Long bursts from black hole-spin energy as observational opportunities for LIGO/VIRGO

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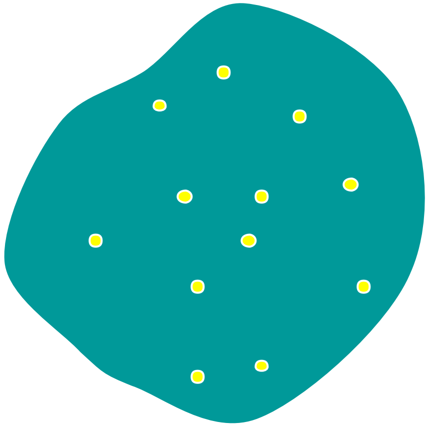
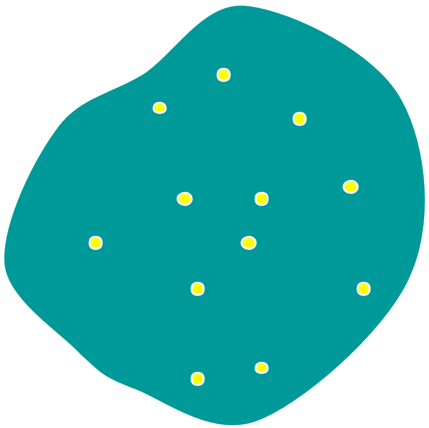
LIGO-G030347-00-R

Star-formation in a molecular cloud

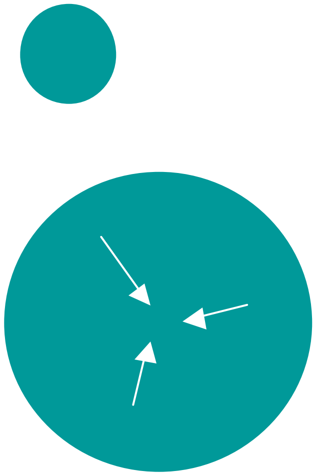


Molecular cloud

Core-collapse in a rotating massive star in a binary

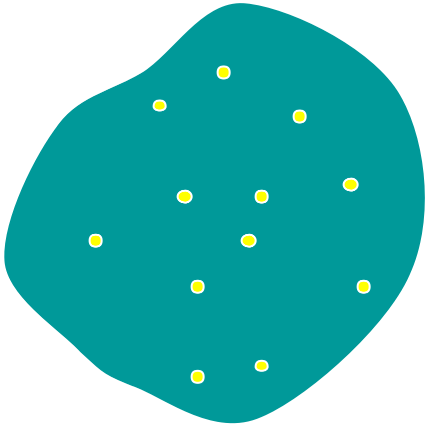


Molecular cloud

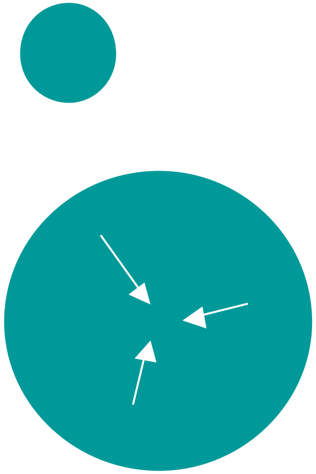


Core-collapse
(Woosley-Paczynski-Brown)

Active stellar nuclei

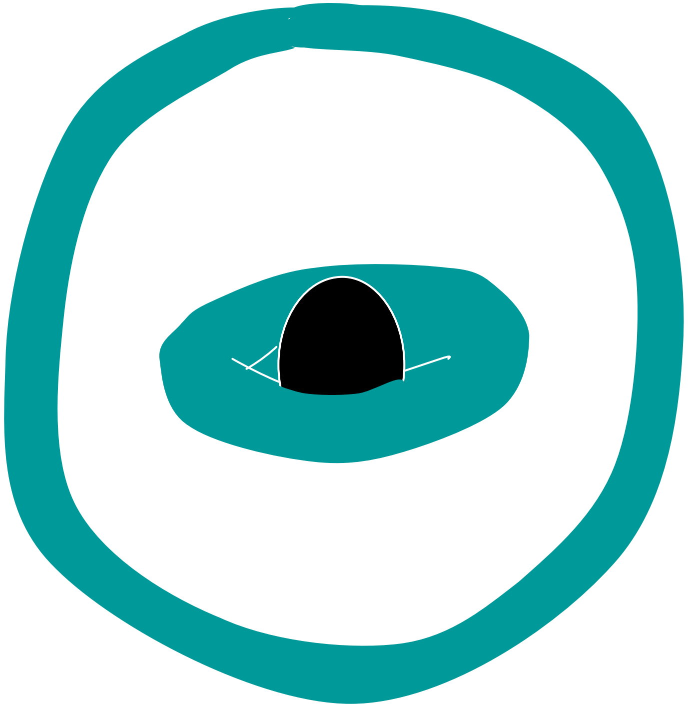


Molecular cloud

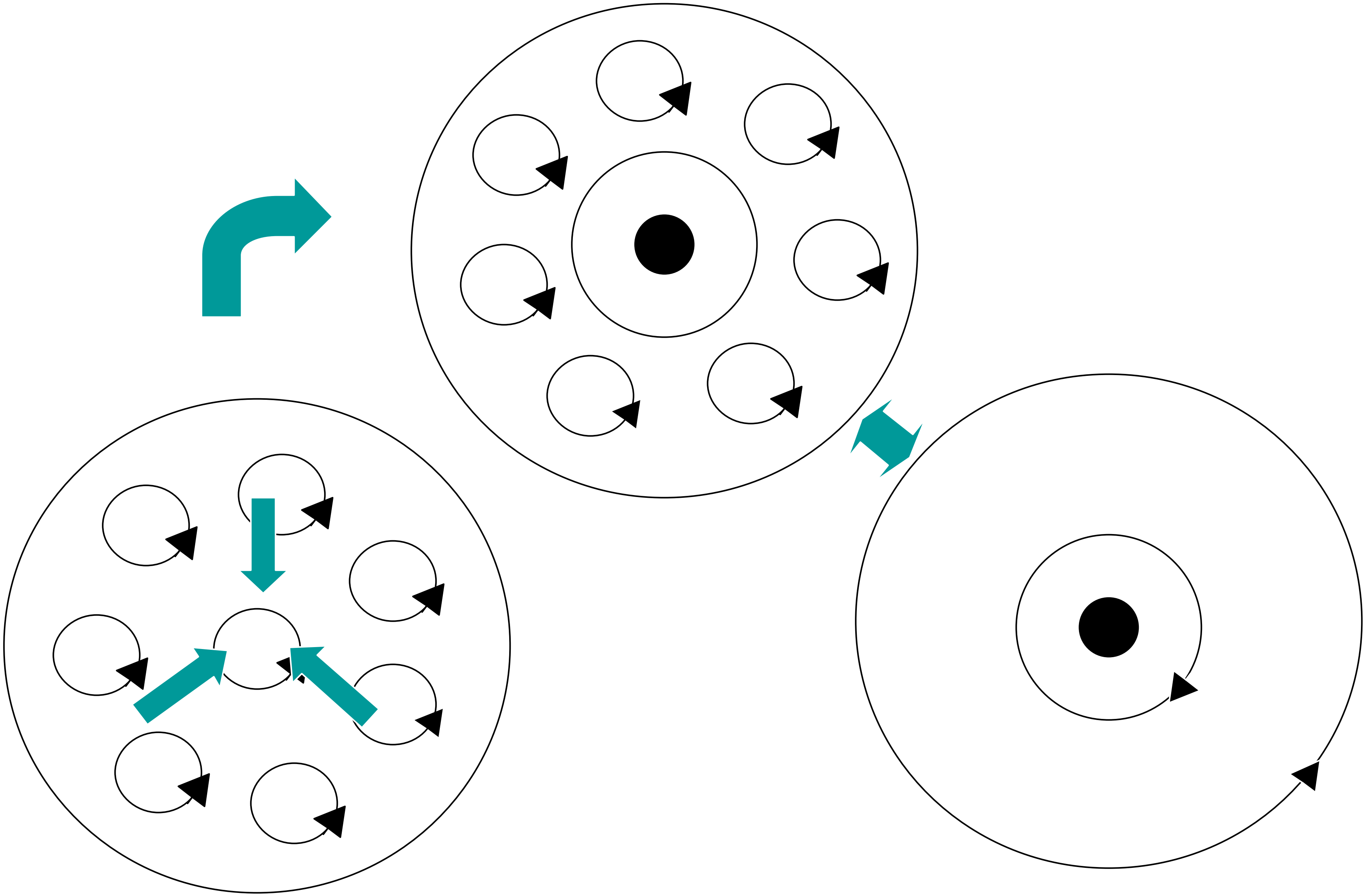


Core-collapse
(Woosley-Paczynski-Brown)

