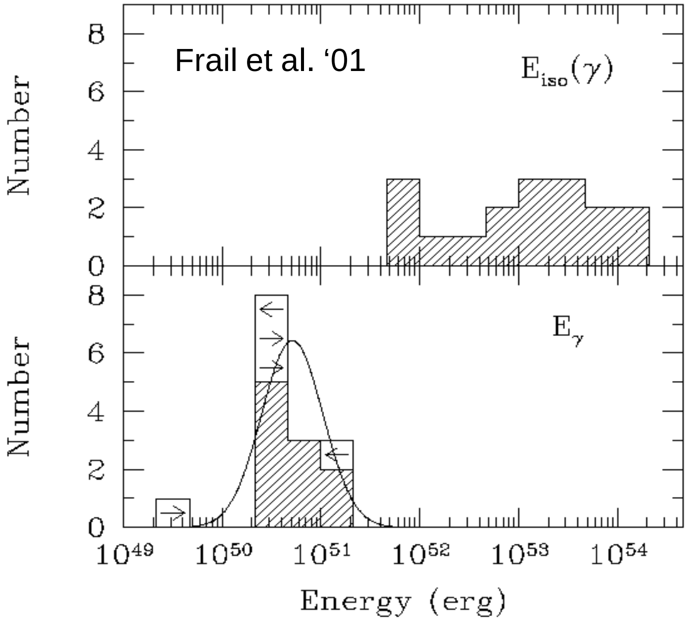
GRB	redshift	angle	instrument
GRB970228	0.695		SAX/WFC
GRB970508	0.835	0.293	SAX/WFC
GRB970828	0.9578	0.072	RXTE/ASM
GRB971214	3.42	>0.056	SAX/WFC
GRB980425	0.0085		SAX/WFC
GRB980613	1.096	>0.127	SAX/WFC
GRB980703	0.996	0.135	RXTE/ASM
GRB990123	1.6	0.050	SAX/WFC
GRB990506	1.3		BAT/PCA
GRB990510	1.619	0.053	SAX/WFC
GRB990705	0.86	0.054	SAX/WFC
GRB990712	0.434	>0.411	SAX/WFC
GRB991208	0.706	<0.079	Uly/KO/NE
GRB991216	1.02	0.051	BAT/PCA
GRB000131	4.5	<0.047	Uly/KO/NE
GRB000210	0.846		SAX/WFC
GRB000131C	0.42	0.105	ASM/Uly
GRB000214	2.03		SAX/WFC
GRB000418	1.118	0.198	Uly/KO/NE
GRB000911	1.058		Uly/KO/NE
GRB000926	2.066	0.051	Uly/KO/NE
GRB010222	1.477		SAX/WFC
GRB010921	0.45		HE/Uly/SAX
GRB011121	0.36		SAX/WFC
GRB011211	2.14		SAX/WFC
GRB020405	0.69		Uly/MO/SAX
GRB020813	1.25		HETE
GRB021004	2.3		HETE
GRB021211	1.01		HETE
GRB030226	1.98		HETE
GRB030328	1.52		HETE
GRB030329	0.168		HETE

<- most nearby! (GRB980425)

<- very nearby! (GRB030329)

Barthelmy's IPN
http://gcn.gsfc.nasa.gov/gcn/
Greiner's catalogue
http://www.mpe.mpg.de/jcg/grbgeb.html
and Frail et al. (2001)





$$T_{90} = \text{few} \times 10 \text{ s}$$

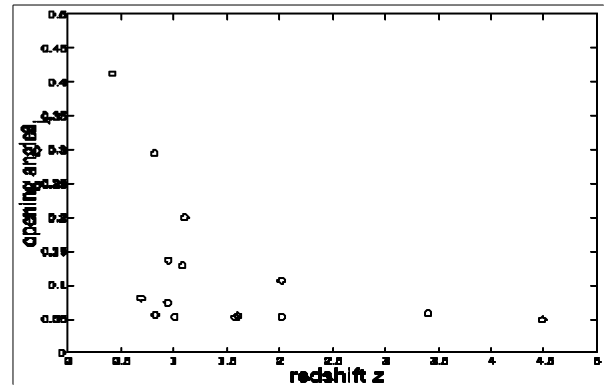
$$E_g = 3 \times 10^{50} \text{ erg}$$

The true-but-unseen GRB-event rate

Unseen event rate = 1/fb or 1/fr times observed event rate

Geometrical beaming factor in GRB-emissions:

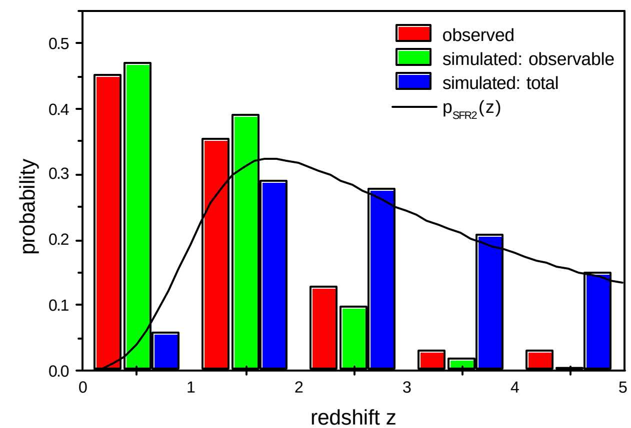
$$1/\ f_b = 500 \ \ \text{(Frail et al. 2001)}$$



Van Putten & Regimbau
2003, submitted

Event loss-rate in flux-limited sample locked to the SFR:

$$1/\ f_r = 450 \ \ \text{(van Putten \& Regimbau, 2003, submitted)}$$



$$\text{True GRB event rate} \cong 0.5\times10^{6}\ /\ \text{year}$$

For a 7 solar mass black hole:

Keplerian period of the torus: $P \approx 4\text{ms}$

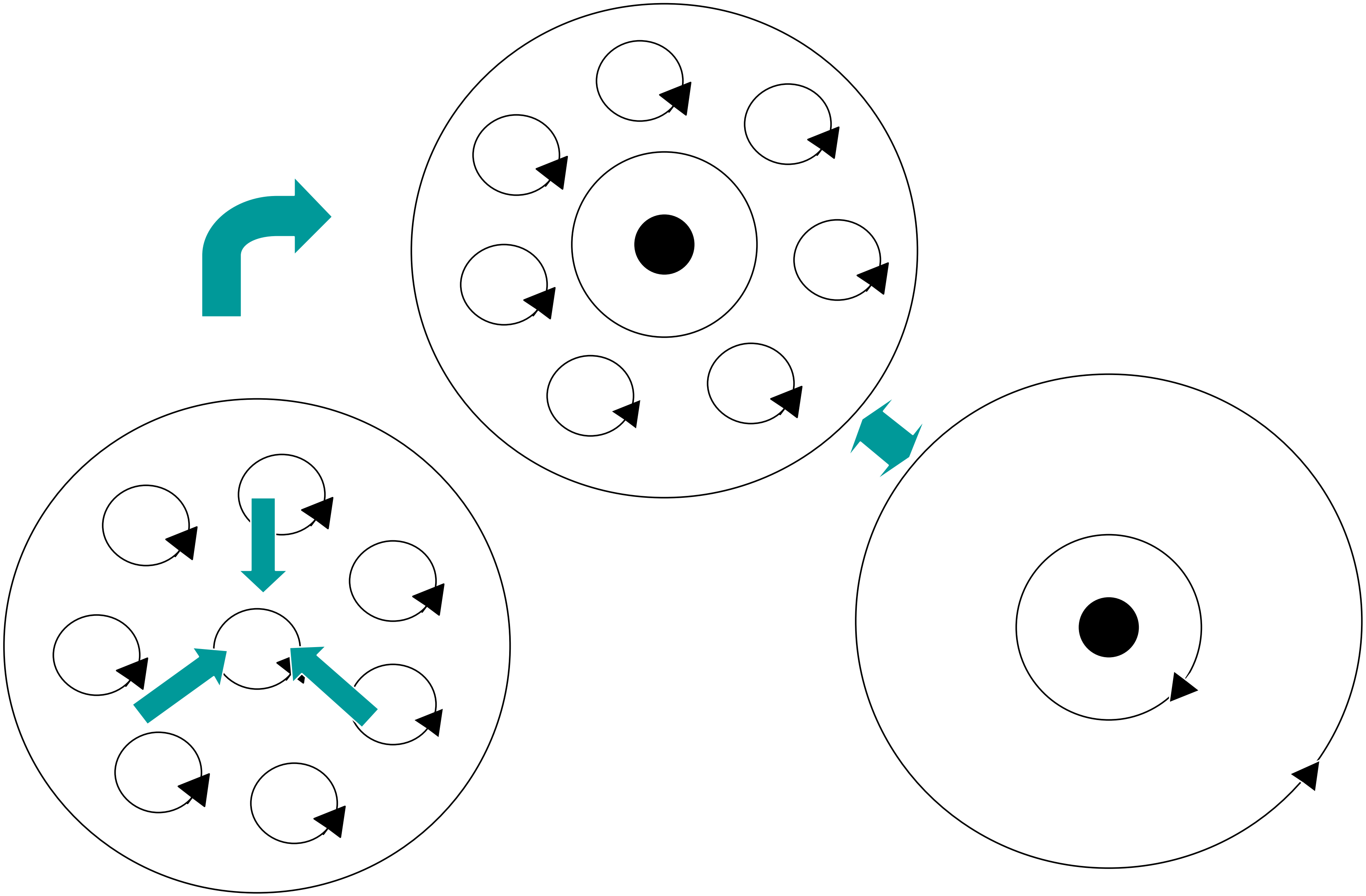
Rotational energy of the black hole: $E_{rot} = 4\times10^{54}\,\text{erg}$

$$g_0 = T_{90} / P \approx 1\times10^4$$

$$g_1 = E_g / E_{rot} \approx 7\times10^{-5}$$

1 event per year within D = 100Mpc

Magnetized nucleus in core-collapse



A causal spin-connection to Kerr black holes

Goldreich and Julian (1969) (spin-down of pulsars (magnetized neutron stars))

