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Black holes, gamma-ray bursts and gravitational waves

Maurice H.P.M. van Putten

A public lecture

sponsored by ACIGA & AIP 2003

Perth 2003

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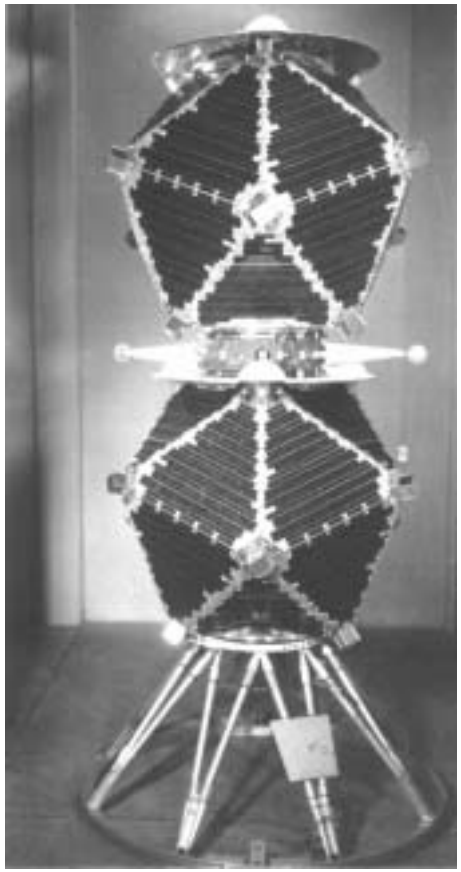
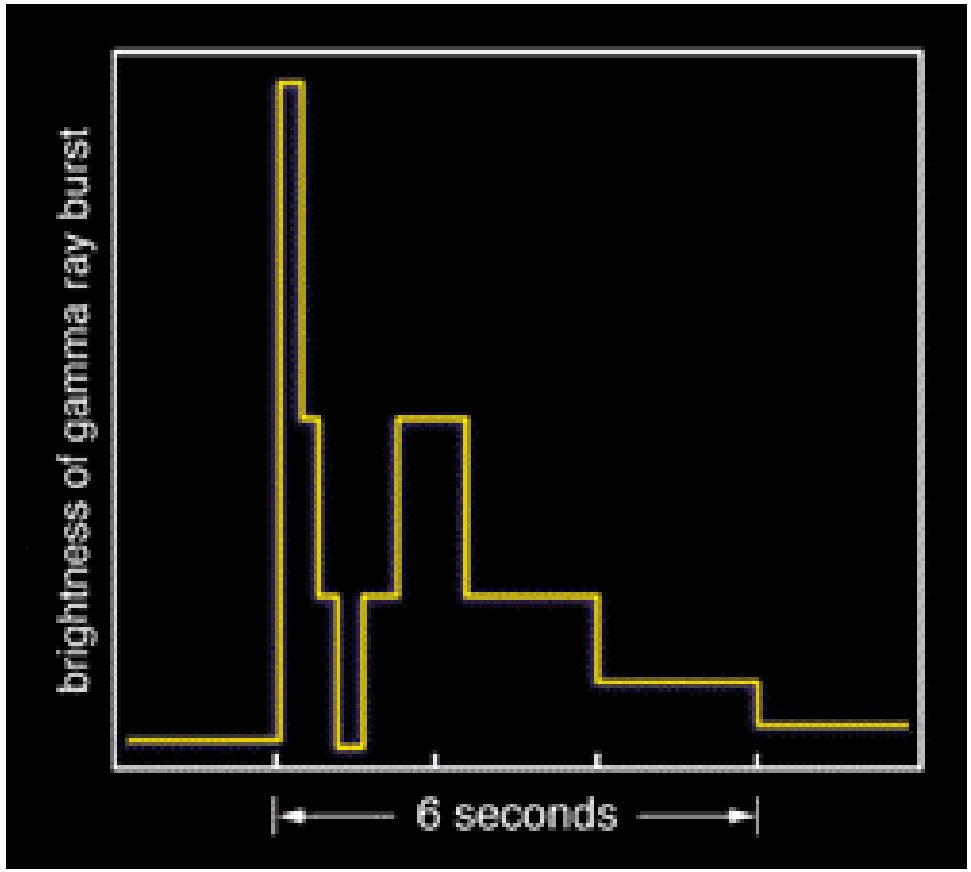
Vela/Konus (1963-1979)



Vela



GRB670702 (Klebesadel & Olson)

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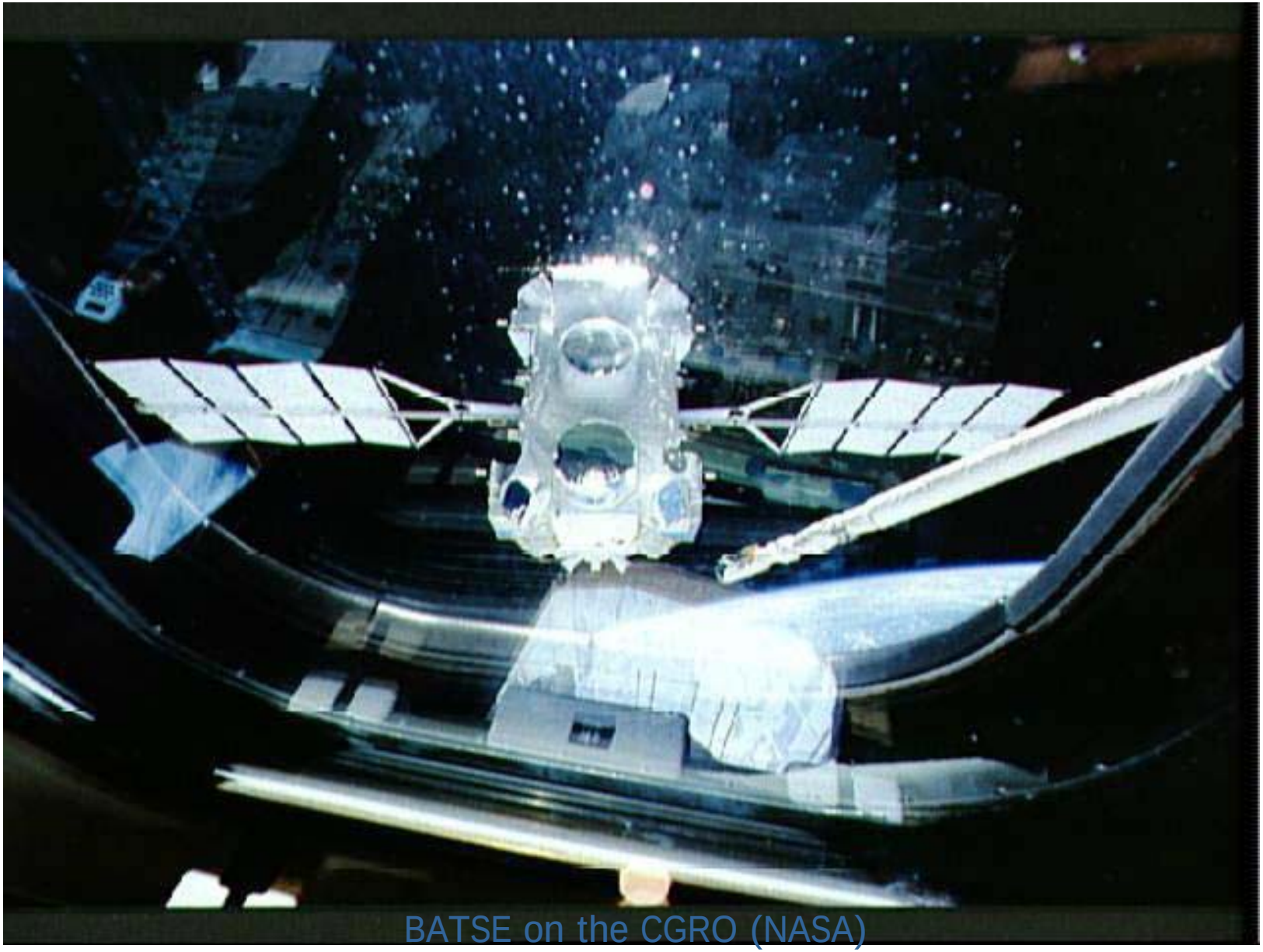
BATSE (1991-2000)