Active nucleus *inside* remnant stellar envelope



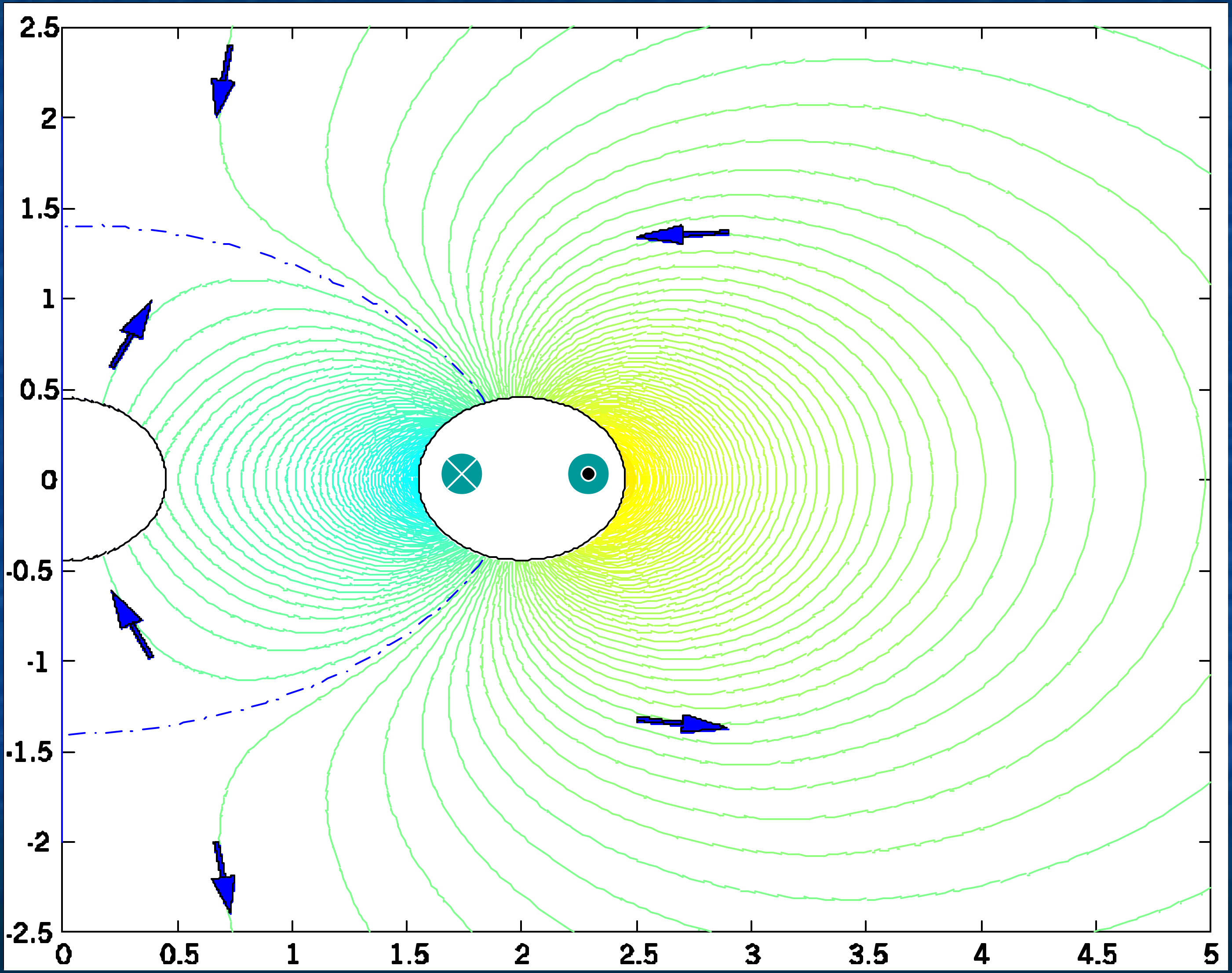
Magnetized nucleus in core-collapse



Suspended accretion state in MeV nucleus

(vacuum case)

separatrix



Van Putten & Levinson, ApJ 2003

Critical point analysis in baryon-rich torus wind

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

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

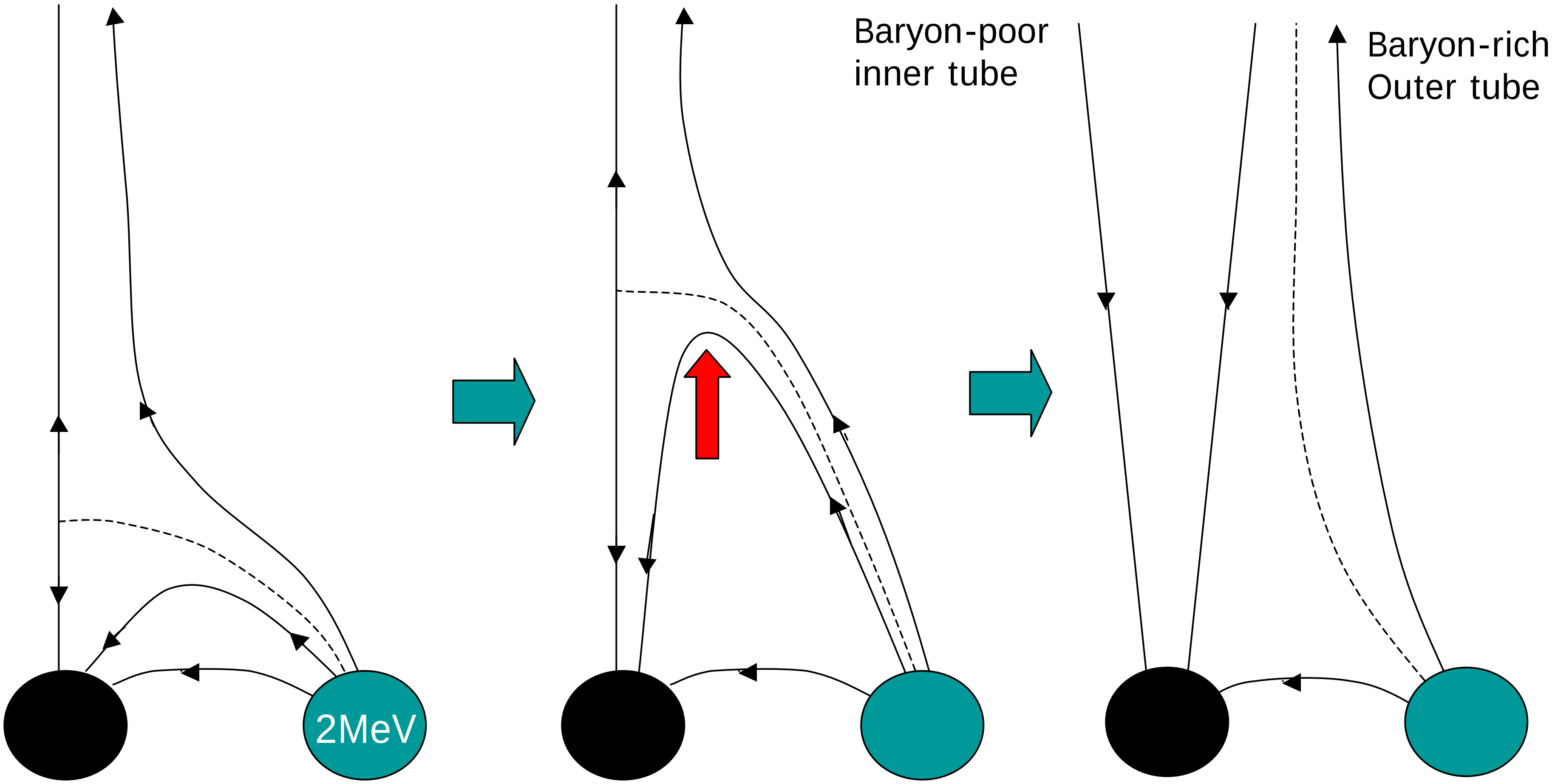
$$M_A[\text{on torus surface}] = \left(\frac{16pp_l}{3B_p^2}\right)^{1/2} \cong 0.07\left(\frac{M_T}{0.1M_S}\right)^{-1/3} L_{52}^{1/3} B_{p15}^{-1}$$

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

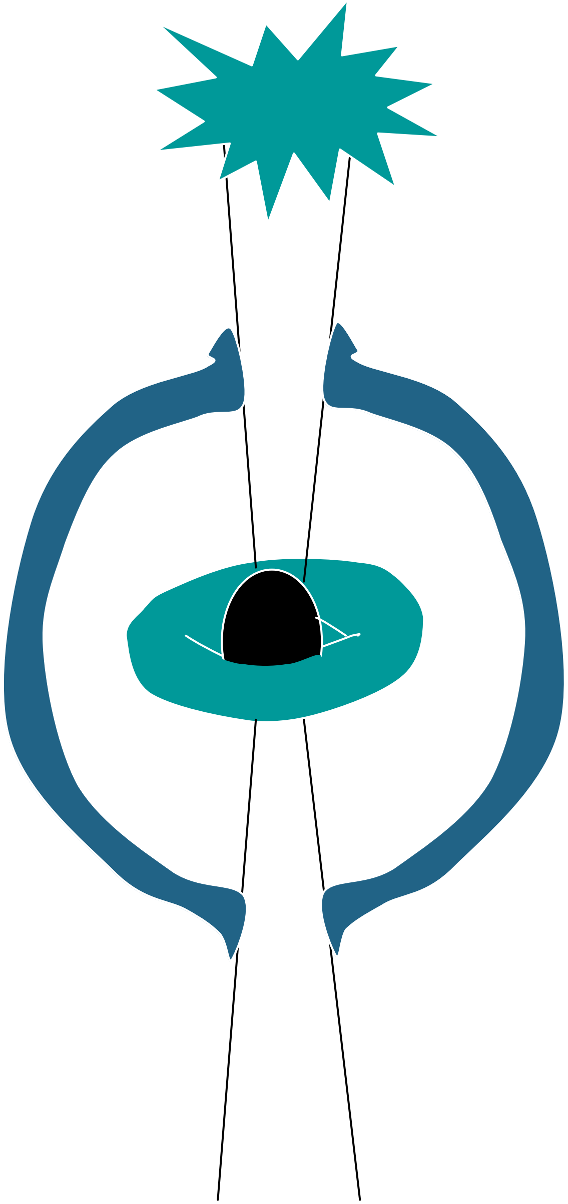
$$\dot{M} \cong 1\times 10^{30}\ \mathrm{g\,s^{-1}}$$