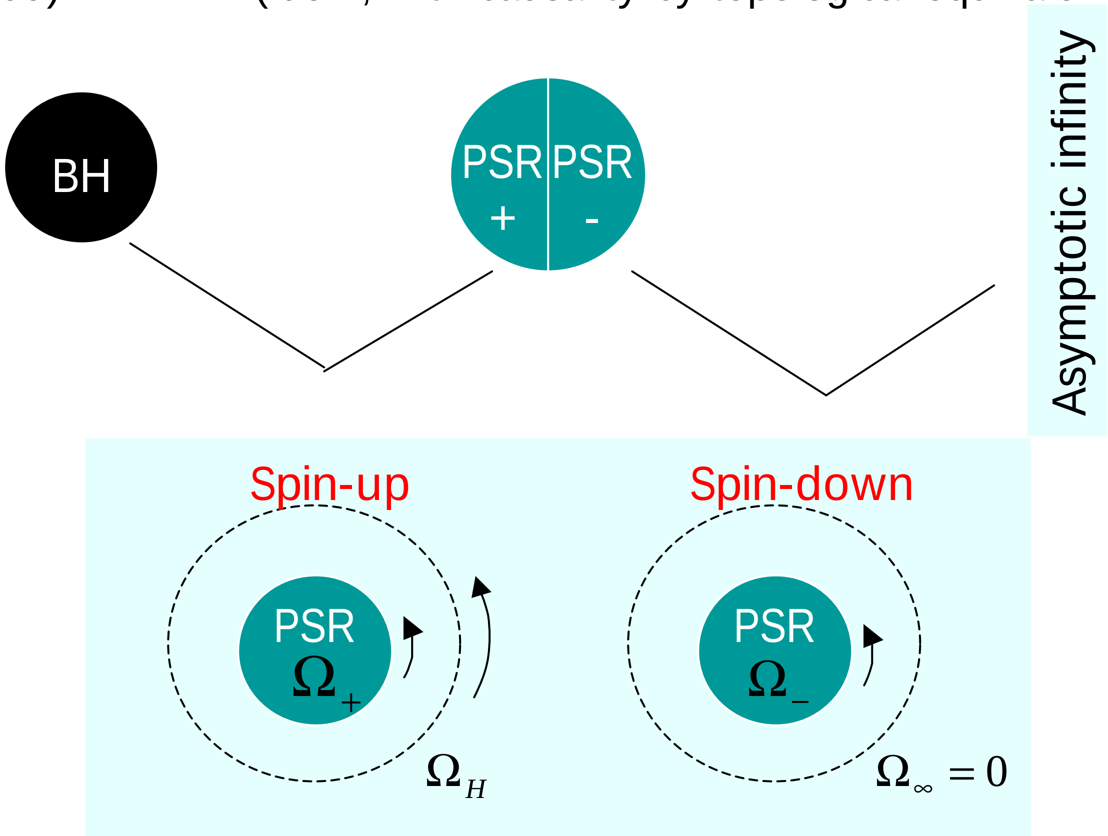
Ruffini & Wilson (1975) (spin-down of black holes, but: weak fields)

Blandford & Znajek (1977) (strong fields, but: causality not addressed, Punsly & Coroniti 1990)

...

Van Putten (1999) (idem, with causality by topological equivalence to PSRs)

...

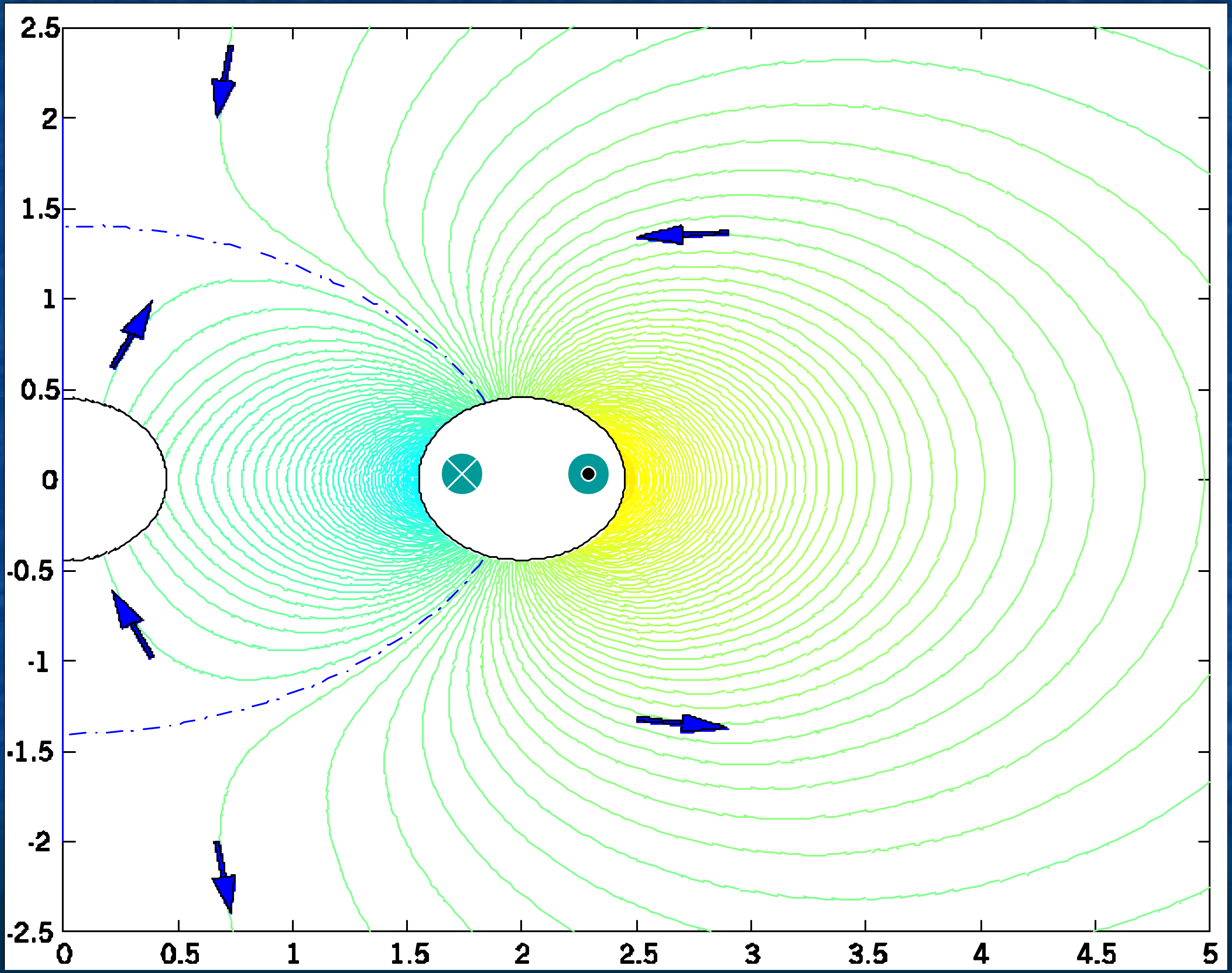


Van Putten & Levinson, ApJ 2003; Science 2002
Van Putten, Phys Rep, 2001; Science 1999

Topology of inner and outer torus magnetospheres

(vacuum case)