BATSE on the CGRO (NASA)

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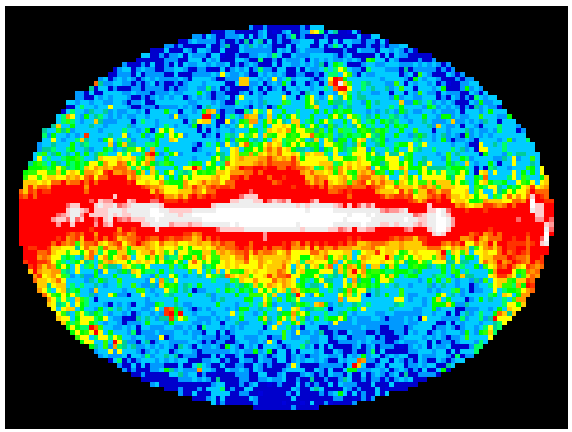

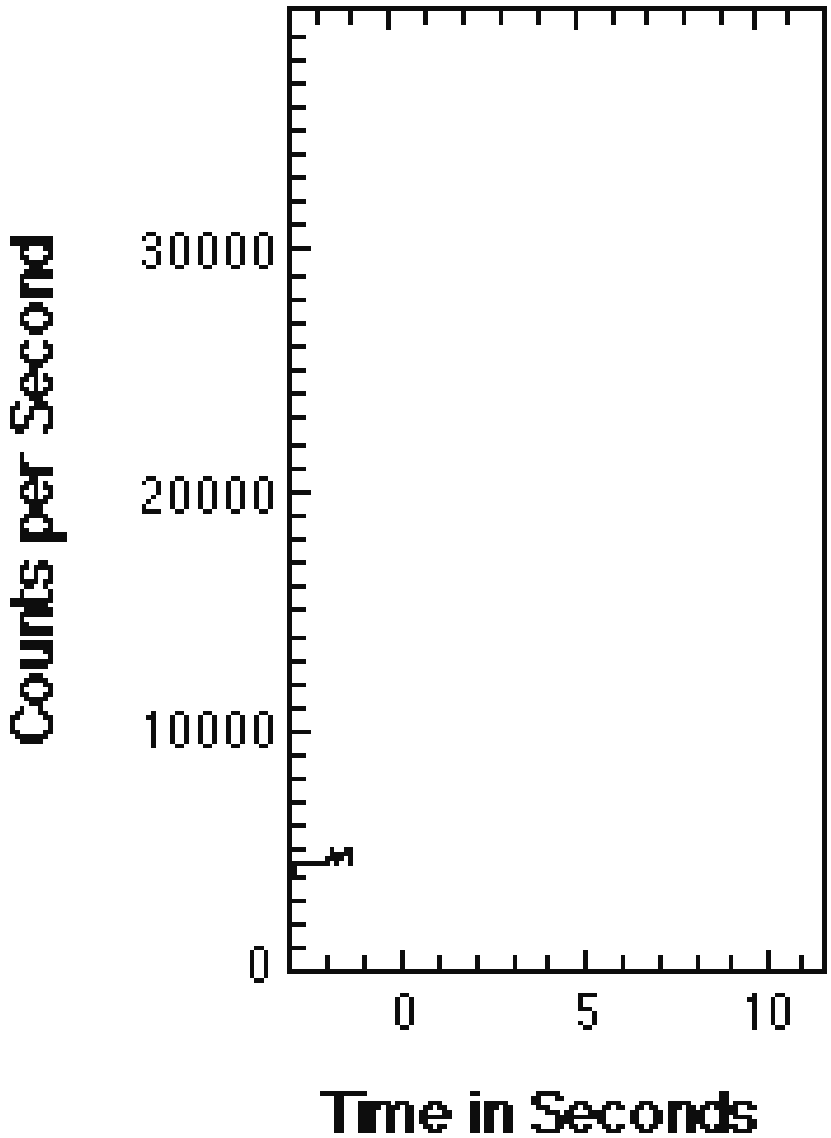

BATSE Group, NASA
http://image.gsfc.nasa.gov/docs/science/know_l1/bursts.html

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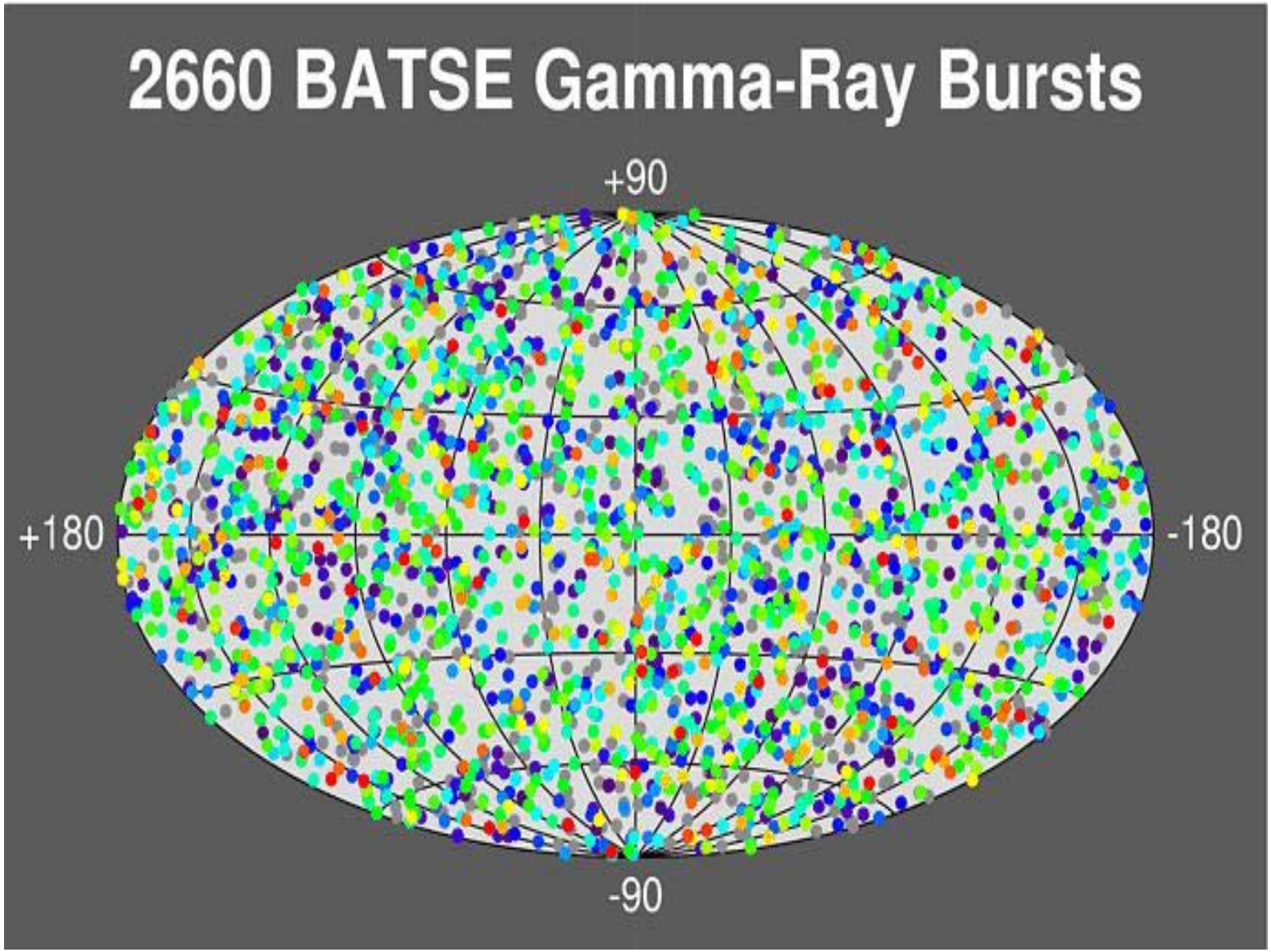