Van Putten & Levinson ApJ 2003

Baryon-rich torus winds create open magnetic flux-tubes

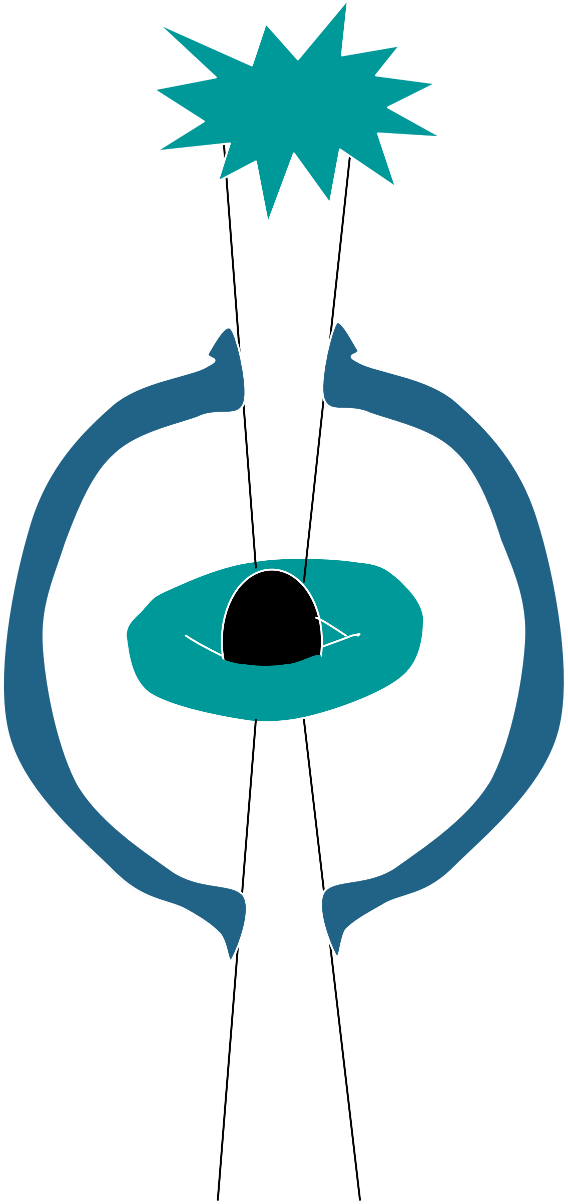


GRB-supernovae from rotating black holes



Jet through remnant envelope
(McFadyen & Woosley'98)

GRB-supernovae from rotating black holes



Jet through remnant envelope
(McFadyen & Woosley'98)

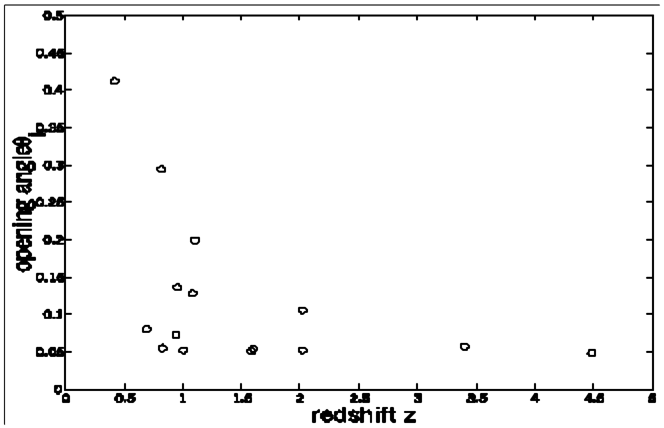
GRBs with redshifts (33) and opening angles (16)

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	<- most nearby!
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	Barthelmy's IPN
GRB000210	0.846		SAX/WFC	http://gcn.gsfc.nasa.gov/gcn/
GRB000131C	0.42	0.105	ASM/Uly	Greiner's catalogue
GRB000214	2.03		SAX/WFC	http://www.mpe.mpg.de/jcg/grbgeb.html
GRB000418	1.118	0.198	Uly/KO/NE	and Frail et al. (2001)
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	<- very nearby!

The true-but-unseen GRB-event rate

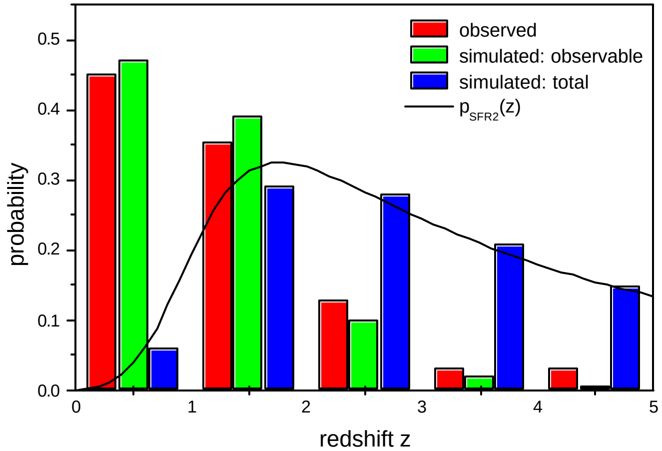
Geometrical beaming factor in GRB-emissions:

$1/f_b = 500$ (Frail et al. 2001, ApJ Lett.)



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

$1/f_r = 450$ (van Putten & Regimbau, 2003, to appear in ApJ Lett)

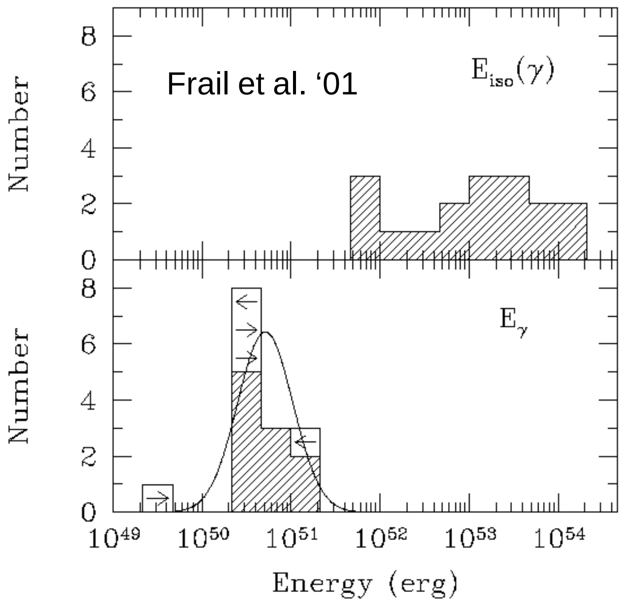


$$\text{True GRB event rate} \cong 0.5\times 10^6 \text{ / year}$$

$$\cong 1 \text{ per year within } 100\text{Mpc}$$

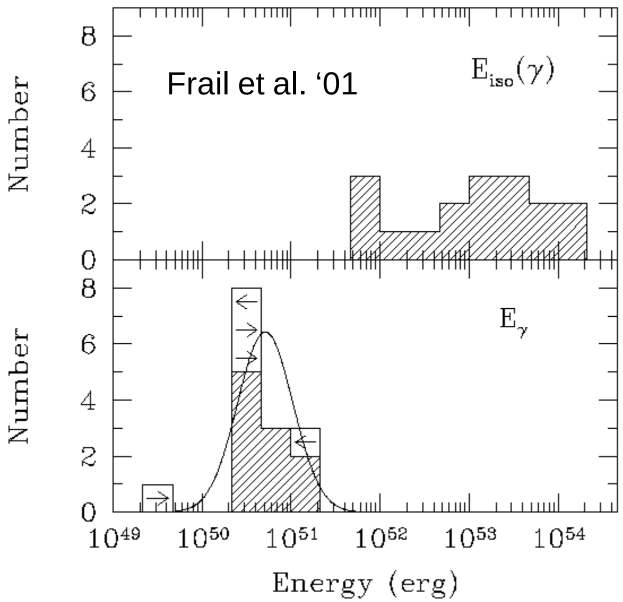
Observed true gamma-ray energies:

$$E_g \cong 1.5\times10^{-4} M_{Solar}$$



Observed true gamma-ray energies:

$$E_g \cong 1.5\times10^{-4} M_{Solar}$$



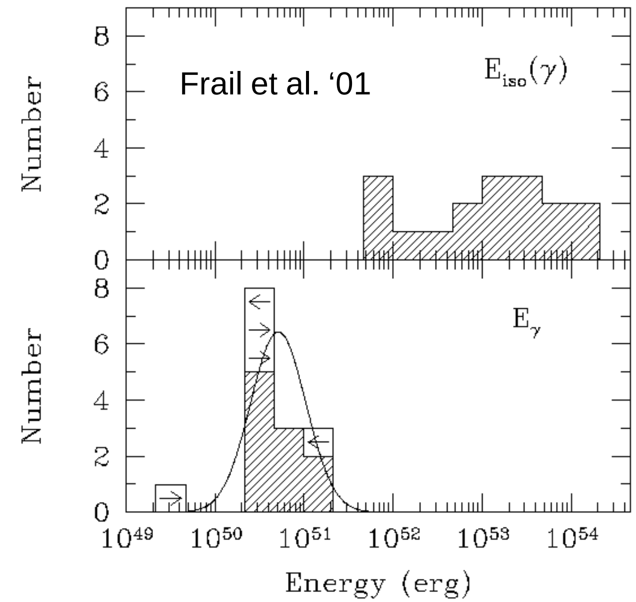
Modeling GRBs from rotating black holes:

$$M_H = 4 - 14 M_{Solar}$$

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

Observed true gamma-ray energies:

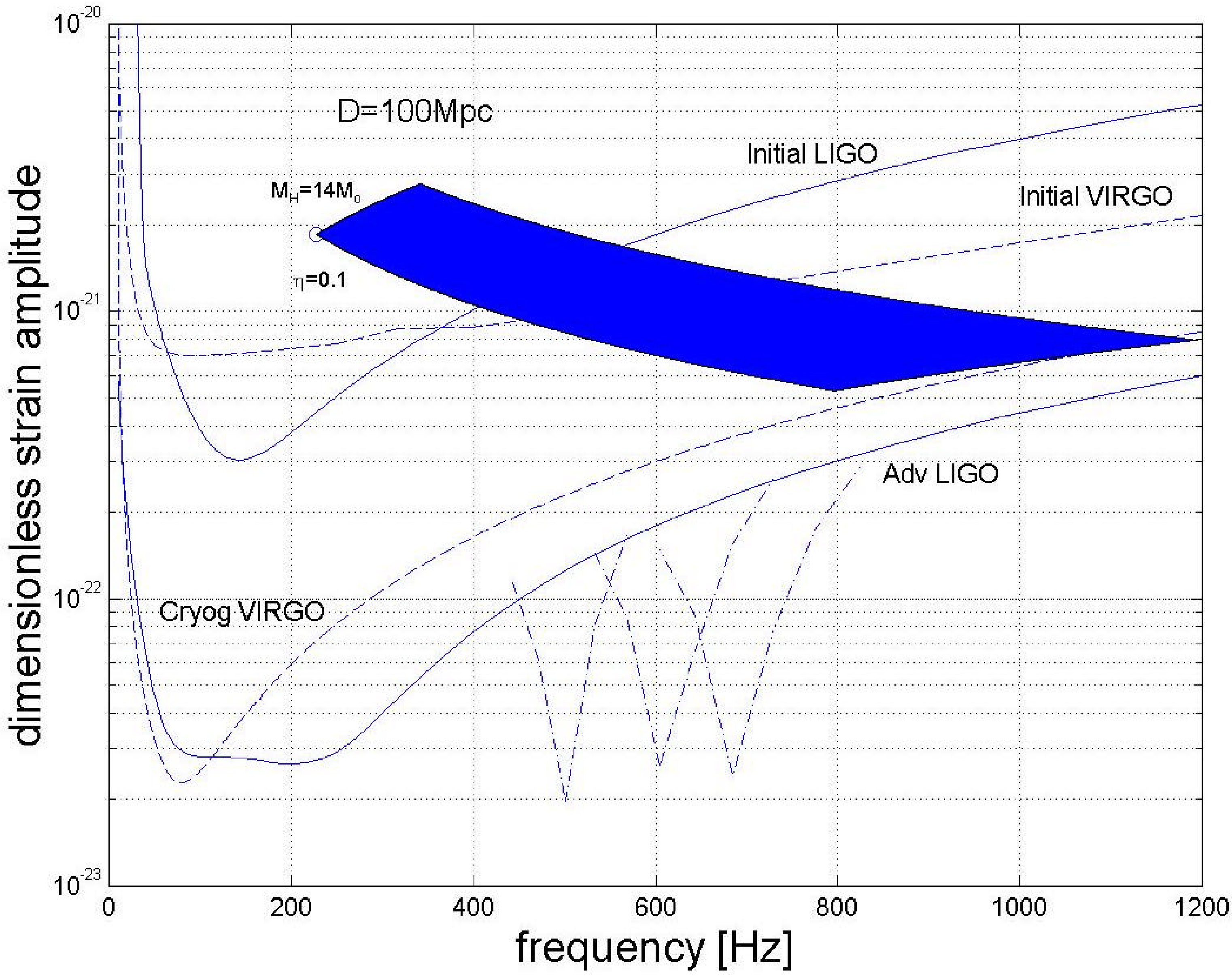
$$E_g \cong 1.5\times10^{-4} M_{Solar}$$



Modeling GRBs from rotating black holes: $(M_H, h = \Omega_T / \Omega_H)$

$$E_{gw} \cong 0.2 M_{Solar} (M_H / 7 M_{Solar})(h / 0.1)$$

$$f_{gw} \cong 0.5\text{kHz}(7 M_{Solar} / M_H)(h / 0.1)$$



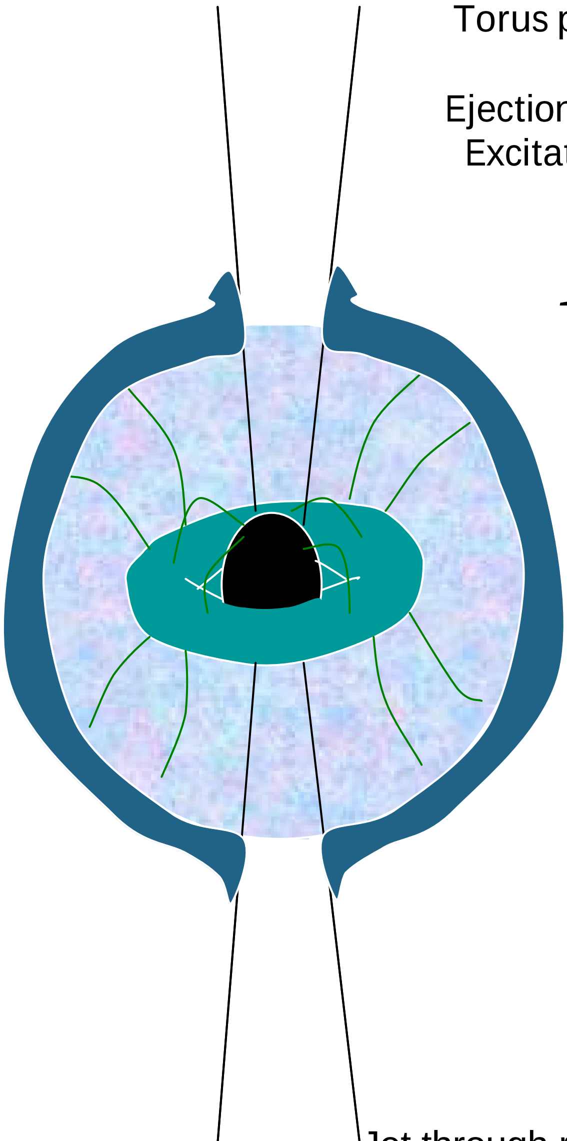
July 4-14 (2003) http://www.ligo.caltech.edu/P/P030041-00.pdf

GRB-supernovae from rotating black holes

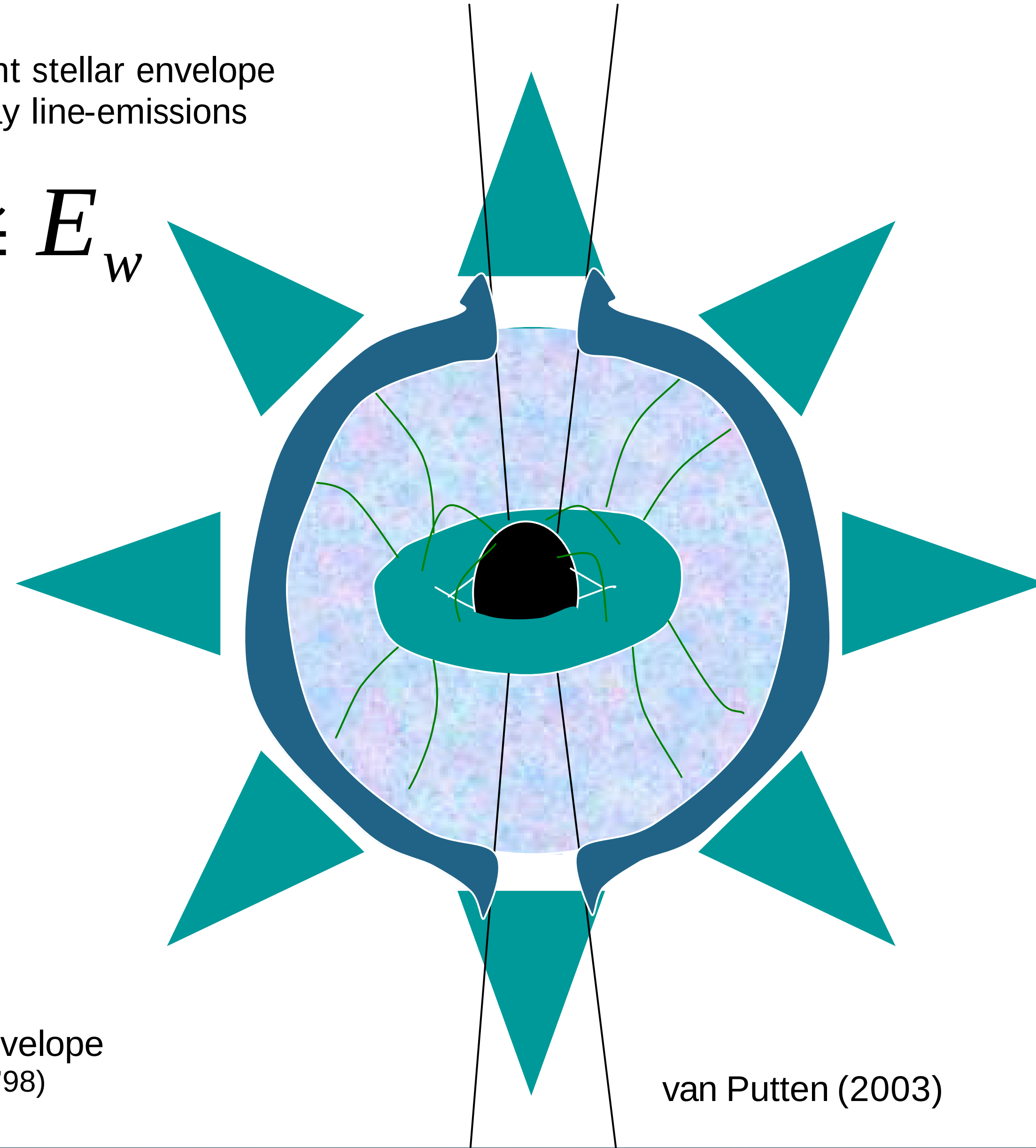
Torus produces winds & radiation:

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

$$E_r \cong E_w$$



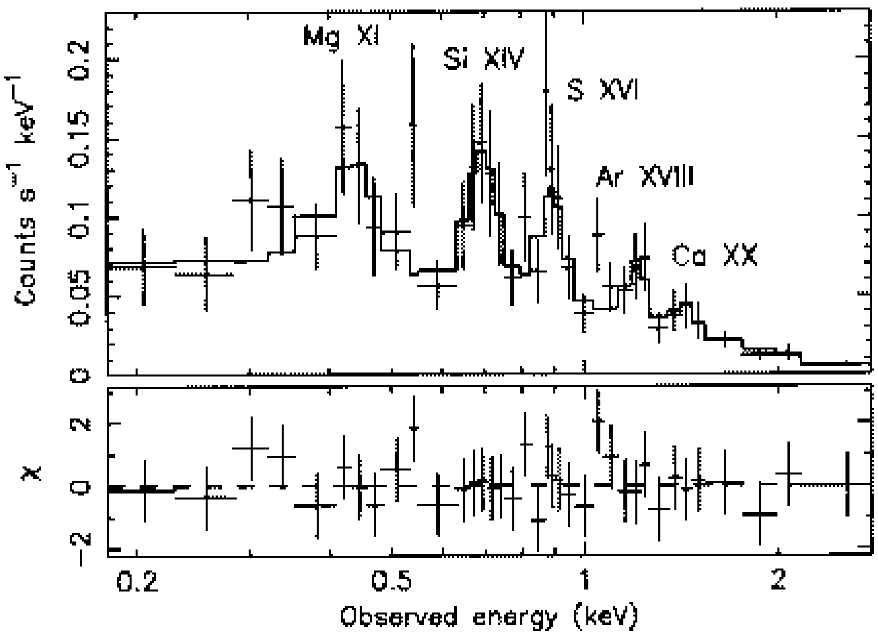
Jet through remnant envelope
(McFadyen & Woosley'98)

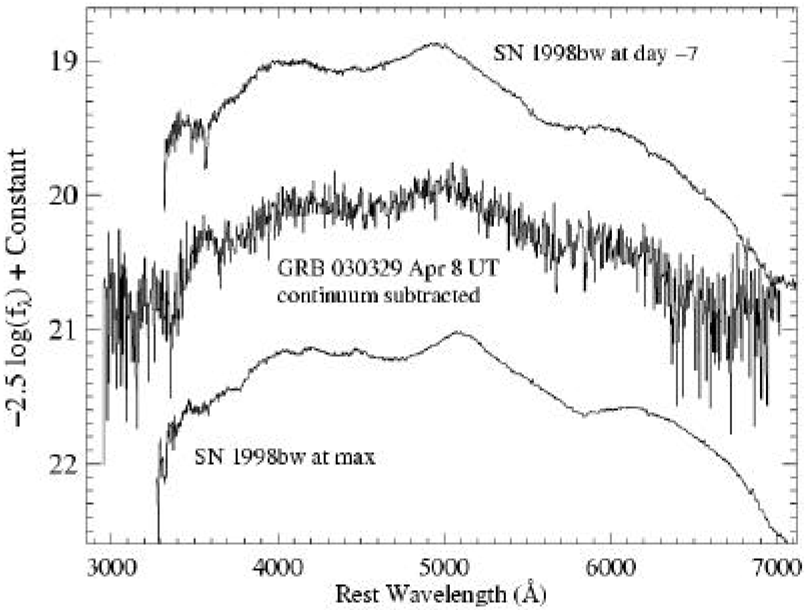


van Putten (2003)

GRB-SNe in 011211 and 030329

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

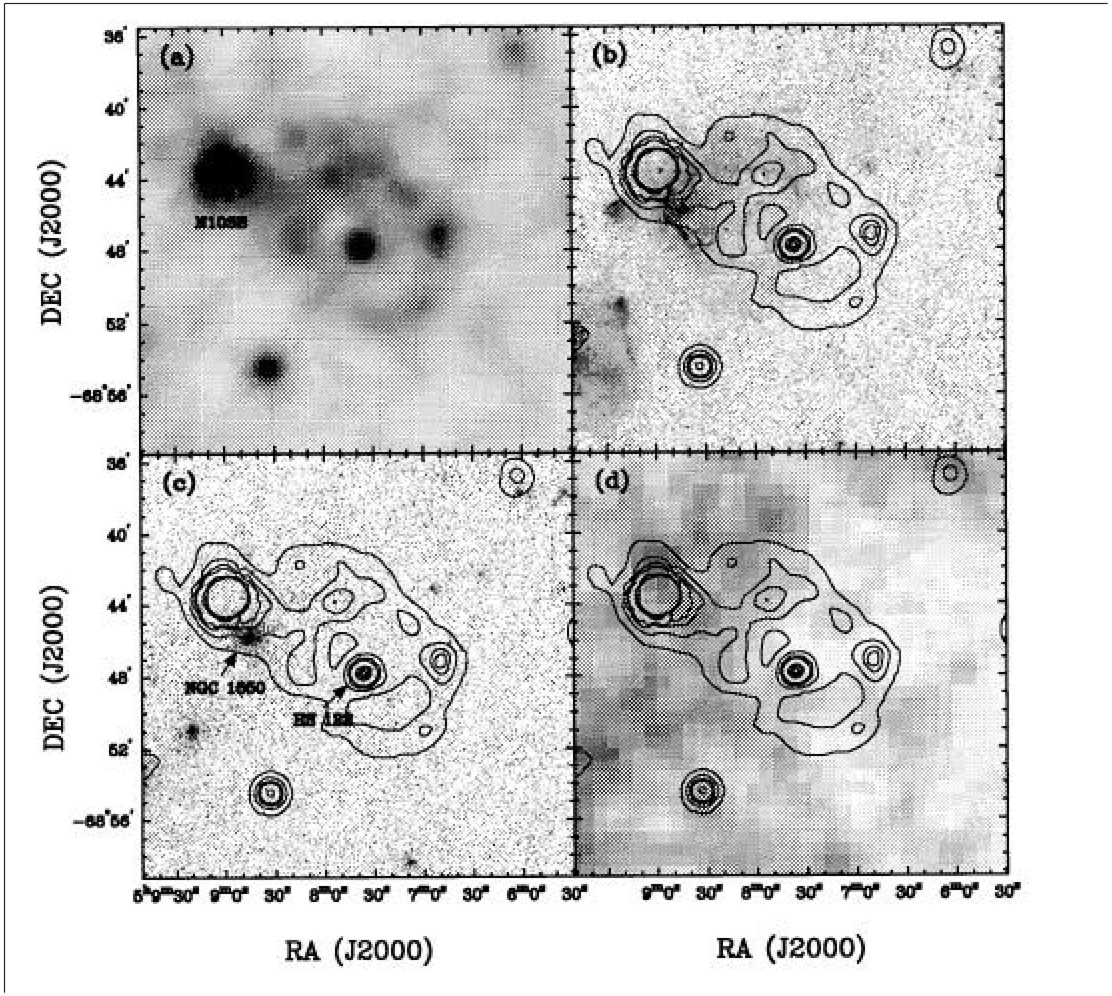




$$E_r \cong 4\times10^{52} \text{ (G. Ghisellini 2002)}$$

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

Morphology of remnants: black hole + optical companion + SNR



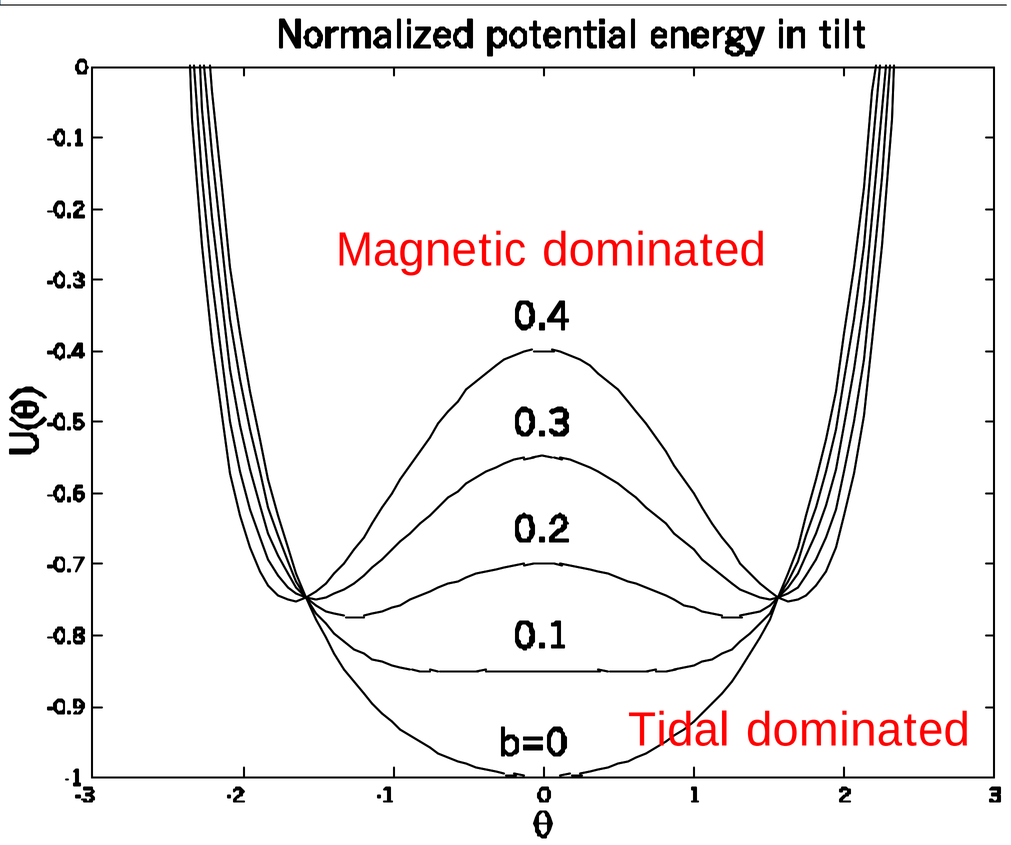
RX J050736-6847.8

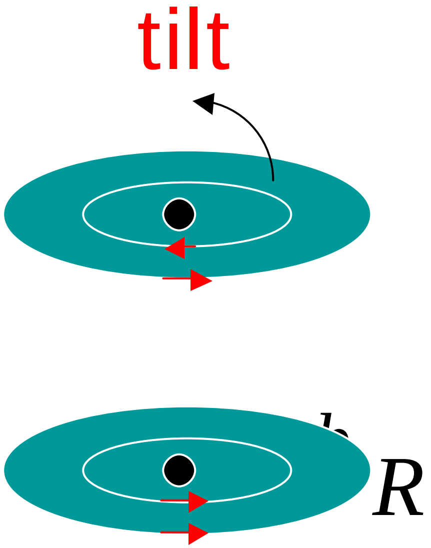
Chu, Kim, Points et al., ApJ, 2000

Outline

- Durations of tens of seconds of long bursts
- Radiation energies from MeV nuclei
- Observational opportunities for LIGO/VIRGO
- Conclusions