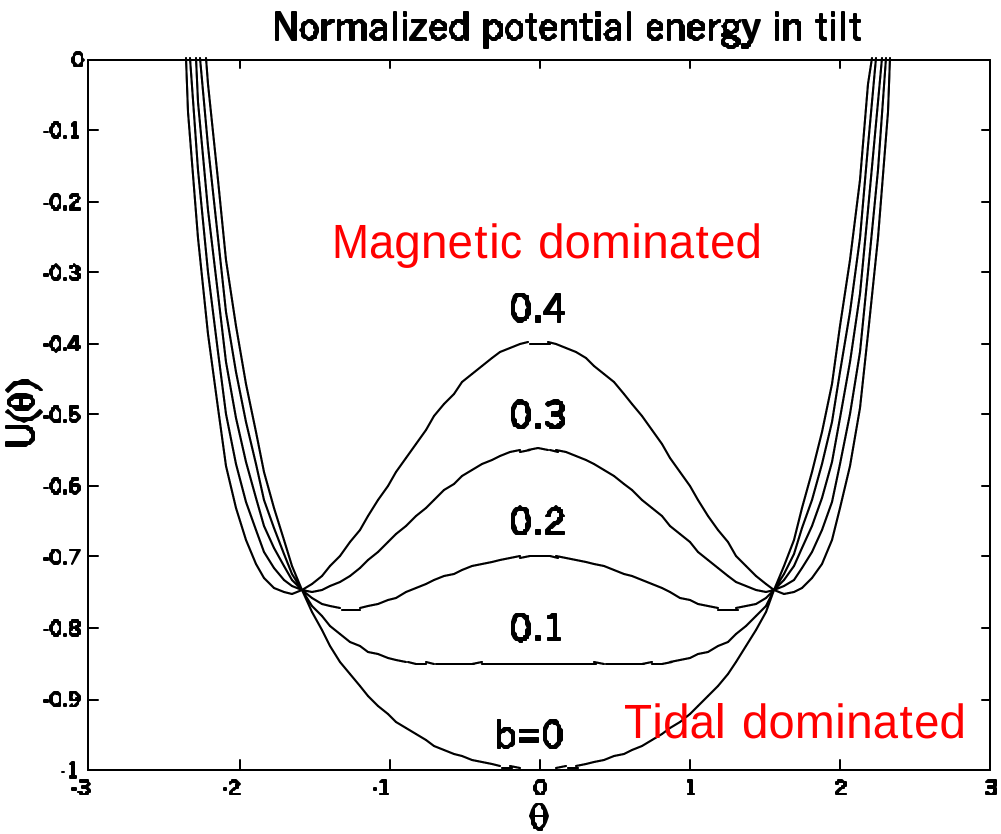
separatrix



Van Putten & Levinson, ApJ 2003

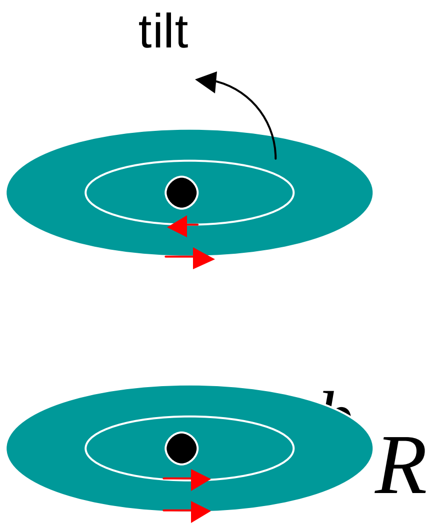
New magnetic stability criterion

Sum of magnetic and tidal interaction



$U_{\uparrow\downarrow} = mB > 0$

$U_{\uparrow\uparrow} = -mB < 0$



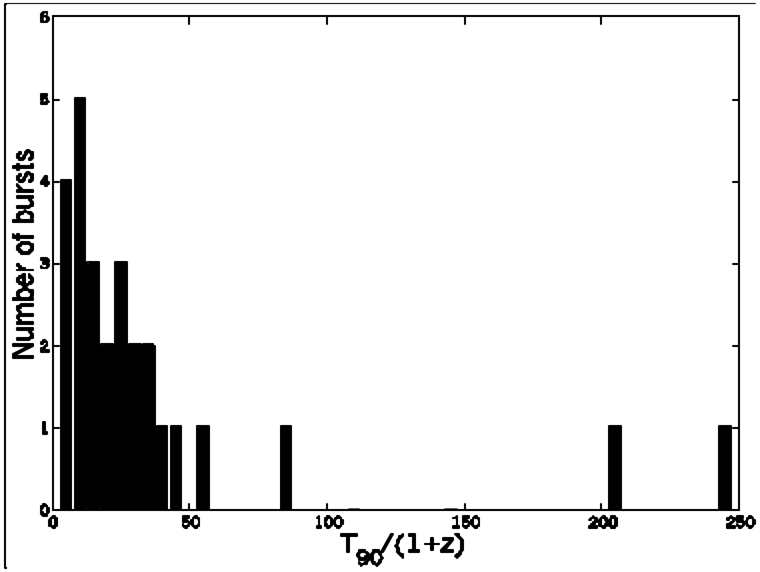
$E_B / E_k < 1/12$ [1/15 for buckling instabilit y]

Van Putten & Levinson, ApJ 2003

Durations of long bursts

Most of the spin-energy is dissipated “unseen” in the event horizon of the black hole

$$T_{90} \cong T_{spin}$$



$$T_{spin} \cong \frac{E_{rot}}{T_H \dot{S}} \geq 40\,\mathrm{s} \left(\frac{M / M_T}{30} \right) \left(\frac{R}{6M_S} \right)^4 \left(\frac{M}{7M_S} \right)$$

Van Putten & Levinson, ApJ 2003

Long durations

Large parameter $g_0 = T_{90} / P$

$$g_0[theory] \cong 2\times10^4 (h/0.1)^{-8/3} (m/0.03)^{-1}$$

$$h = \Omega_T / \Omega_H \approx 0.1$$

$$m = M_T / M_H \approx 0.03$$

$$g_0[observed] \cong 1\times10^4$$

Critical point analysis in baryon-rich torus wind

MeV-torus cools by neutrino emission (electron-positron capture on nuclei)

$$T_{10} \cong 2L_{52}^{1/6}\left(\frac{M_T}{0.1M_S}\right)^{-1/6}$$

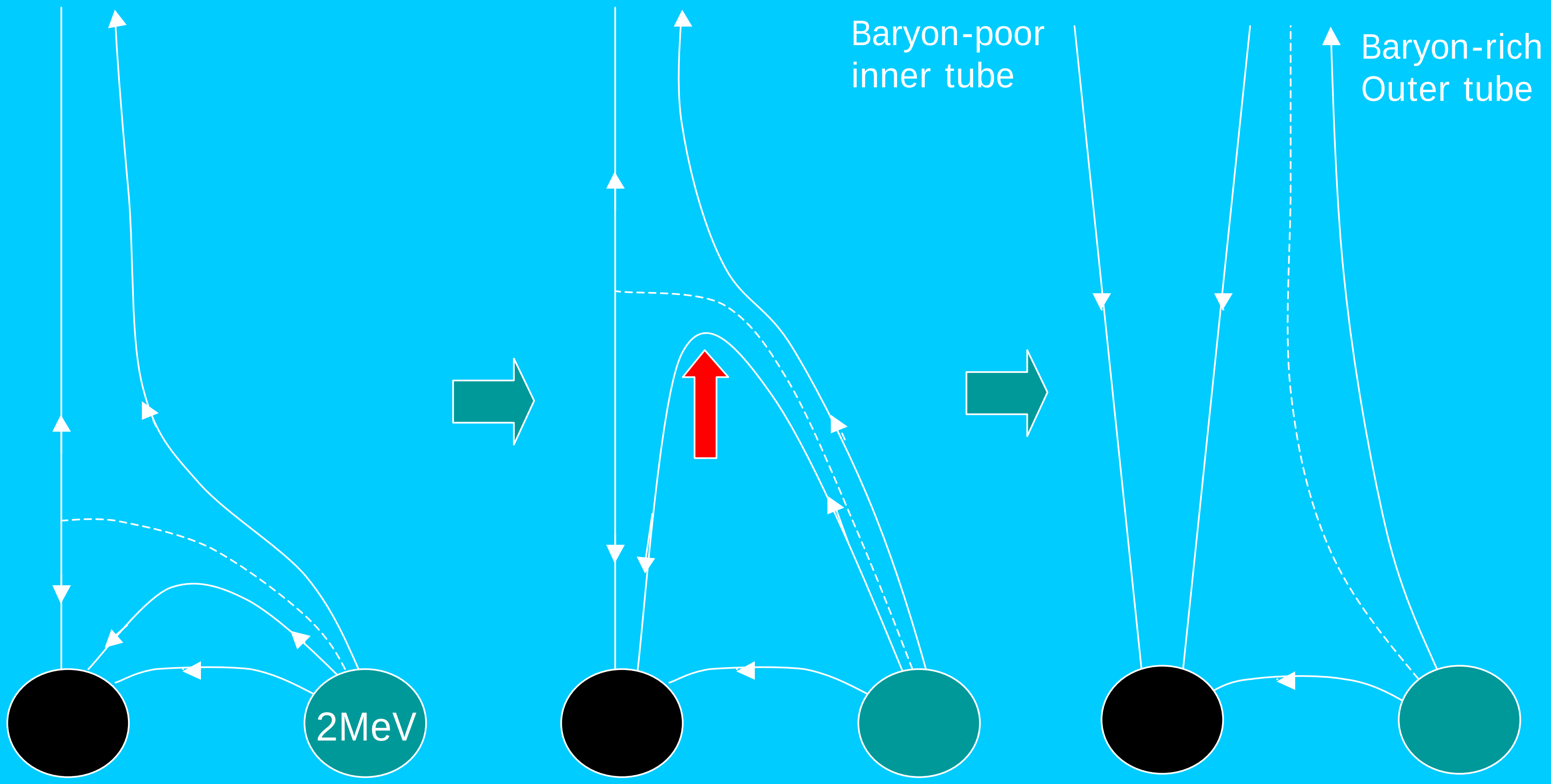
$$M_A[\text{on torus surface}] = \left(\frac{16pp_l}{3B_p^2}\right)^{1/2} \cong 0.07\left(\frac{M_T}{0.1M_S}\right)^{-1/3} L_{52}^{1/3} B_{p15}^{-1}$$

$$r_{bc}c_s \cong 10^{17}\left(\frac{M_H}{10M_S}\right)^{-1/2}\left(\frac{M_T}{0.1M_S}\right)^{-2/3} \times r_{c7}^{1/2}\left(\frac{x_c}{r_c}\right)^{-1} L_{52}^{2/3}\,\text{g cm}^{-2}\,\text{s}^{-1}$$

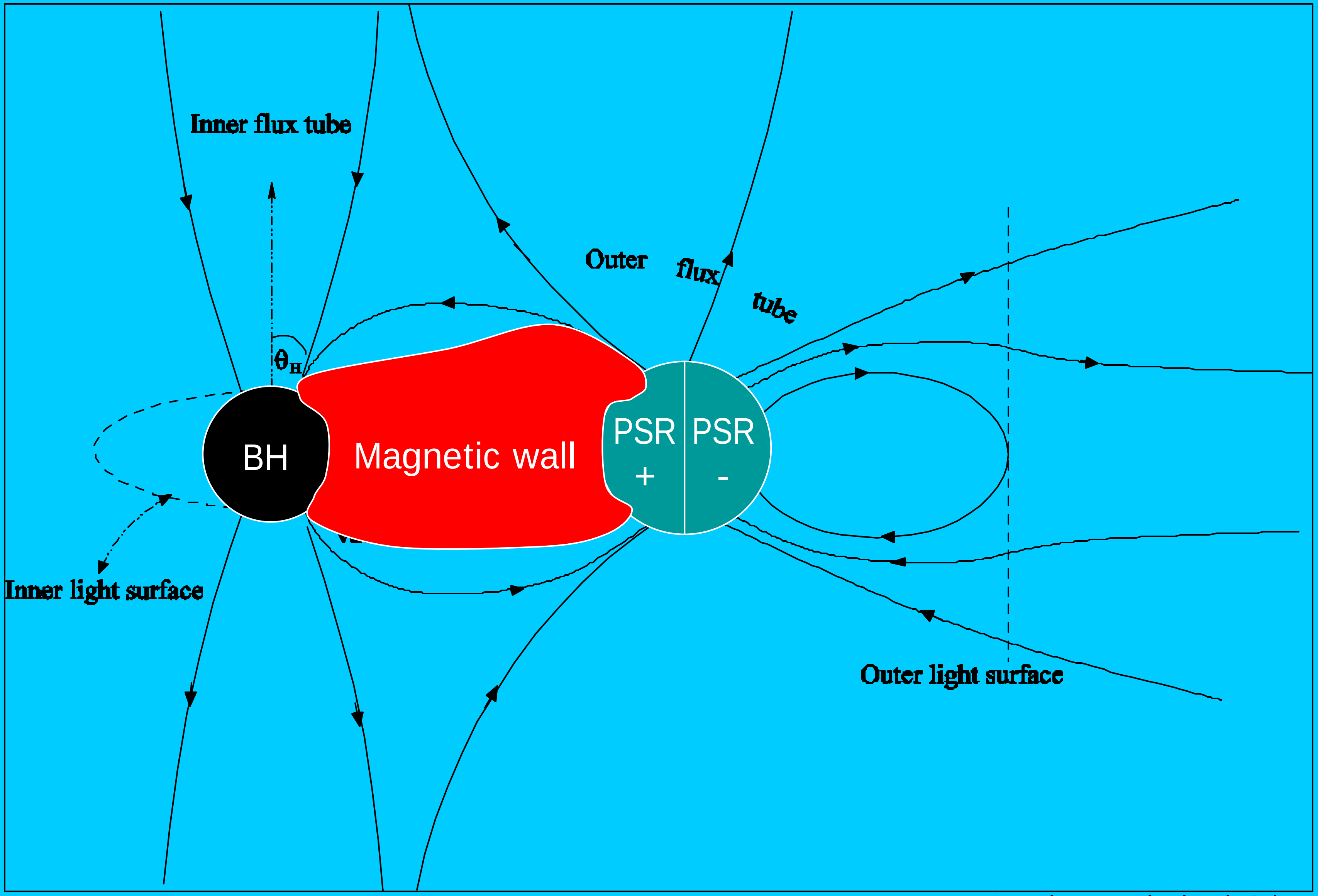
$$\dot{M} \cong 1\times 10^{30}\ \text{g s}^{-1}$$