Cosmological origin: isotropic energy emissions up to 1MSolar

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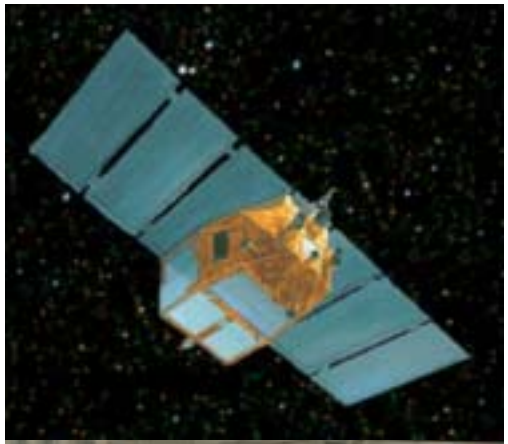
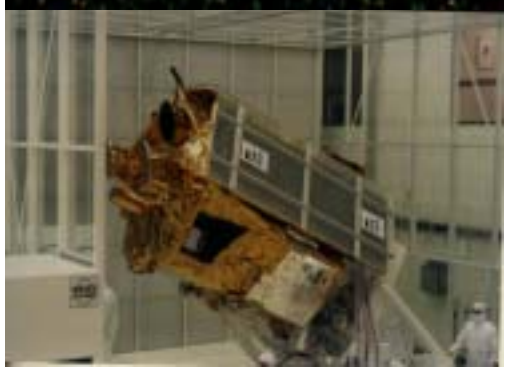
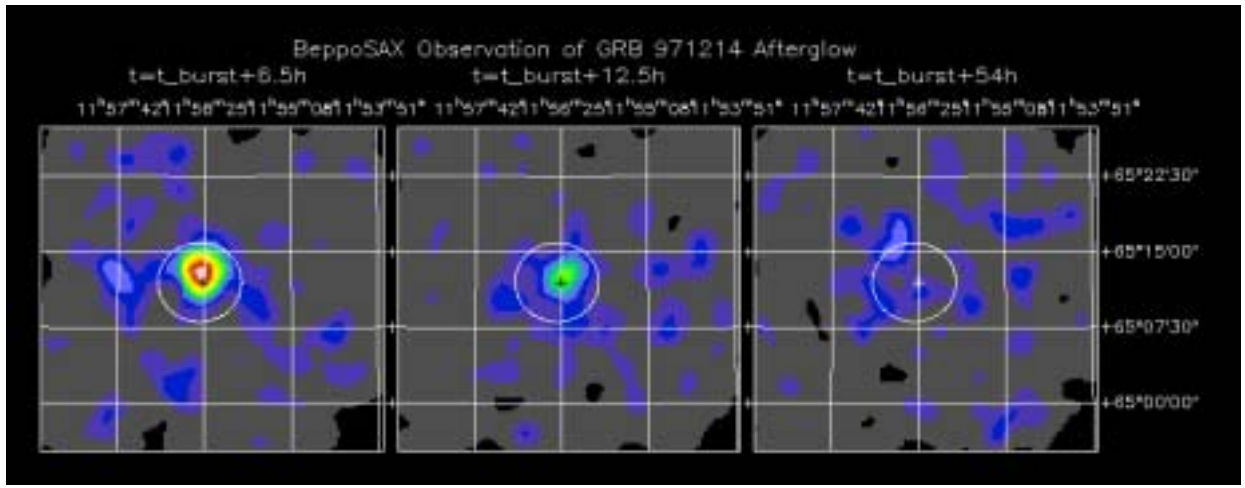
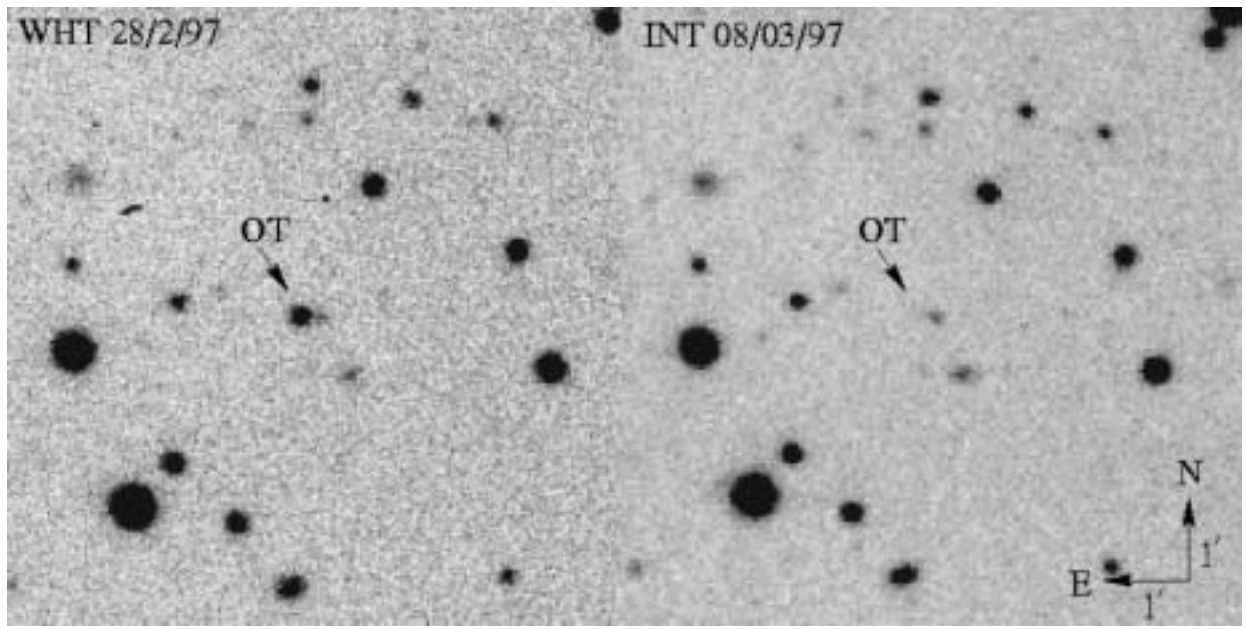
Beppo-Sax (Italian-Dutch, 1996-2002)