Magnetic stability criterion





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

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

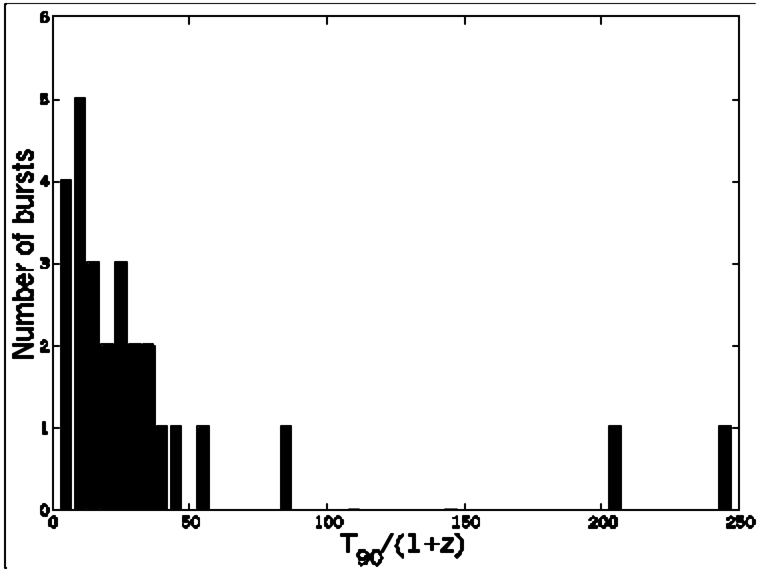
$\Rightarrow$ $E_B / E_k < 1/12$ [1/15 for buckling instability]

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 $g_0 = T_{90} / P$

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

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

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

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

Small energy output in baryon-poor outflows

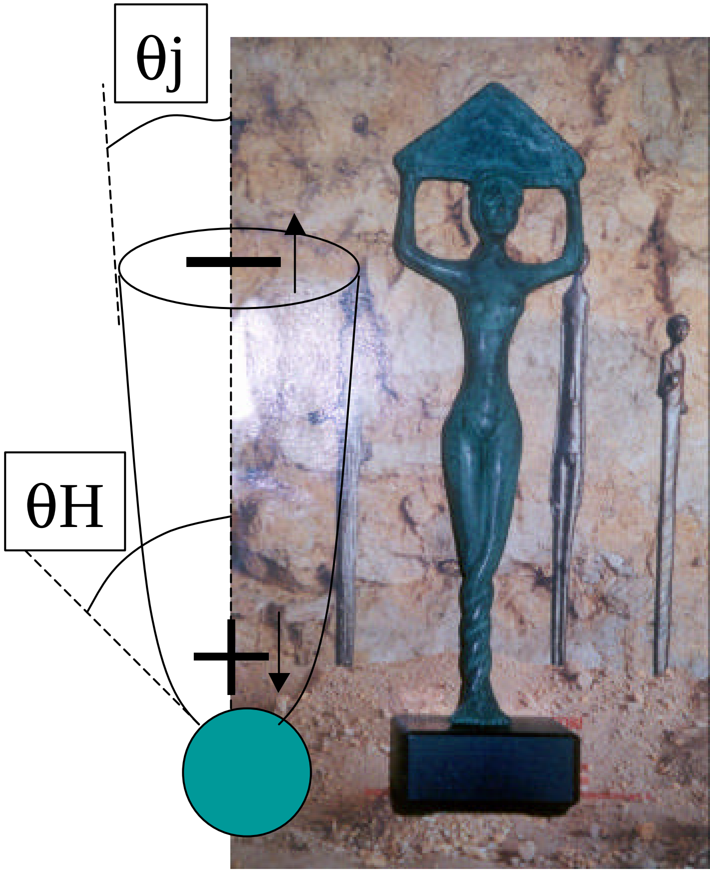
Baryon - free output in open flux - tube along rotation axis