Van Putten & Levinson ApJ 2003

Torus winds create open magnetic flux-tubes



The active stellar nucleus: a black hole in suspended accretion

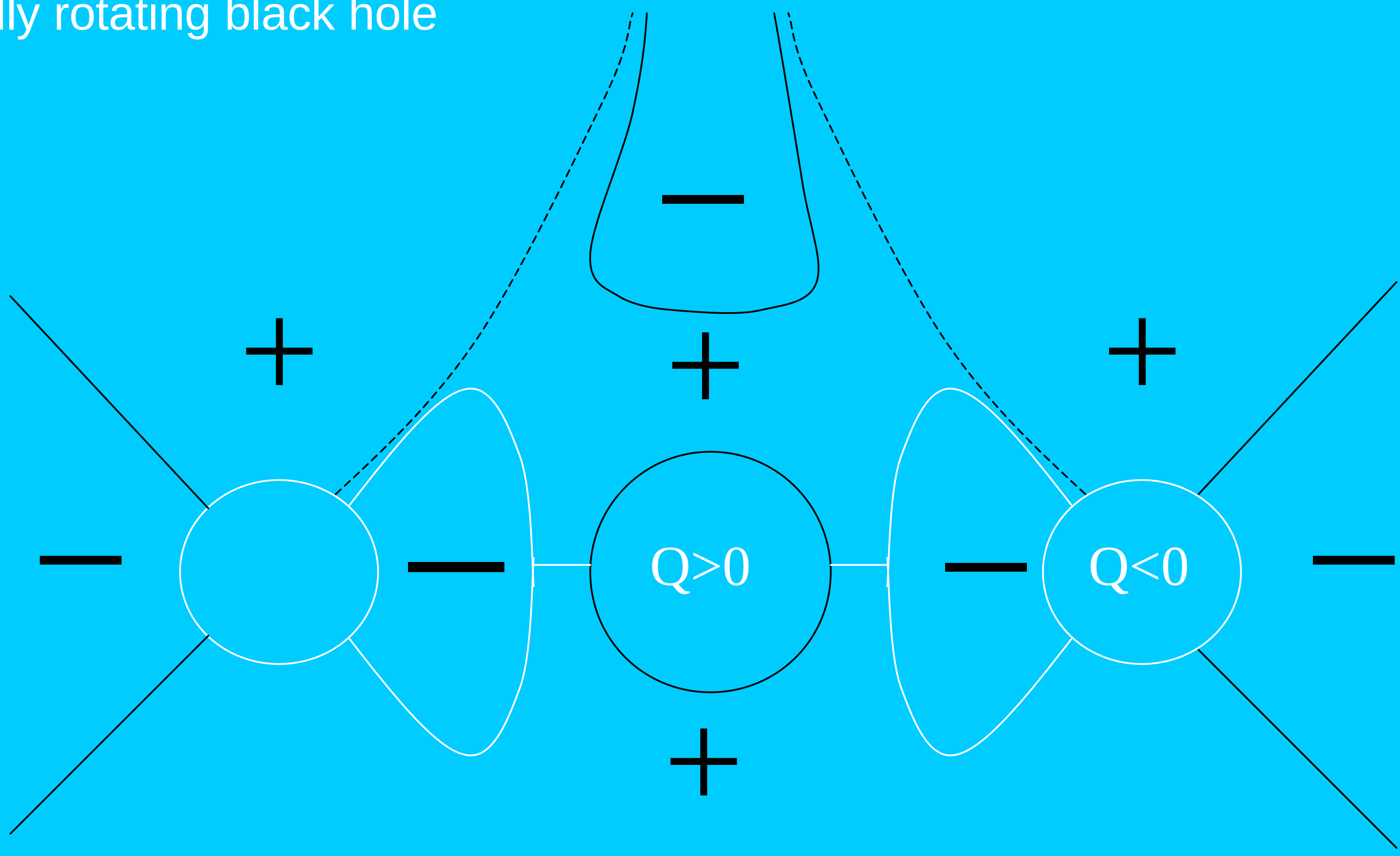


Van Putten & Levinson, submitted; Science 2002
Van Putten, Phys Rep, 2001; Science 1999

Equilibrium charge distribution

Rapidly rotating black hole

ρ–topology



Energy in baryon-poor outflows

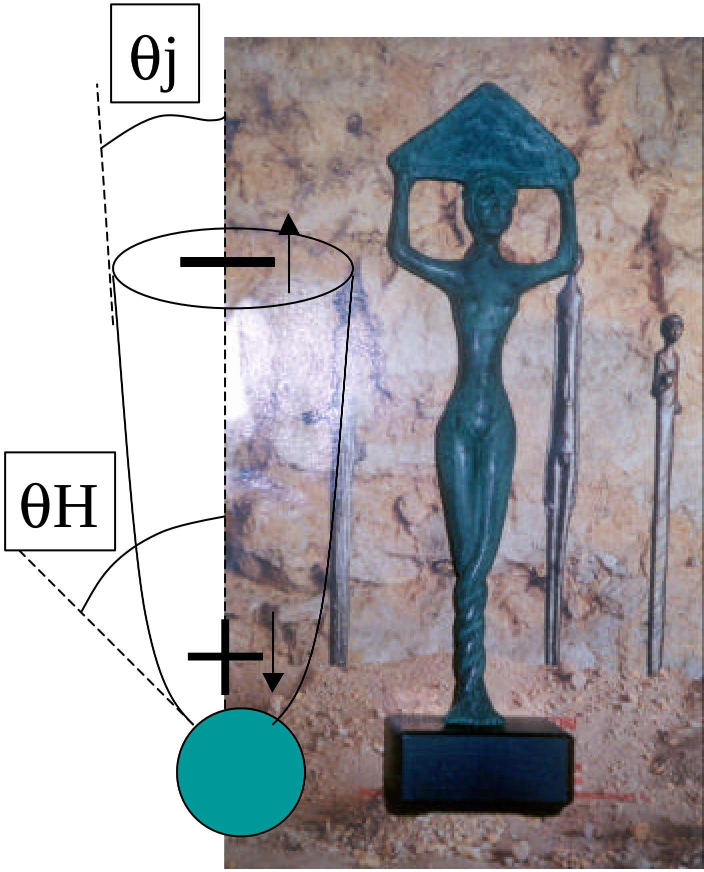
Outflow in open flux - tube along rotation axis