GRB971214 z=3.418









GRB970228 z=0.695

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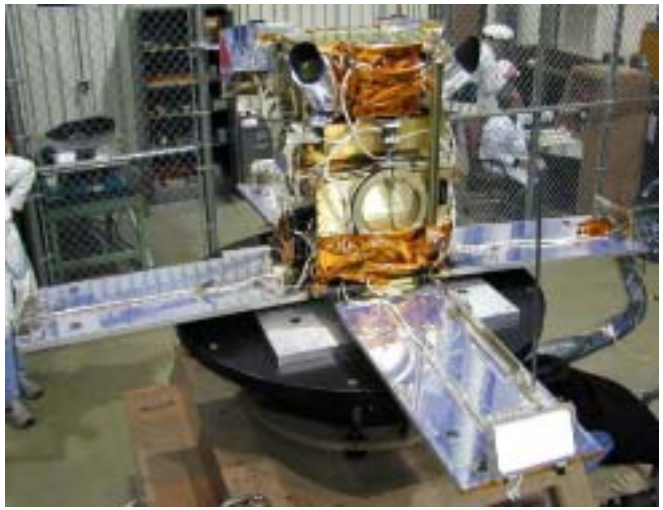
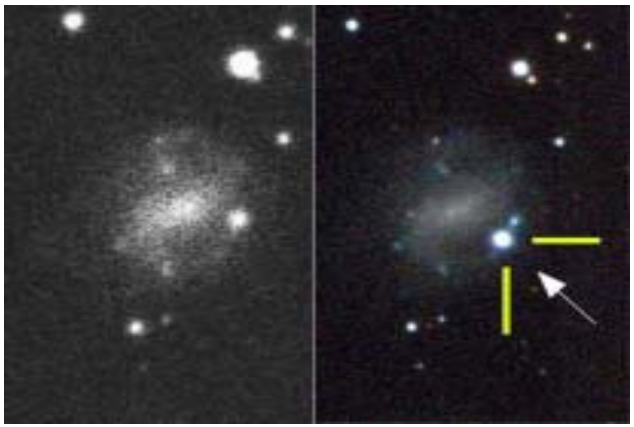
GRBs with known redshifts



HETE-II

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	Barthelmy's IPN
GRB000131	4.5	<0.047	Uly/KO/NE	http://gcn.gsfc.nasa.gov/gcn/
GRB000210	0.846		SAX/WFC	Greiner's catalogue
GRB000131C	0.42	0.105	ASM/Uly	http://www.mpe.mpg.de/jcg/grbgeb.html
GRB000214	2.03		SAX/WFC	and Frail et al. (2001)
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	<- very nearby!

GRB association to supernovae



SN1998bw (ESO, 1998)
Galama et al. 1998

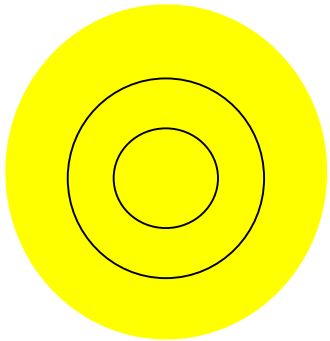
GRB030329/SN2003dh
(z=0.168, D=800Mpc)

GRB980425/SN1998bw
(z=0.008, D=37Mpc)

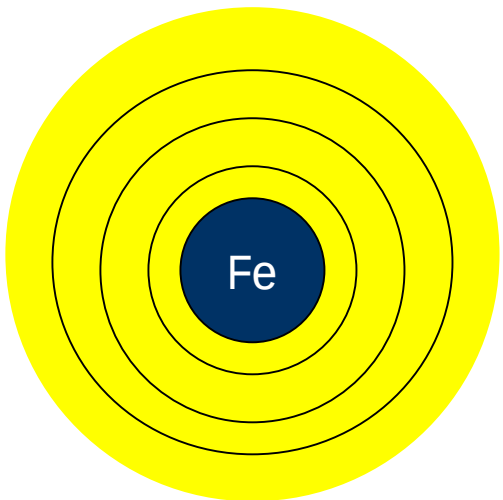
Stanek, K., et al., 2003
(also: Garnavich et al. 2003,
Hjorth et al. 2003)

GRBs belong to a class of supernovae --- a known astronomical phenomenon

Supernovae of massive stars (M>8MSolar)



H,He,C,O,Si burning produces
Fe core, pressure is thermal



Core pressure becomes degenerate
at low temperature after cooling

Chandrasekhar (1931): maximal mass of a *degenerate* object is 1.4MSolar

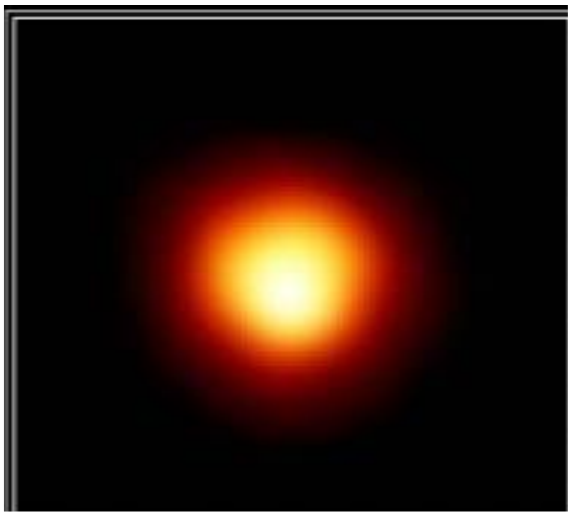
Beyond Chandrasekhar limit, further collapse into a neutron star (Landau)

Shock rebounce produces a supernova plus a burst in neutrinos

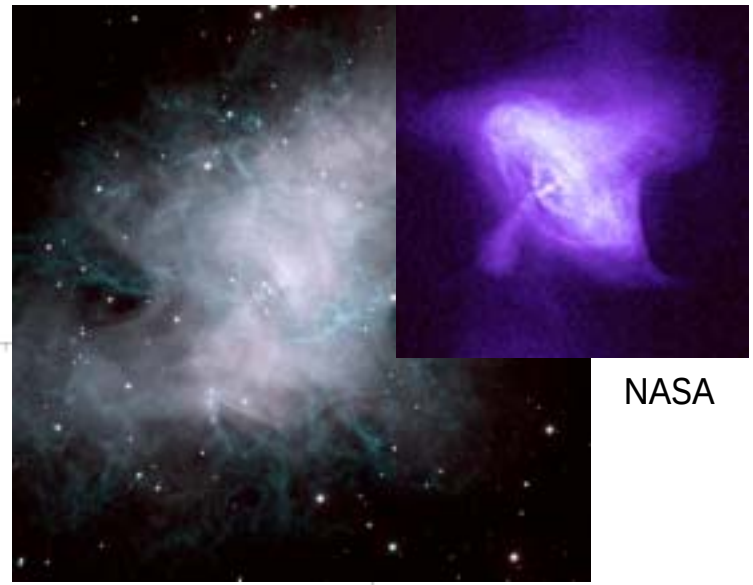
Exceeding the neutron star mass limit leaves a black hole – the most compact object