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

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

Poloidal curvature of flux - surfaces

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



Van Putten & Levinson ApJ 2003

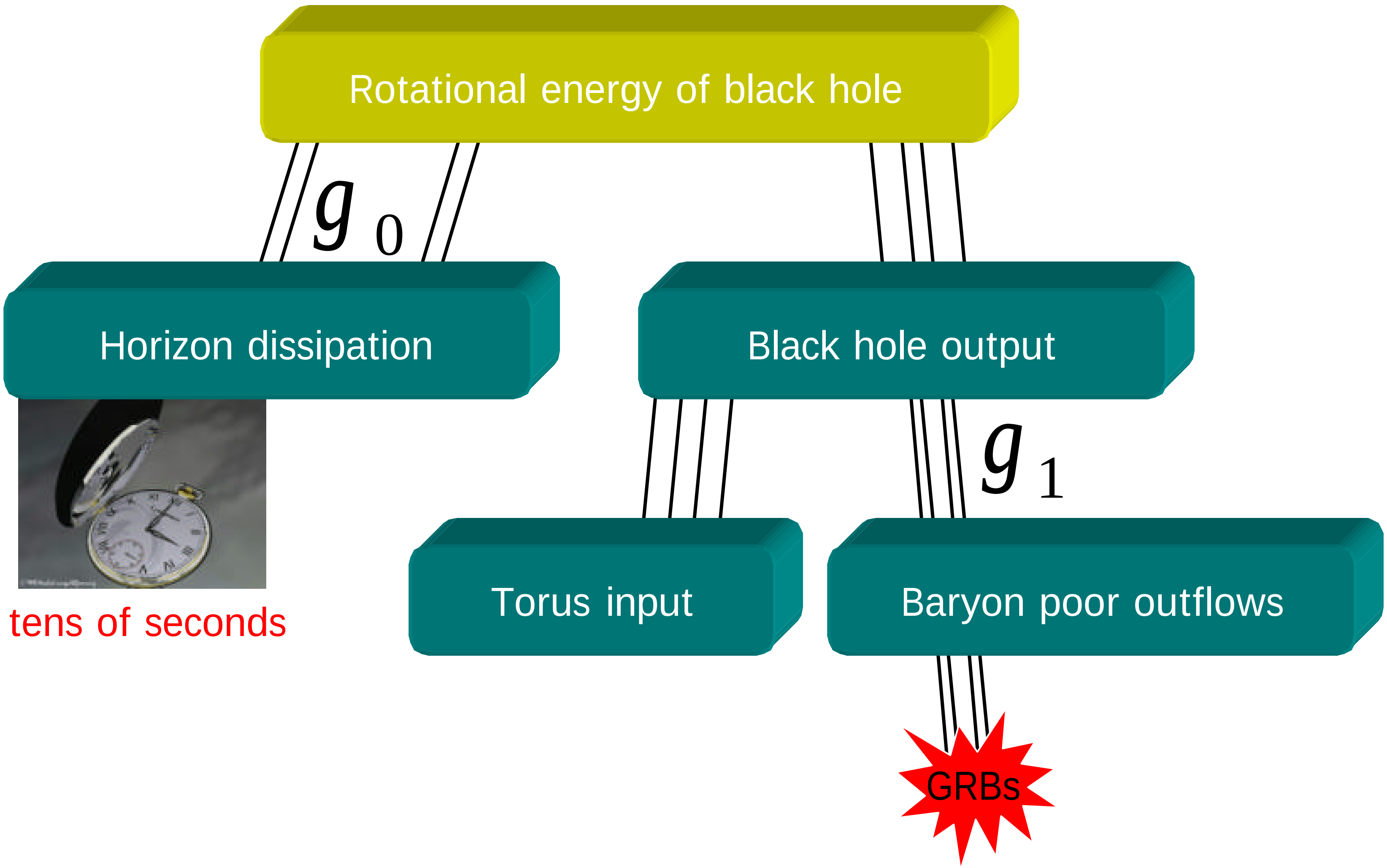
Small GRB-energies

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

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

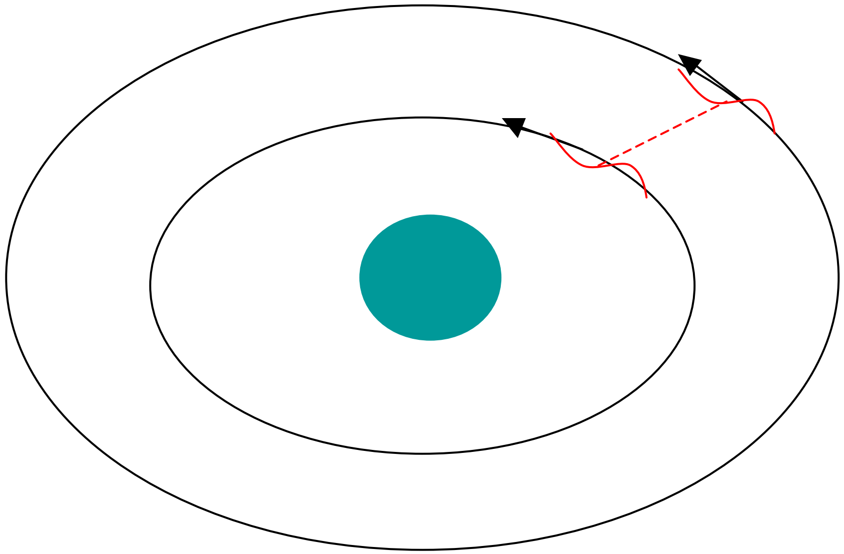
$$g_1[observed] \cong 7\times10^{-5}$$

Timescales and radiation energies



Linearized stability analysis for the torus

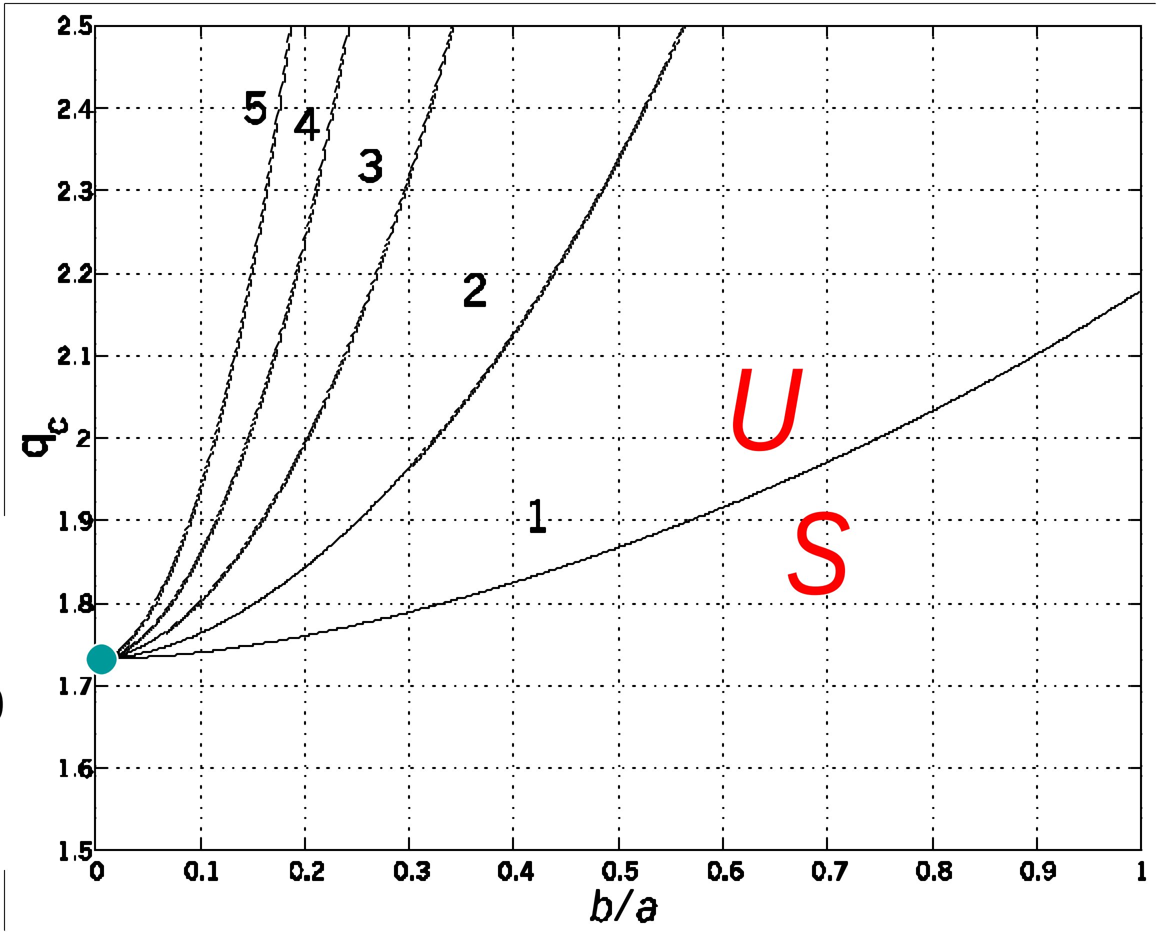
Free surface waves on inner and outer boundaries mutually interact (Papaloizou-Pringle 1984)



m=2 buckling mode

Multipole mass-moments in tori

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



Infinite slenderness :

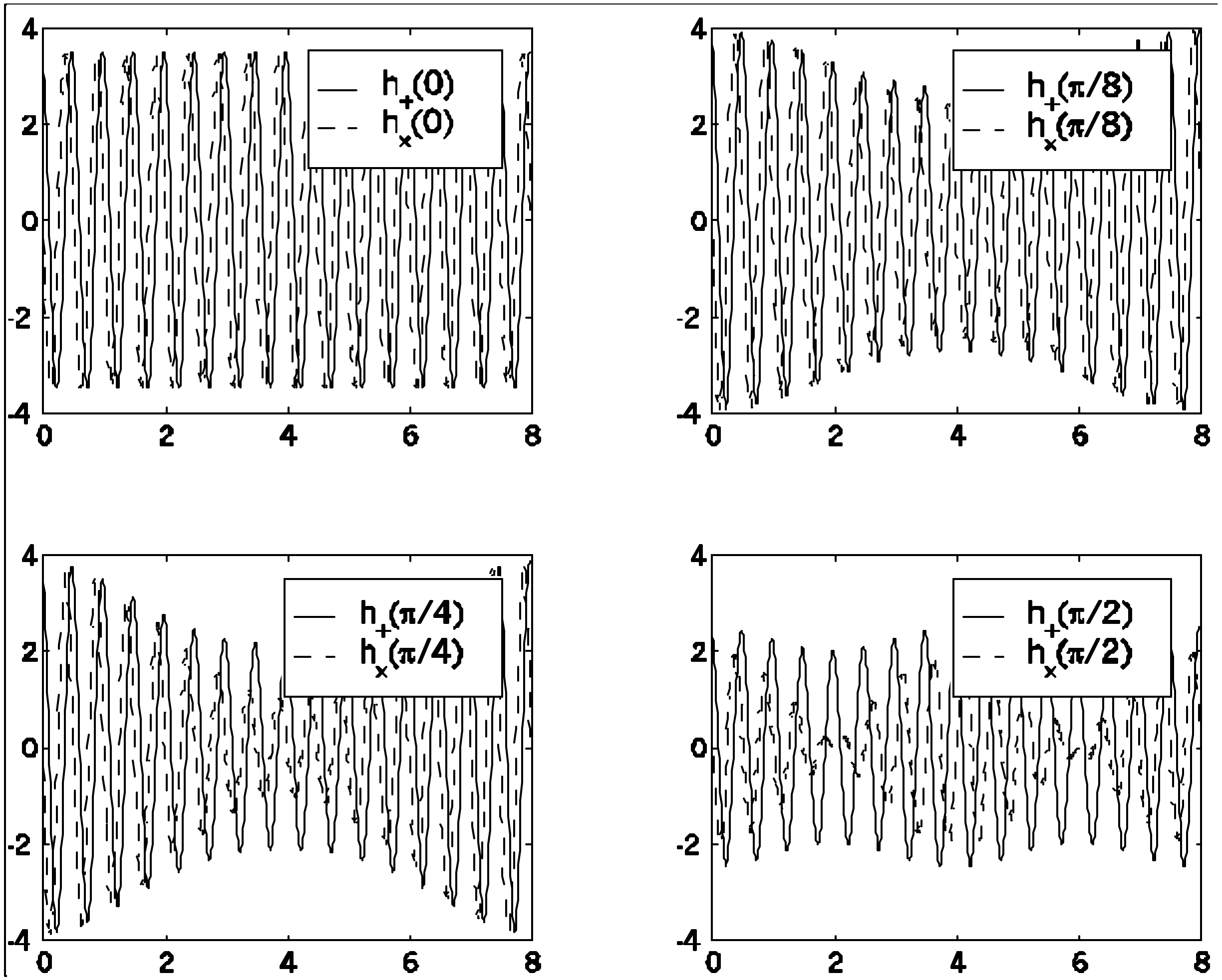
$q_c = \sqrt{3}$ as $b/a \sim 0$

Papaloizou - Pringle (1984)

Goldreich et al. (1986)

Finite slenderness (Van Putten, 2001, ApJ Lett.)