$$E_j \cong T_{90}\Omega_H^2 A_j^2 / 4$$

$$A_j \cong BM_H^2 q_H^2$$

Poloidal curvature of flux - surfaces

$$q_H \cong M_H / R \cong (h/2)^{2/3}$$



Van Putten & Levinson ApJ 2003

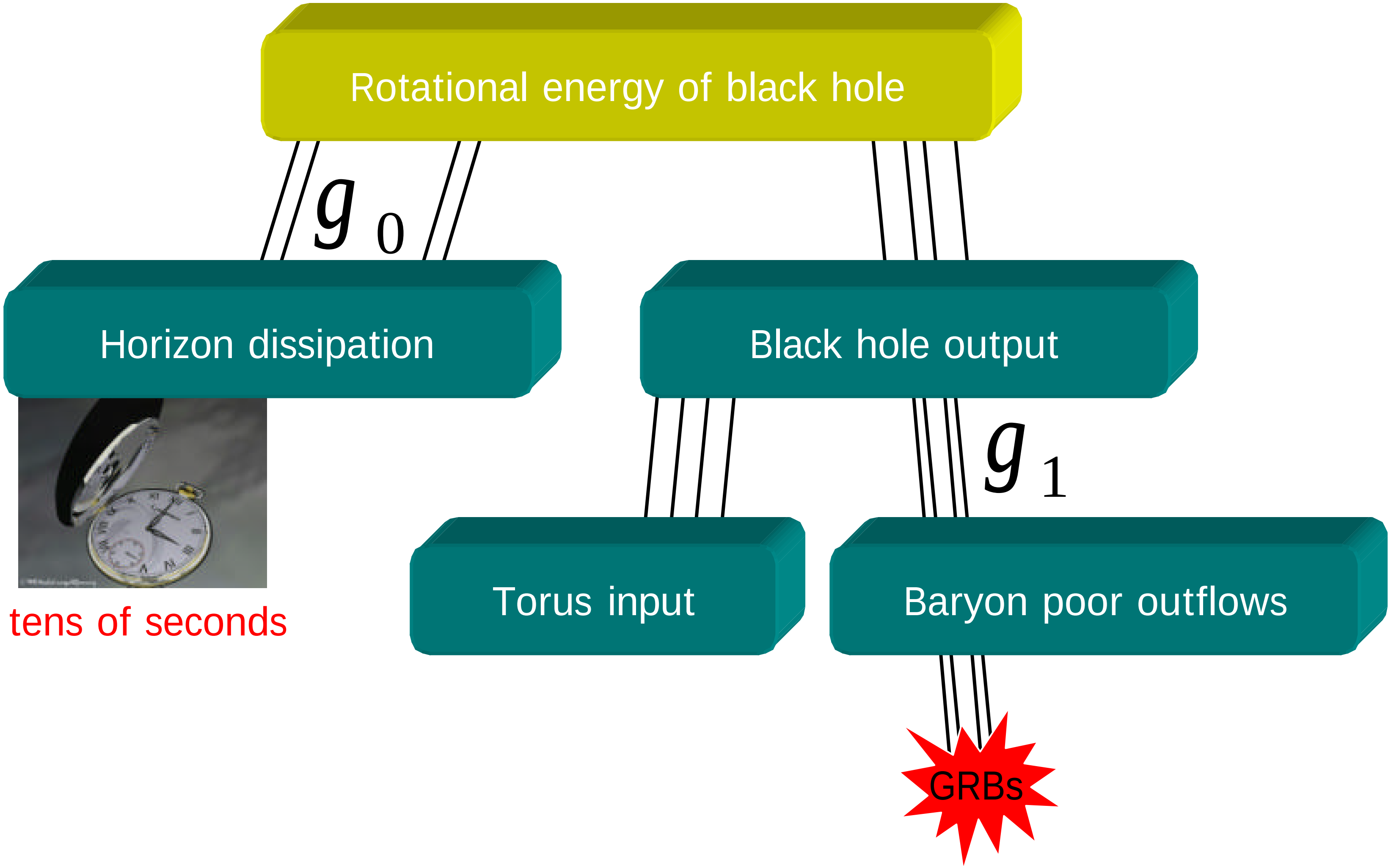
Small GRB-energies

Small parameter $g_1 = \frac{E_g}{E_{rot}}$

$$g_1[theory] \cong 1\times10^{-4}\left(h/0.1\right)^{8/3}(e/0.15)$$

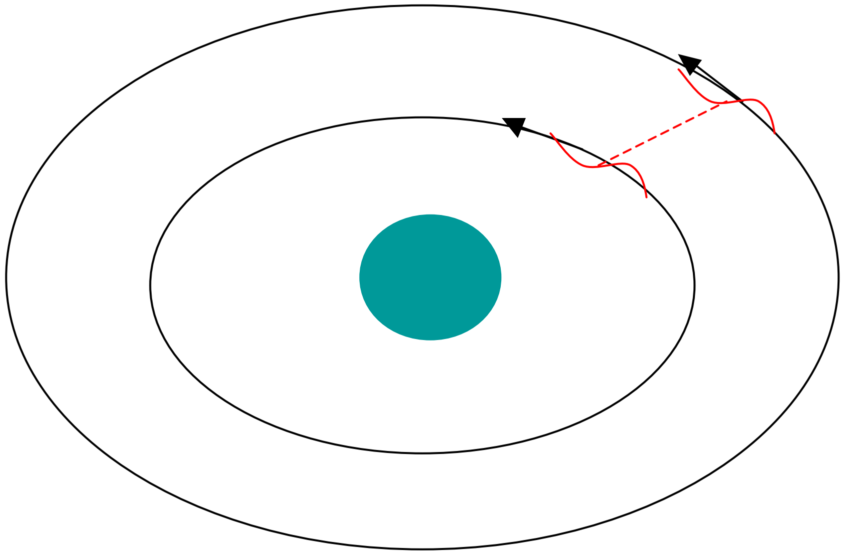
$$g_1[observed] \cong 7\times10^{-5}$$

Durations and GRB-energies



Linearized stability analysis for the torus

Free surface waves on inner and outer boundaries mutually interact (Papaloizou-Pringle 1984)



m=2 buckling mode

Waves in a differentially rotating and incompressible toroidal fluid

(A) Following Papaloizou - Pringle (1984), consider the linearized stability analysis for an unperturbed torus (between Kepler and Rayleigh's criterion):

$$\begin{cases} \Omega(r) = \Omega_a \left(\dfrac{a}{r}\right)^q & \left(q \in [3/2, 2]\right) \\ \partial_r h^e = \Omega^2 r - \dfrac{M}{r^2} & \left(h = \dfrac{P}{r}\right) \end{cases}$$

(B) Velocity potential for incompressible, irrotational perturbations (van Putten 2002)

$$j = e^{imq - iw' t} \Sigma_n a_n(r) z^n, \quad \Delta j = 0$$

of azimuthal mode number m and corotation frequency w'

(C) Linearized Euler equations of motion (Goldreich et al. 1986)

$$\begin{cases} -isu - 2\Omega v = -\partial_r (h + \Phi) \\ -isv + 2Bu = -ik(h + \Phi) \\ -isw = -\partial_z h \end{cases}$$

where $2B = (2-q)\Omega$ (variable), $k = m/r$, $s = w' - m(\Omega - \Omega_a)$,

subject to zero enthalpy boundary conditions $h = 0$.

A free boundary value problem

(A) Decoupling of EOM :

$$(\partial_r^2 + r^{-1}\partial_r - m^2 r^{-2})a_0 = qr^{-1}a_0'$$

(B) Leading - order expansion in z (van Putten 2002)

$$j = a_0 - \frac{z^2 q}{2r}\partial_r a_0 + O(z^4),$$

with $a_0 = r^{p_+} + l r^{p_-}$, $p_\pm = q/2 \pm \sqrt{q^2/4 + m^2}$

(C) Boundary conditions at $h^e(r_\pm) = 0$ (Goldreich et al. 1986)

$$k(s^2 j + is\Phi) + (2Bs + kh_r^e) j_r = 0.$$

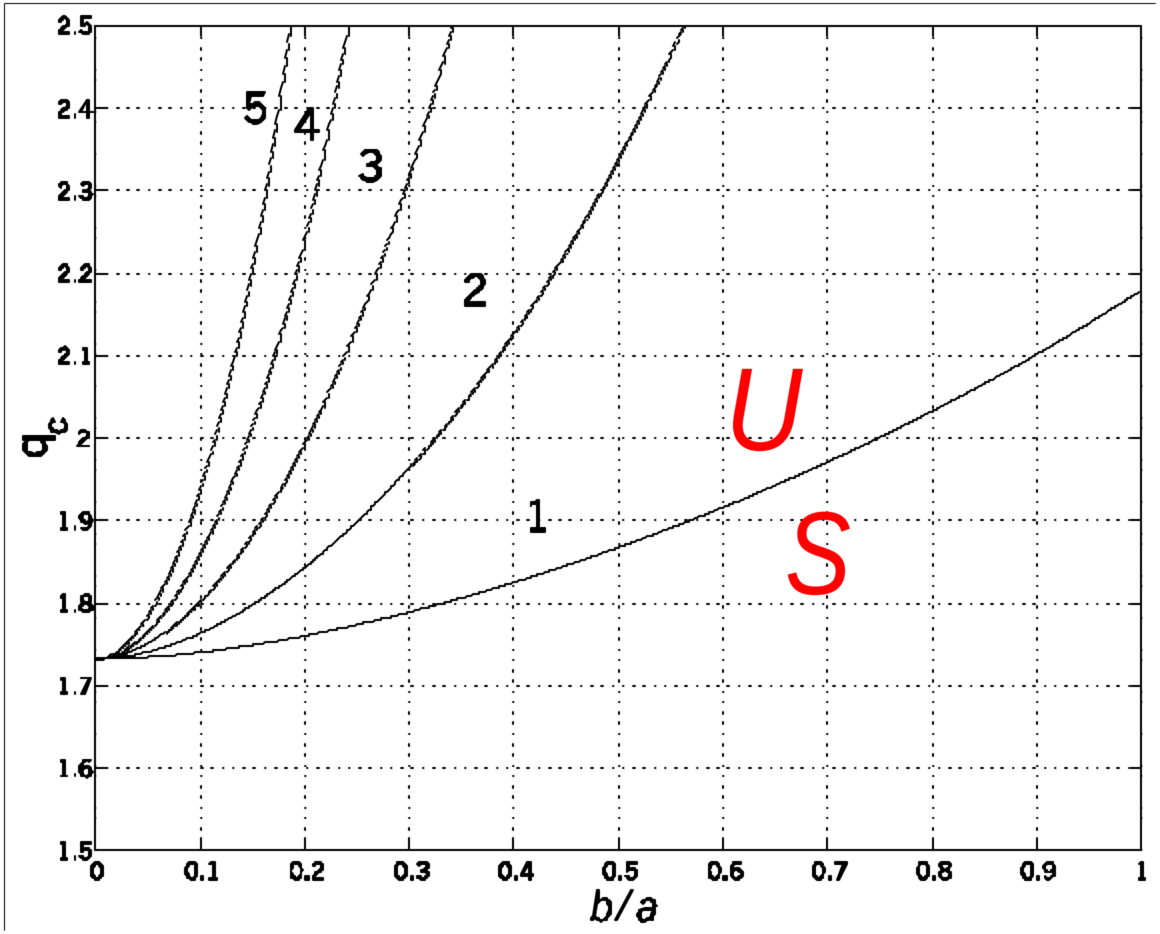
Multipole mass-moments in tori

$$\Omega(r) = \Omega_a \left(\frac{a}{r}\right)^q \quad \left(q \in [3/2, 2]\right)$$

$q_c = \sqrt{3}$ as $b/a \sim 0$

Papaloizou - Pringle (1984)

Goldreich et al. (1986)



Gravitational radiation-reaction force (m=2)