Compact objects formed in supernovae of massive stars

Betelgeuse: 20 MSolar

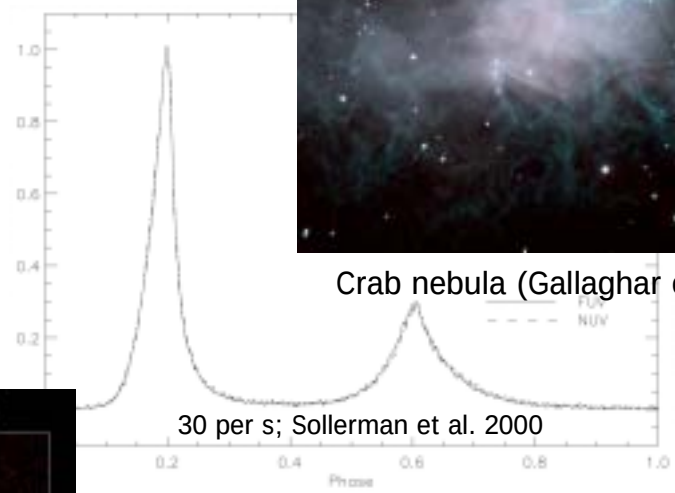


Dupree & Gilliland 1999

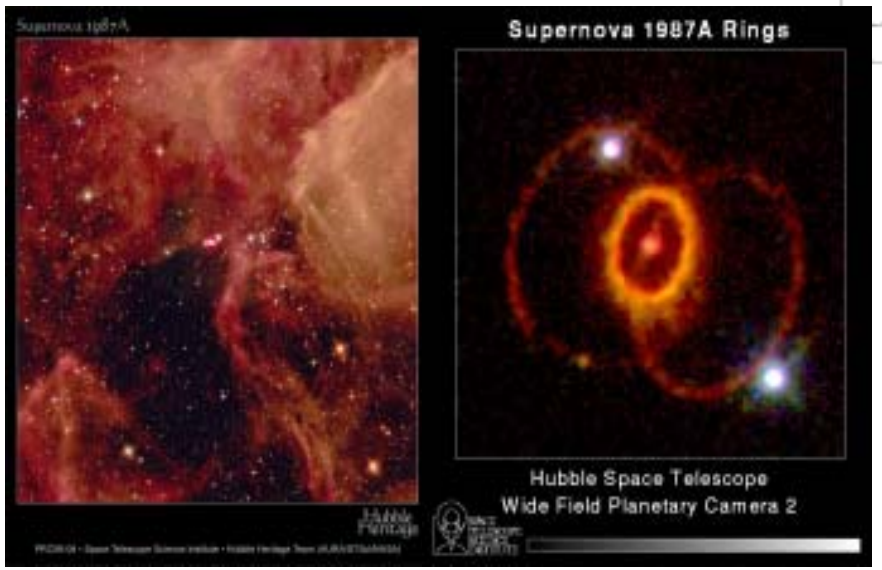


NASA

Crab nebula (Gallaghar et al. 2000)



30 per s; Sollerman et al. 2000



A black hole?

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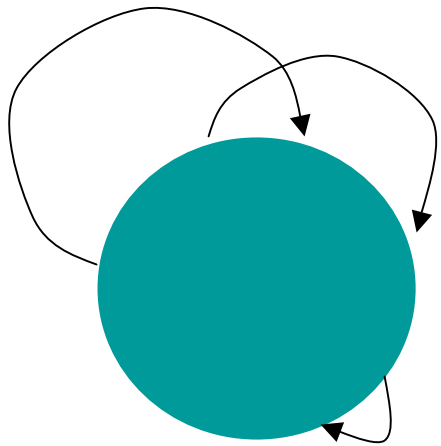
Compact objects out of which no particle or light escapes (Michel 1794, Laplace 1798)

$$H = U + E_k < 0:$$

$$\frac{1}{2}mc^2 - G\frac{mM}{R} < 0$$



$$\Rightarrow \; \mathrm{R} < \mathrm{R_S} = \frac{2GM}{c^2} = 3\left(\frac{M}{M_\Theta}\right)\mathrm{km}$$

Black objects in Newton's of gravitation

Maxwell (1879):

light described by electromagnetic waves with c=3e8m/s

Einstein (1915):

radically new spacetime structure: abandon Newton's absolute space and time and insist that c is *universal*

In this new spacetime gravitation takes on an entirely new character:

(a) black holes as fundamental objects (simplest objects, M,J,Q)

(b) gravitational waves from astrophysical sources & early universe

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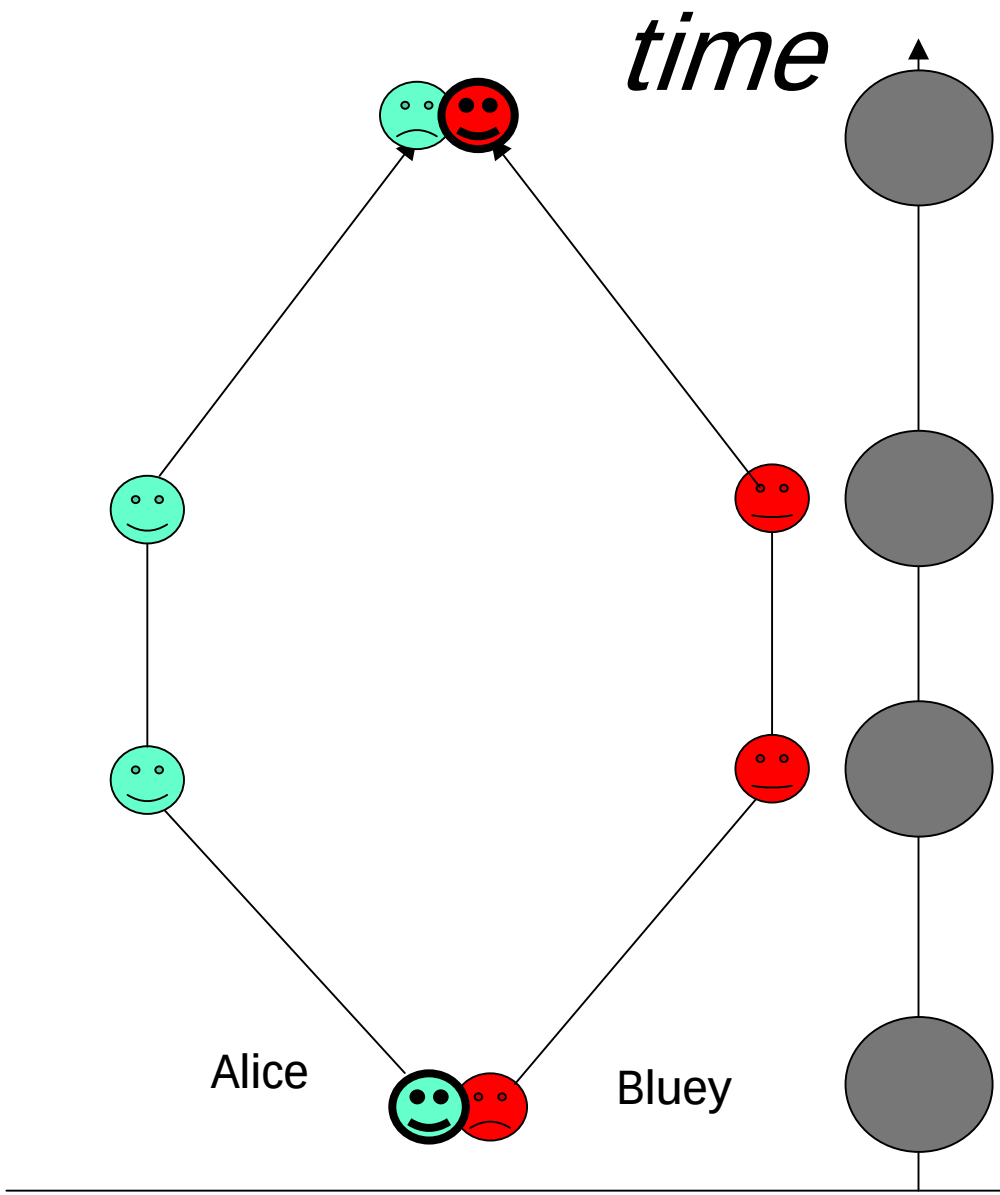
Age reversal between Bluey and Alice