Phase-modulated wave-forms



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

$$q = p/6$$

Gravitational radiation in suspended accretion

Balance in angular momentum and energy flux

$$t_{+} = t_{-} + t_{rad}$$

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

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

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

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

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

4e53 erg in gravitational radiation

4e52 erg in torus winds producing SNe

6e52 erg in MeV-neutrinos

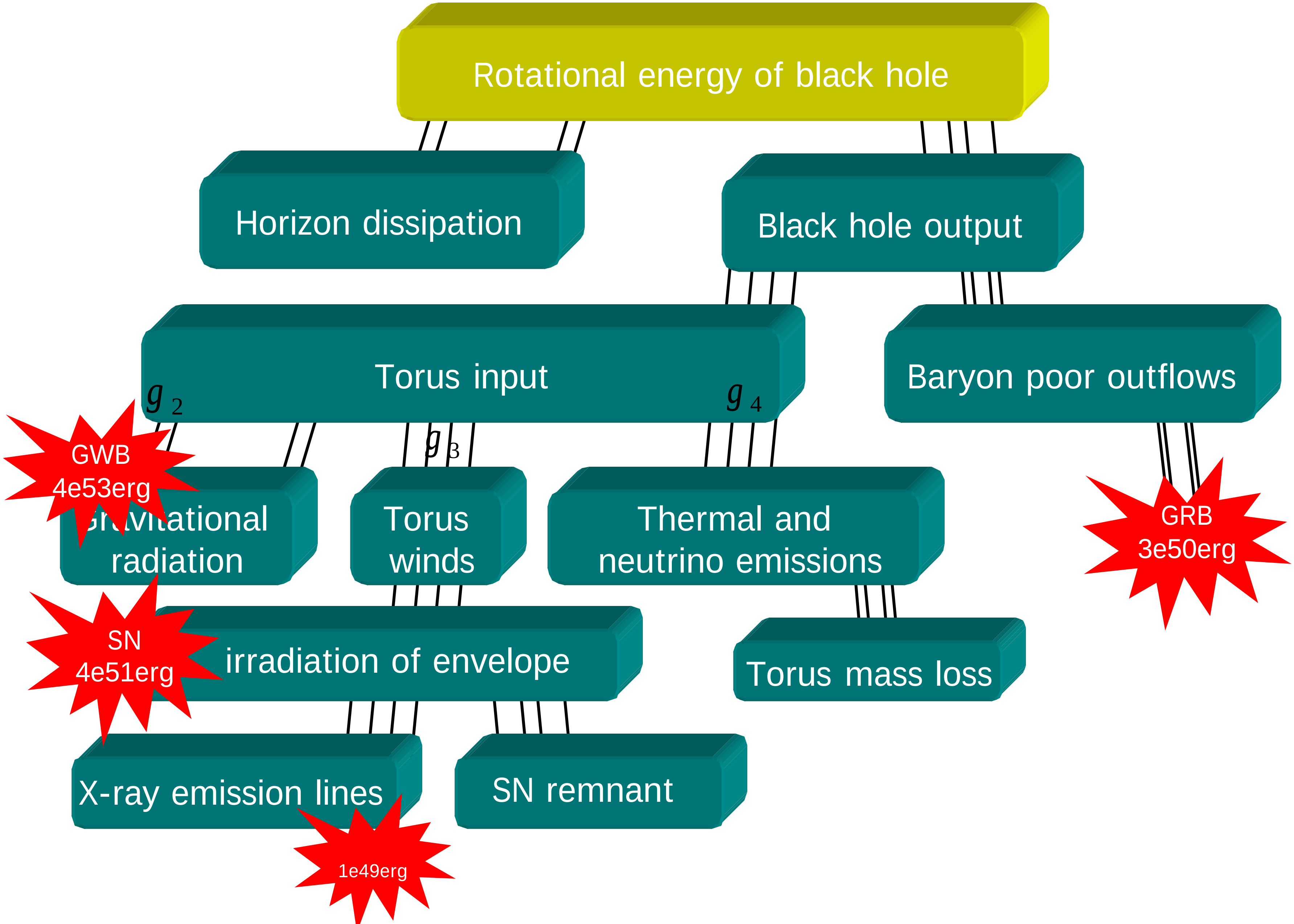
$$h = \Omega_T / \Omega_H \cong 10\%$$

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

A link between gravitational waves and the electromagnetic spectrum

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

Radiation energies from MeV nuclei



Observational opportunities for LIGO/VIRGO

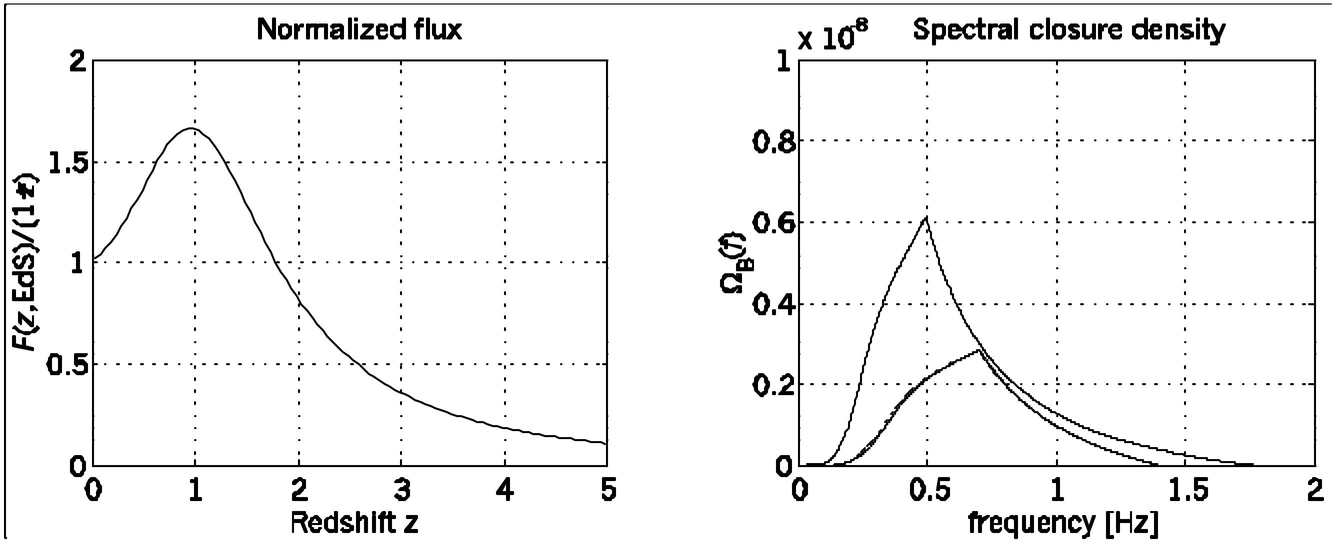
Matched filtering

$$\left(\frac{S}{N}\right)_{mf} \cong 8\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{5.7\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)^{-1}\left(\frac{h}{0.1}\right)^{-3/2}\left(\frac{M_H}{7M_{Solar}}\right)^{5/2}\left(\frac{d}{100\mathrm{Mpc}}\right)^{-1}$$

Correlating two detectors in narrow band mode

$$\left(\frac{S}{N}\right)_{cs} = 12\, f_4^{D1} f_4^{D2}\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{5.7\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)_{D1}^{-1}\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{5.7\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)_{D2}^{-1} h_{0.1}^{-5/3} M_{H7}^{5} d_8^{-2} B_{0.1}^{-1/2} m_{0.03}^{1/4}$$

Stochastic background radiation in gravitational waves



$$\left(\frac{S}{N}\right)_B = 5\times\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{5.7\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)_{H1}^{-1}\left(\frac{S_h^{1/2}(500\mathrm{Hz})}{5.7\times10^{-24}\,\mathrm{Hz}^{-1/2}}\right)_{H2}^{-1} h_{0.1}^{-9/2} T_{1yr}^{1/2} \quad (M_H = 4-14 M_{Solar})$$

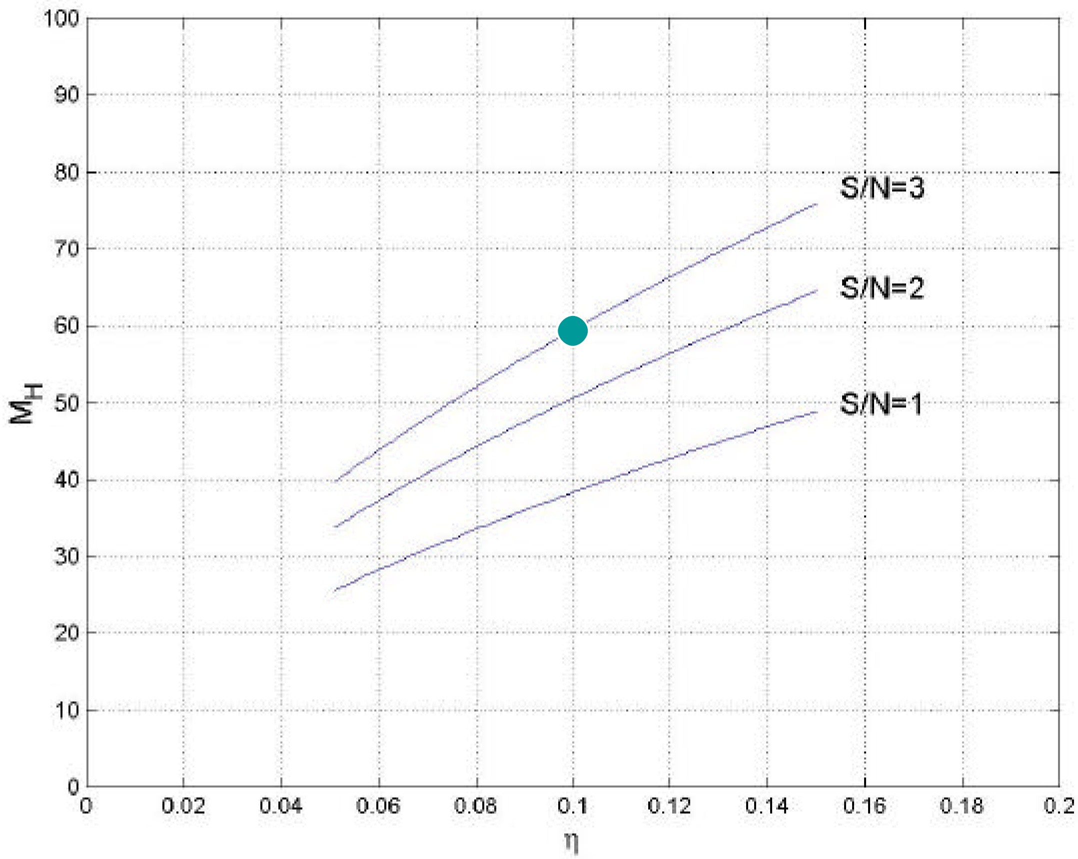
S2(LLO)-upper bound on black hole-mass in GRB 030329

$$d = 800\text{Mpc}$$

$$S_h^{1/2}(500\text{Hz}) = 4\times10^{-22}\,\text{Hz}^{-1/2}$$

"No-detection":

S/N < 3 in mf



$$M_H[\text{GRB}030329] < 60M_{Solar}$$

Conclusions

Long GRBs

- produce 0.2Msolar in a burst of GWs of tens of seconds, once a year within 100Mpc
- describe a ‘Big Blue Bar’ in the h(f)-diagram, in the high-frequency LIGO/VIRGO range

S2(LLO) shows a sensitivity range of 1Mpc, and a upper bound of 60 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 GRBs to the stochastic background radiation in gravitational waves (Omega=6e-8)

Opportunity: LIGO/VIRGO detections correlated with wide-angle emissions from an associated radio loud supernova, possibly correlated with extremely weak GRB-emissions as in GRB980425