Burke - Thorne potential

$$\Phi_{BT} = \frac{1}{5} x_i x_j \left(I^{ij} - \frac{1}{3} I \delta^{ij} \right), \quad I_{ij} = \Sigma \int_0^{2\pi} \int_{r_- + h_-}^{r_+ + h_+} x_i x_j \, dx dy,$$

Thus,

$$I_{xx} = \frac{\pi \Sigma}{2} \left[r_+^3 h_+ - r_-^3 h_- \right], \text{ etc.} \quad \Rightarrow \quad \Phi_{BT} = \tfrac{1}{5} (x + iy)^2 I_{xx}$$

The potential in the EOM becomes

$$\Phi = \partial_t^5 \Phi_{BT} = -i\omega^5 \Phi_{BT}$$

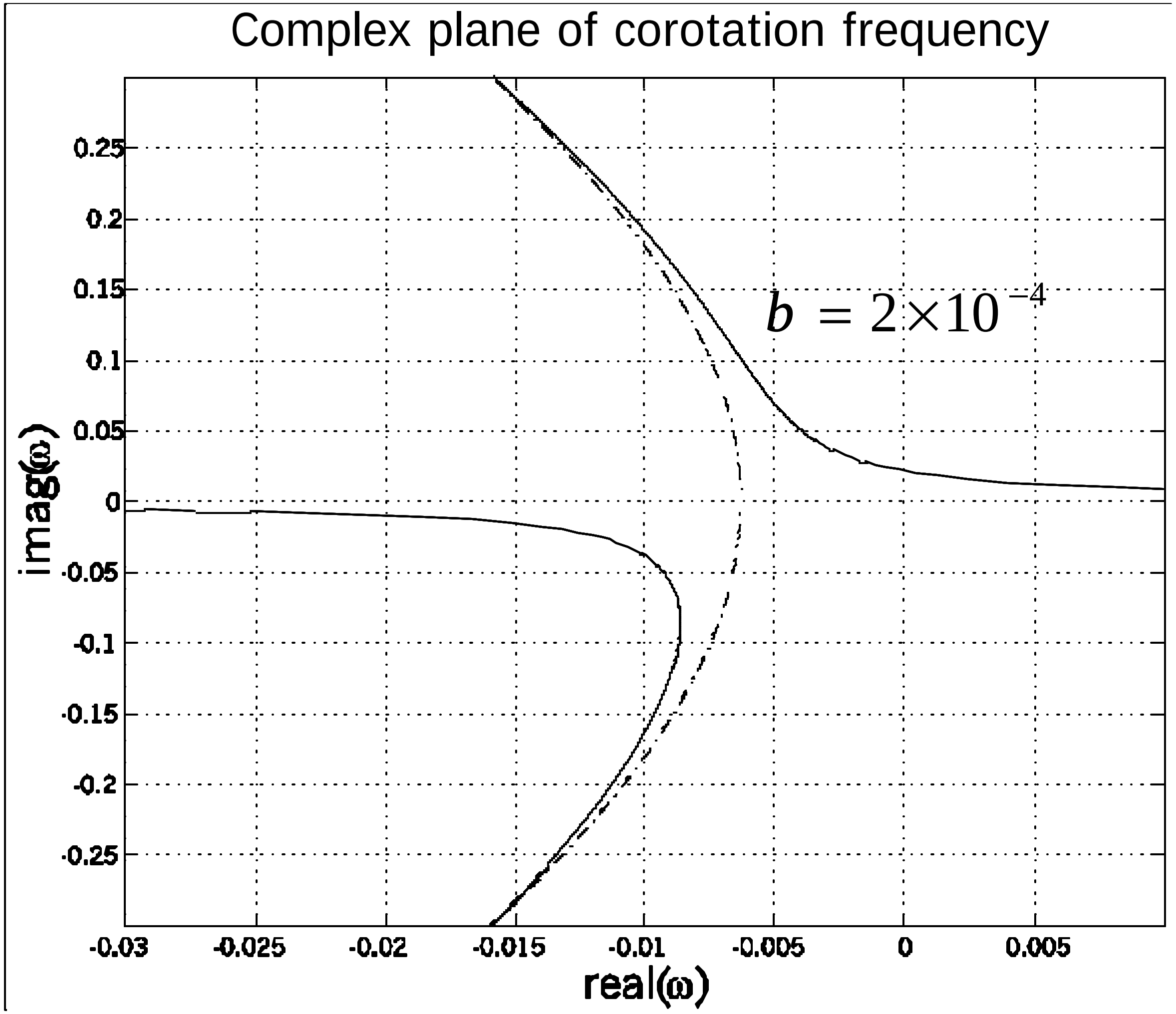
and so

$$i\sigma_\pm \Phi_\pm = i\beta (r_\pm / a)^2 [(r_\pm / a)^3 \varphi_r(r_+) - (r_\pm / a)^3 \varphi_r(r_-)]$$

with

$$\beta = \tfrac{1}{10} \pi a \Sigma (\omega a)^5 \sim 10^{-4}$$

Gravitational radiation-reaction force on quadrupole emissions



Increase in imaginary value: backreation promotes instability

Gravitational radiation in suspended accretion

Balance in angular momentum and energy flux

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

$$\Omega_+ \tau_+ = \Omega_- \tau_- + \Omega \tau_{rad} + P$$

with the constitutive ansatz for dissipation

$$P \approx A_r^2 (\Omega_+ - \Omega_-)^2$$

by turbulent MHD stresses, into thermal emissions and MeV-neutrino emissions

Black hole-beauty: emissions from the torus

Asymptotic results for small slenderness

$$g_2 = \frac{E_{gw}}{E_{rot}} \sim h$$

4e53 erg in gravitational radiation

$$g_3 = \frac{E_w}{E_{rot}} \sim h^2$$

4e52 erg in torus winds producing SNe

$$g_4 = \frac{E_{diss}}{E_{rot}} \sim dh$$

6e52 erg in MeV-neutrinos

$$h = \Omega_T / \Omega_H \cong 10\%$$

$$d = \tfrac{1}{2} \text{ minor-to-major radius of torus}$$

Remnants of beauty

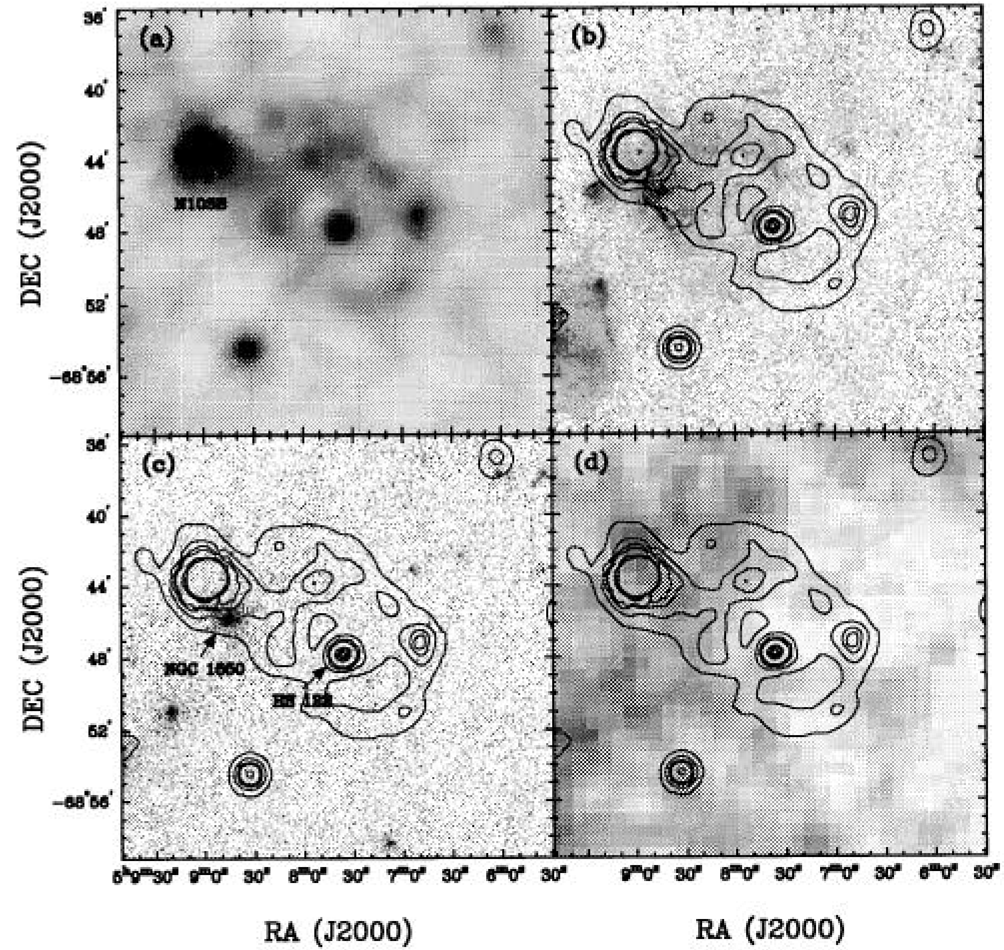
Morphology of GRB-supernova remnant:

Black hole in a binary with optical companion surrounded by SNR

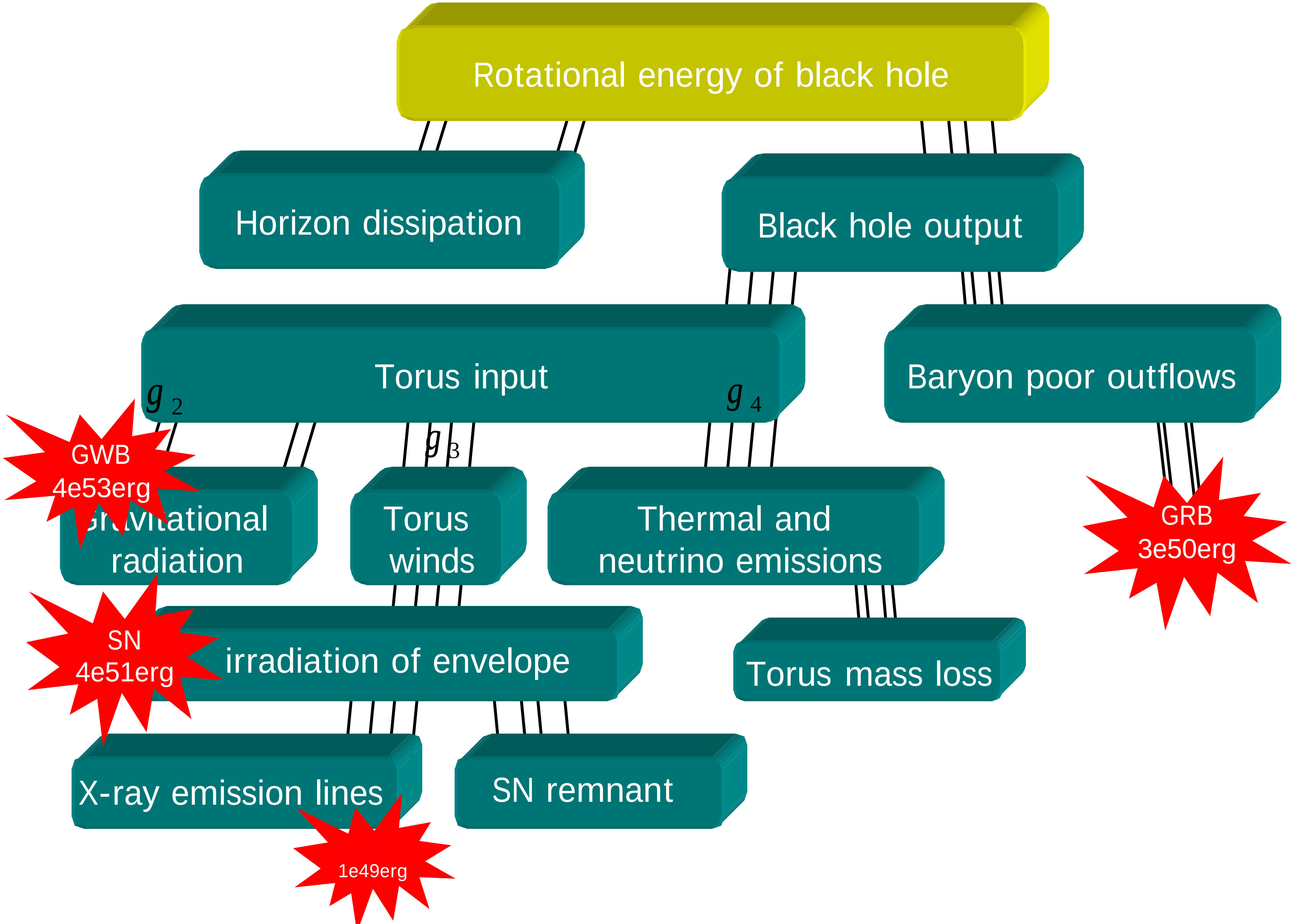
RX J050736-6847.8

Chu, Kim, Points et al., ApJ, 2000

(Candidate GRB-SN remnant)



Calorimetry on active stellar nuclei

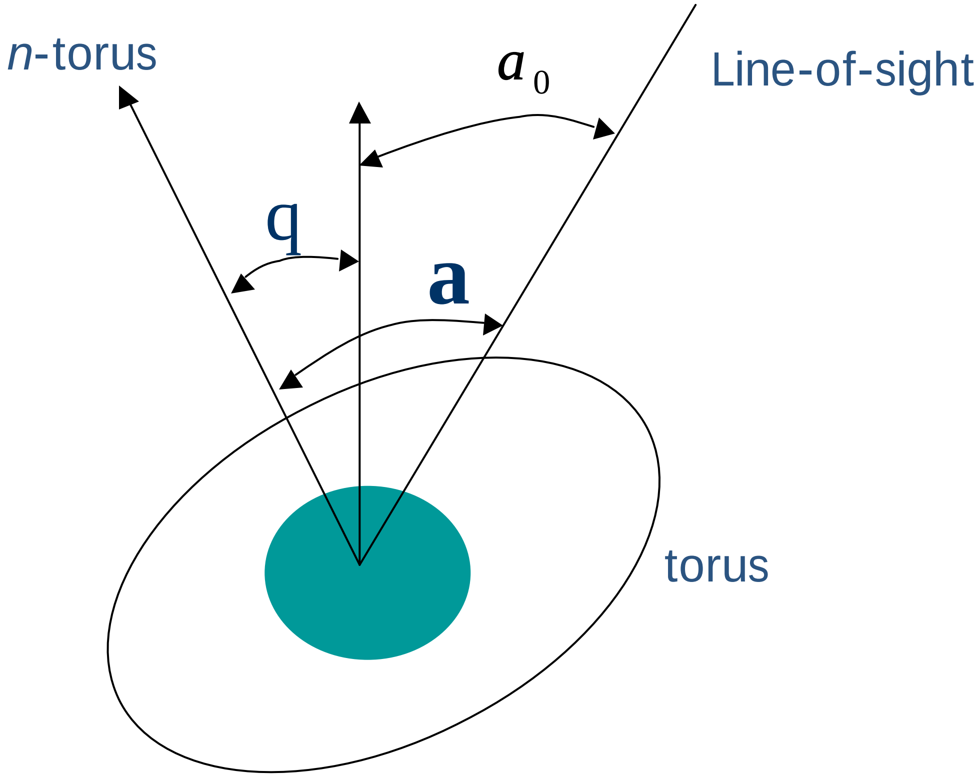


Observational constraint on gravitational wave-frequency from wind-energy

$$f_{gw} \approx 455\mathrm{Hz}\sqrt{\frac{E_w}{3.65\times10^{52}\,\mathrm{erg}}}\left(\frac{7M_O}{M}\right)^{3/2} \quad (m=2)$$

(scaling value of wind energy corresponds to eta=0.1)

Phase-modulation of observed radiation by Lense-Thirring precession



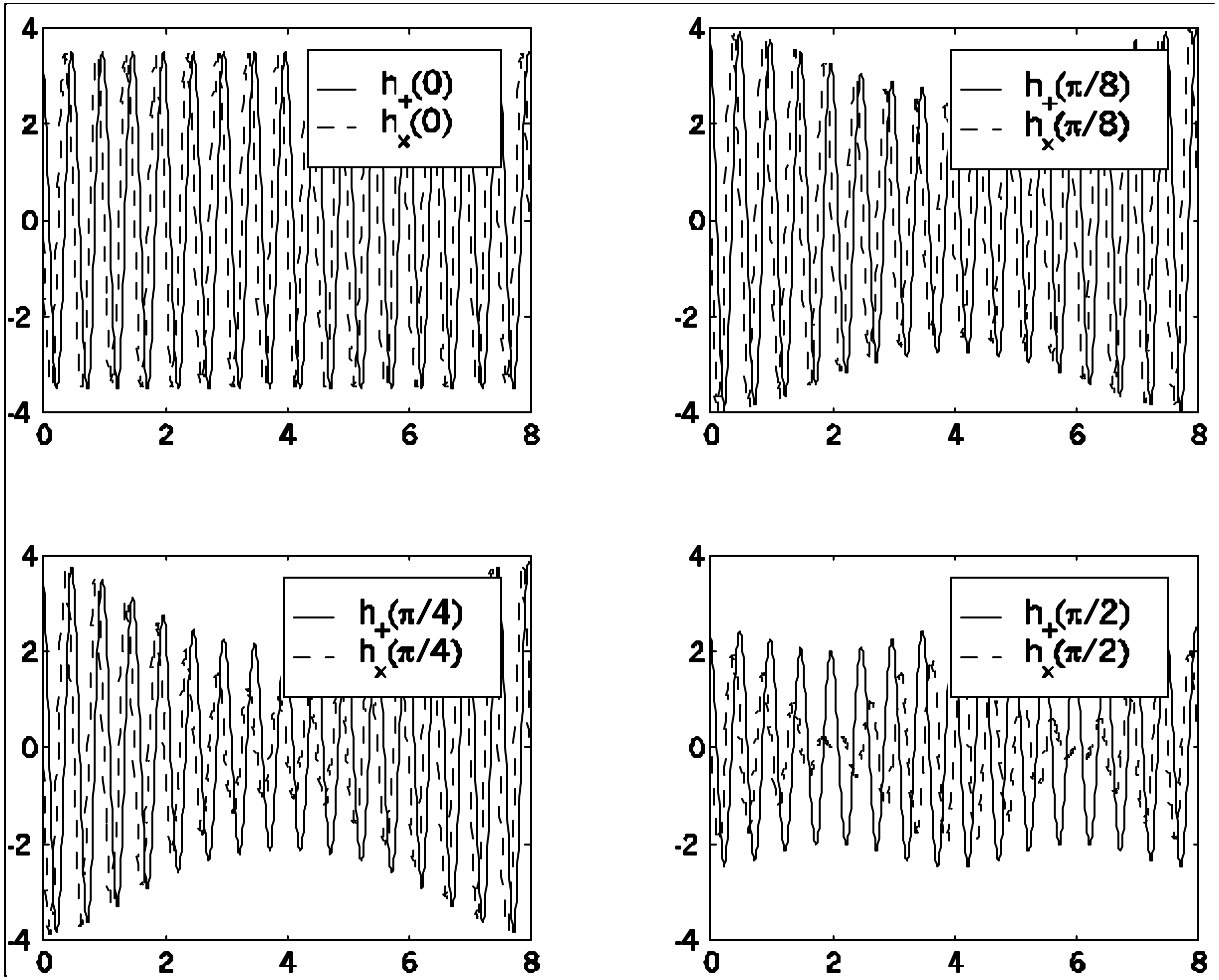
$$h_+ = 2r^{-1}(1+\cos^2 a)\cos(2\Omega_T t)$$