$$\frac{\text{Aging Bluey}}{\text{Aging Alice}} = 1$$

$$\frac{\text{Aging Bluey}}{\text{Aging Alice}} < 1$$

$$\frac{\text{Aging Bluey}}{\text{Aging Alice}} = 1$$

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"Bluey freezes" at Schwarzschild radius $\frac{2GM}{c^2}$

Time stands still on a horizon surface (rel. infinity)

'Frozen stars' are compact and black : black holes

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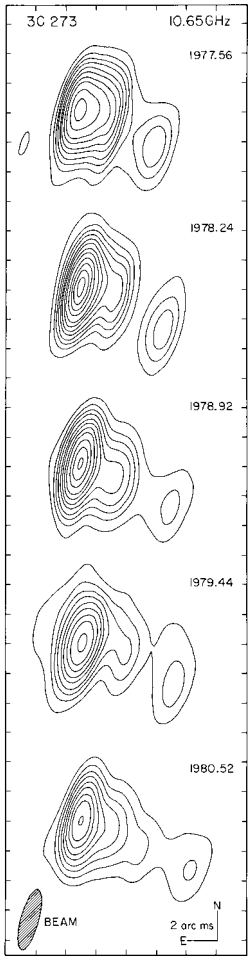
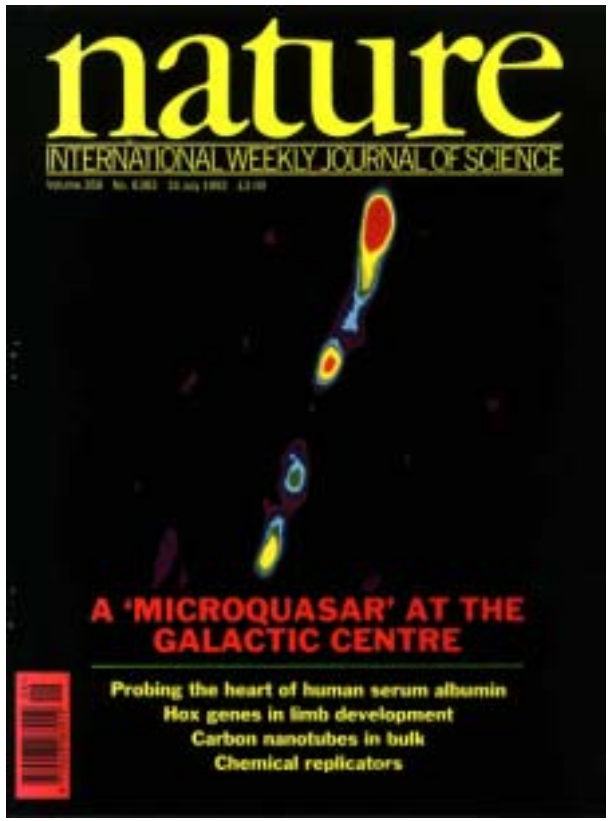
Rotating black holes as active nuclei in the universe



Quasar 3C273
(Pearson et al 1981)

Supermassive BHs

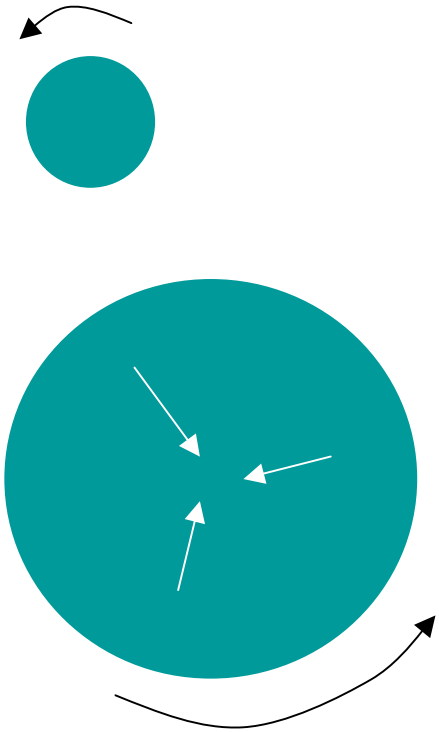


Mirabel & Rodriques 1992

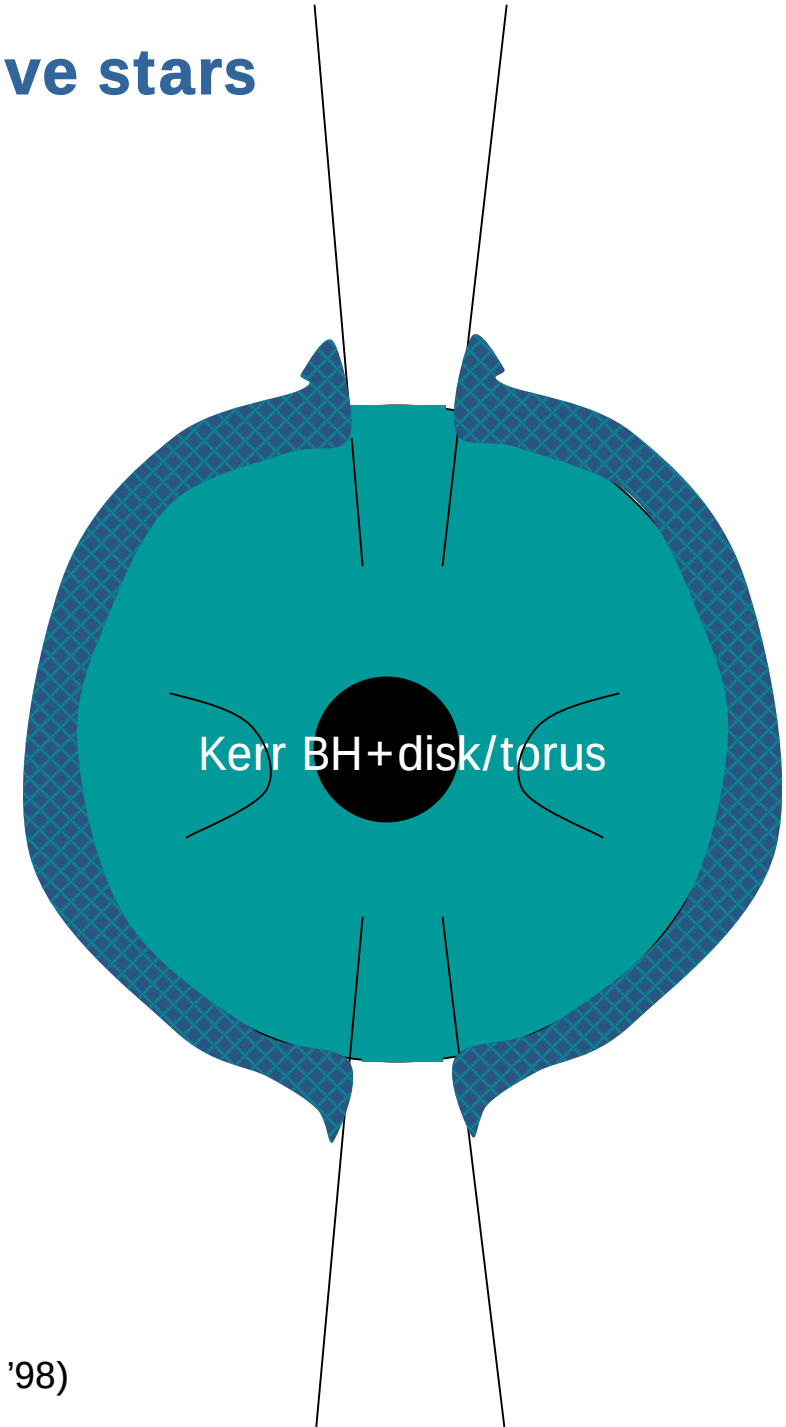
Stellar mass black holes

Rotating (Kerr) black holes store up to 29% of mass-energy in rotation

Kerr BH in core-collapse of massive stars in binaries

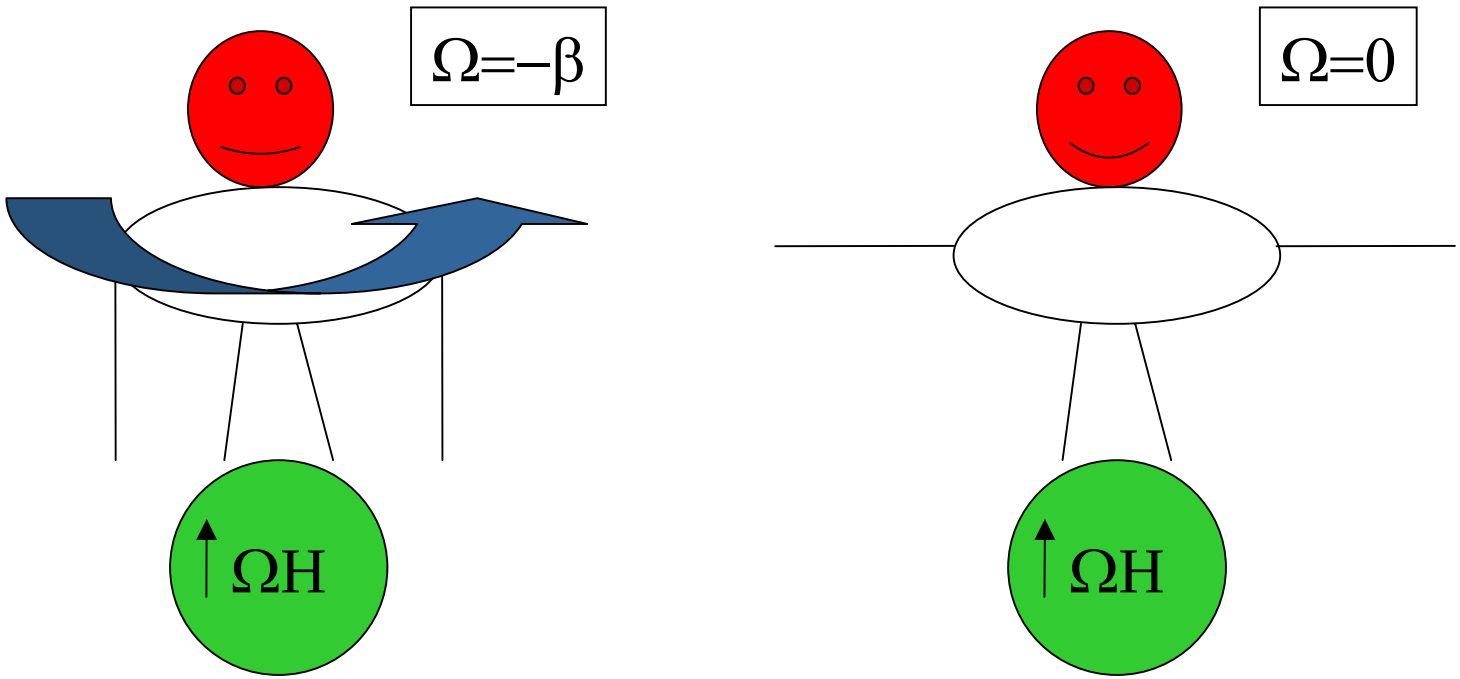


Core-collapse in binary
Woosley(1993)
Paczynski(1998)
Brown et al.(2000)