$$h_\times = -4r^{-1}\cos a \sin(2\Omega_T t)$$

$$\cos a = \sin a_0 \sin q \cos(\Omega_{LT} t) + \cos a_0 \cos q$$

Van Putten, Lee, Lee & Kim, 2003, in preparation

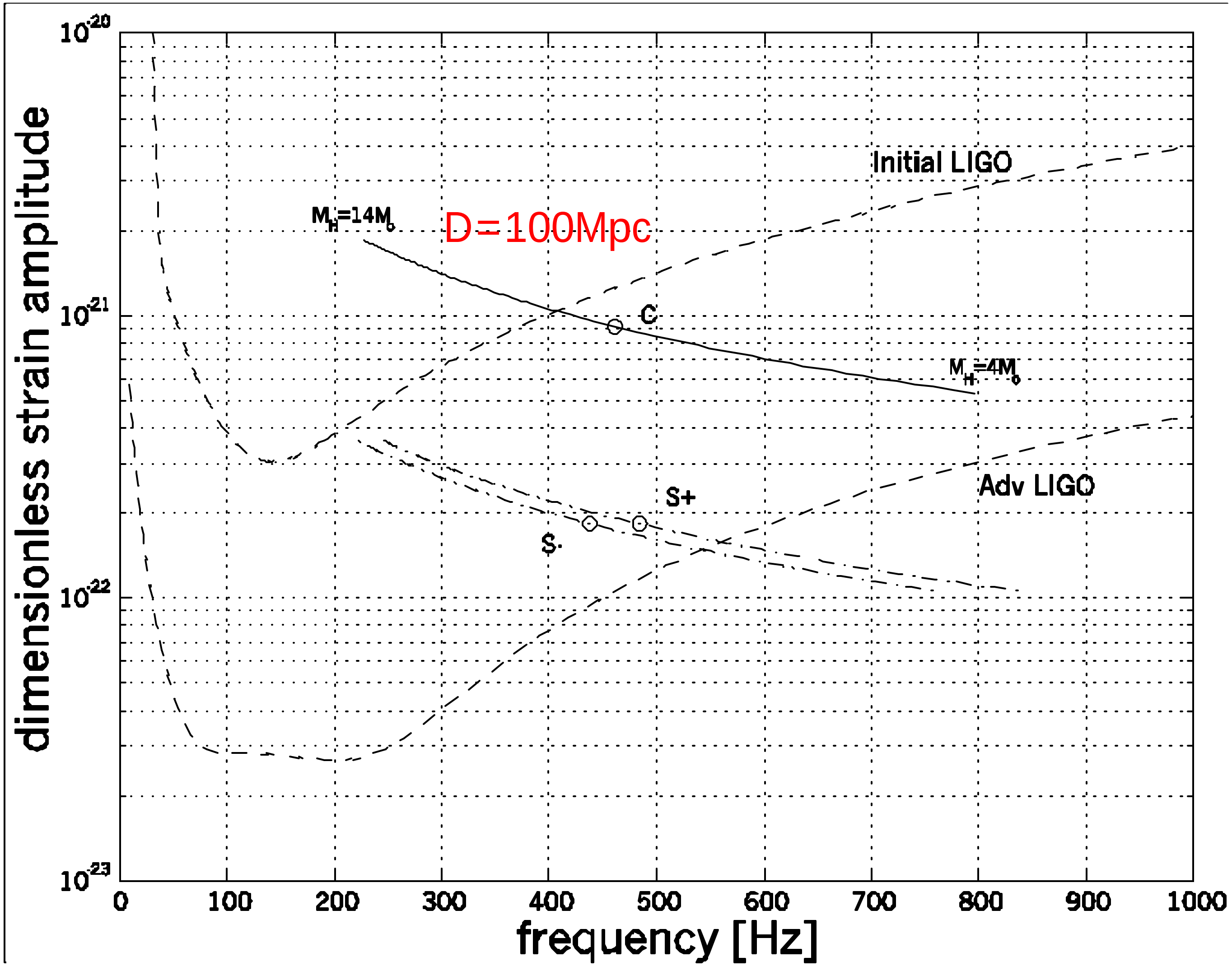
Phase-modulated wave-forms



$$a_0 = 0, p/8, p/4, p/2$$

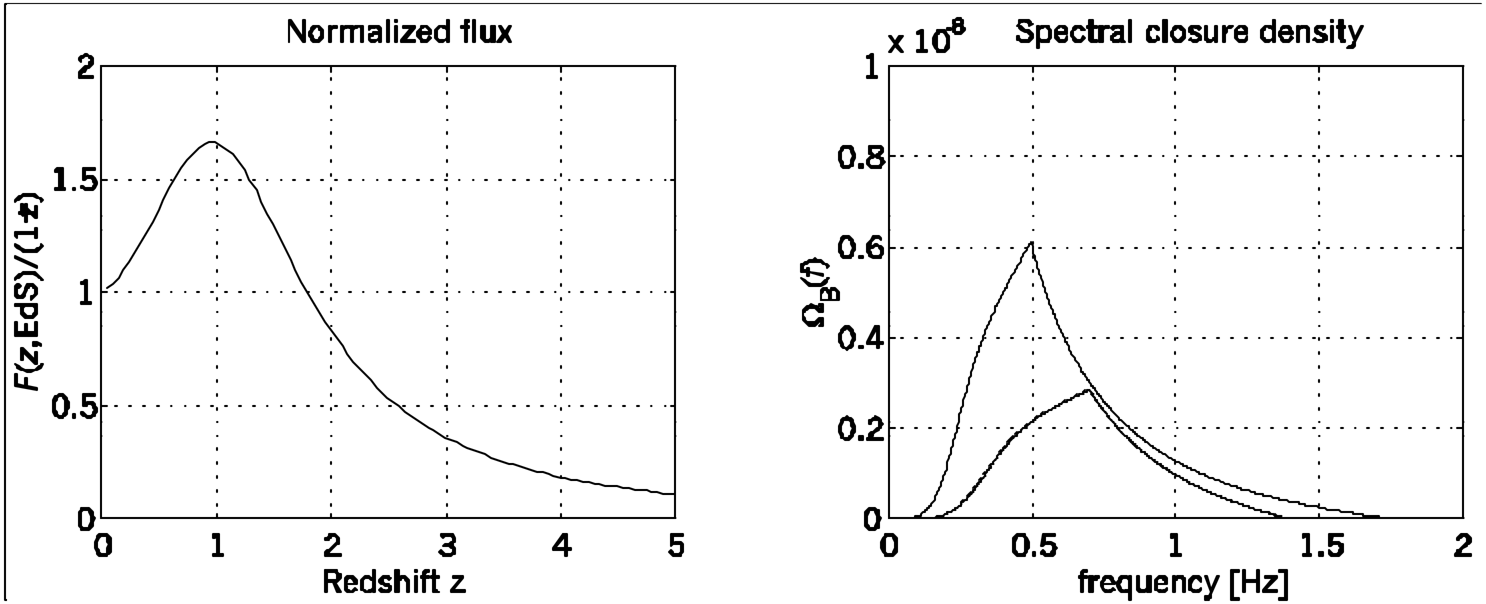
$$q = p/6$$

h(f)-diagram in matched filtering



Van Putten, in preparation (2003)

Stochastic background radiation in gravitational waves



Coward, van Putten & Burman 2002
Van Putten et al., in preparation (2003)

Observational opportunities for Adv LIGO

Matched filtering

$$\left(\frac{S}{N}\right)_{mf} \cong 8\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{4\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)^{-1}\left(\frac{h}{0.1}\right)^{-3/2}\left(\frac{M_H}{7M_{Solar}}\right)^{5/2}\left(\frac{d}{140\mathrm{Mpc}}\right)^{-1}$$

Correlating two detectors

$$\left(\frac{S}{N}\right)_{cs} = 1.5\times\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{4\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)_{D1}^{-1}\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{4\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)_{D2}^{-1} h_{0.1}^{-5/3} M_{H7}^{5} d_8^{-2} B_{0.1}^{-1} m_{0.03}^{1/4}$$

$$\left\langle\frac{S}{N}\right\rangle = \begin{cases} 8.5 & \text{averaged over } M_H = 4-14\times M_S \\ 1.2 & \text{averaged over } M_H = 5-8\times M_S \end{cases}$$

Van Putten (2003), in preparation

Lower bound on black hole-mass in GRB 030329

Spp we use matched filtering and define “no detection”: S/N<1

Entertain the possibility of a rapidly rotating torus: $h = 0.2$

Current Livingston sensitivity: $\left(\frac{S_h^{1/2}(500\text{Hz})}{4\times 10^{-24}\,\text{Hz}^{-1/2}} \right)^{-1} = 0.01$

$$\left(\frac{S}{N} \right)_{mf} \cong 8\times 0.01\times 2^{3/2}\times \left(\frac{M_H}{7M_{Solar}} \right)^{5/2} \times (140\text{Mpc}/800\text{Mpc}) < 1$$

$$M_H < 25 M_{Solar}$$

Conclusions

GRB-SNe from rotating black holes have long durations (gamma0=1e4), small true GRB-energies (gamma1=1e-4) and an true event rate of 1 per year in D=100Mpc

Durations of tens of seconds correspond to the lifetime of rapid spin of the black hole (gamma0[theory]=gamma0[observation]). Most of black hole spin-energy is dissipated in the event horizon.

GRB-SNe produce 4e53 erg in gravitational radiation via a causal spin-connection between the black hole and a surrounding torus in suspended accretion (gamma2=0.1)

The true GRB-energies represent a small fraction of black hole-spin energy, released through an open tube with finite horizon angle (gamma1[theory]=gamma1[observation])

Matched filtering gives (formally) rise to a current LIGO sensitivity range of 1Mpc, and a (formal) upper bound of 25 Solar masses in GRB 030329

The sensitivity range of Adv LIGO using matched filtering is 100Mpc

Correlation between two detectors may apply to searches for individual events, as well as searches for the contribution of GRB-SNe to the stochastic background radiation in gravitational waves (Omega-B=6e-8)

Opportunity: gravitational radiation from hypernovae: LIGO/VIRGO detections coincident (in position on the sky) with the expected wide-angle optical emissions from an associated supernova and non-coincident with the associated GRB-emissions