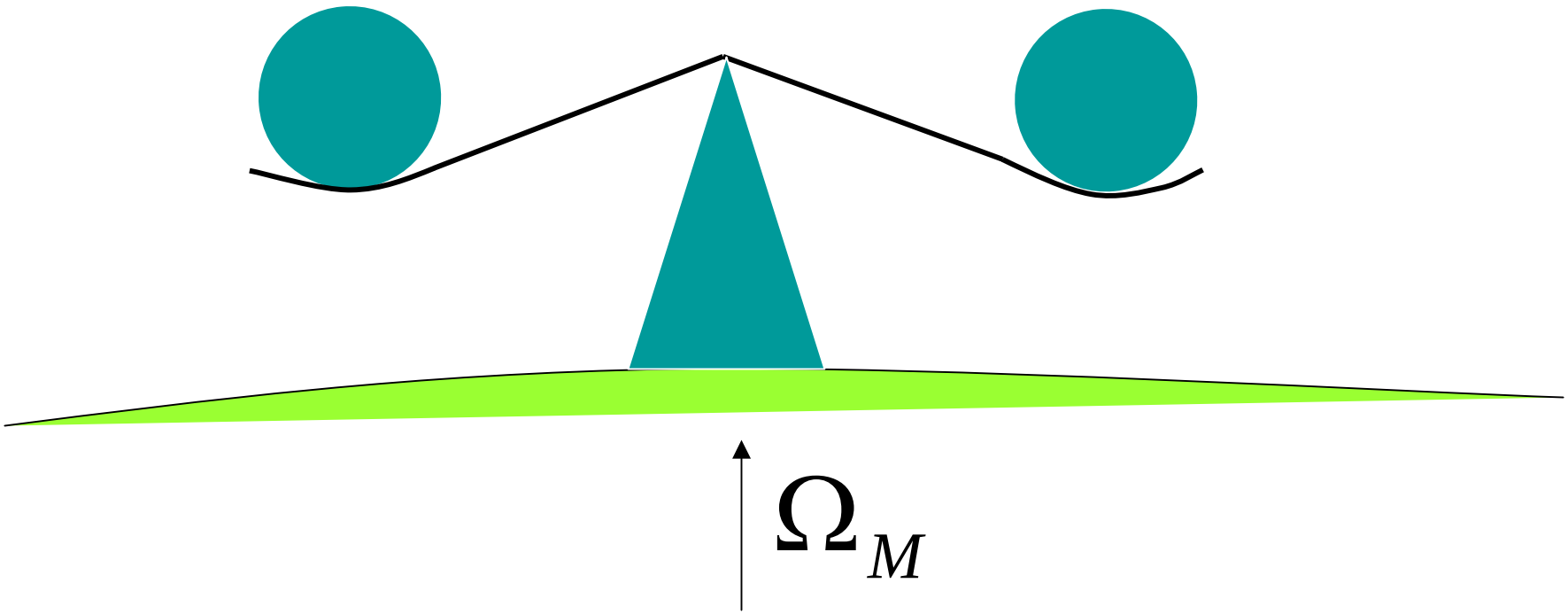


Jet penetrating remnant stellar envelope (McFadyen & Woosley '98)

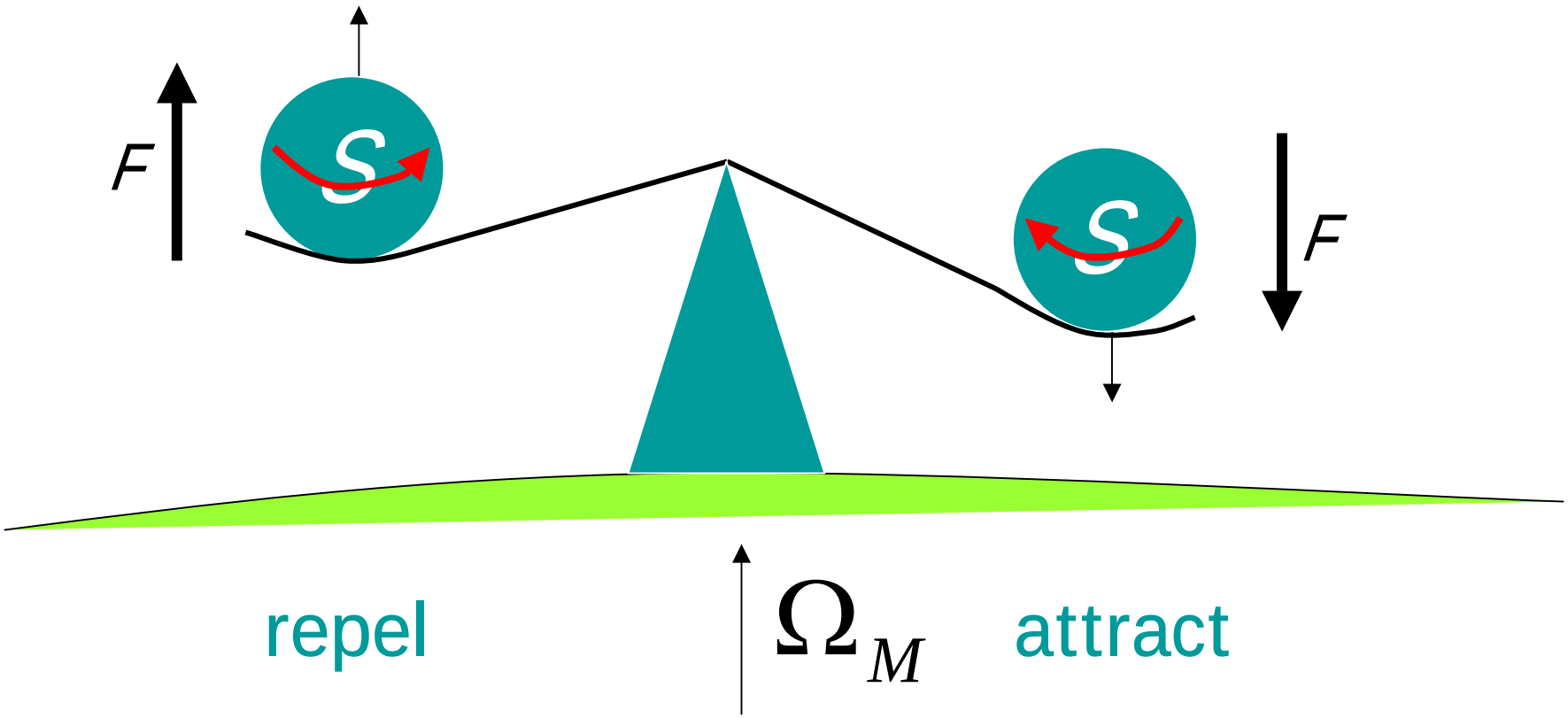
Rotating black holes: frame-dragging (Kerr 1963)



Spin-angular momentum interactions



Spin-angular momentum interactions



$\Rightarrow$ Black hole-luminosities by shedding like-angular momentum to infinity (consistent with Rayleigh criterion)

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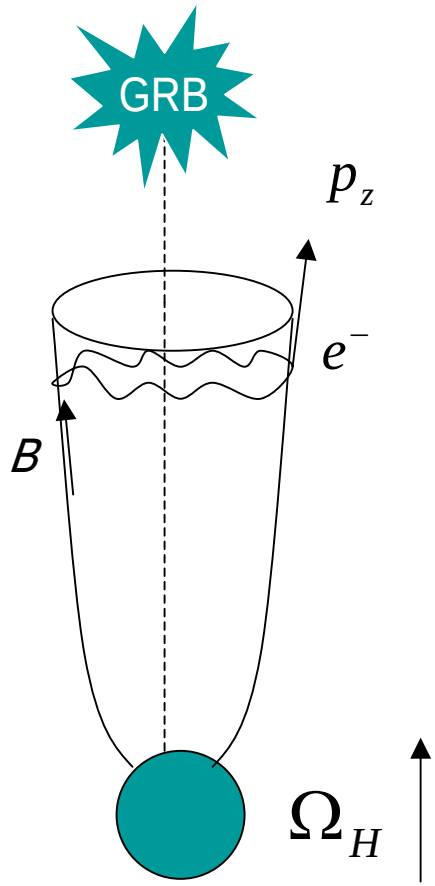
GRB from spin-orbit coupling to charged particles

$$\nu = eA_{\varphi} \propto B$$

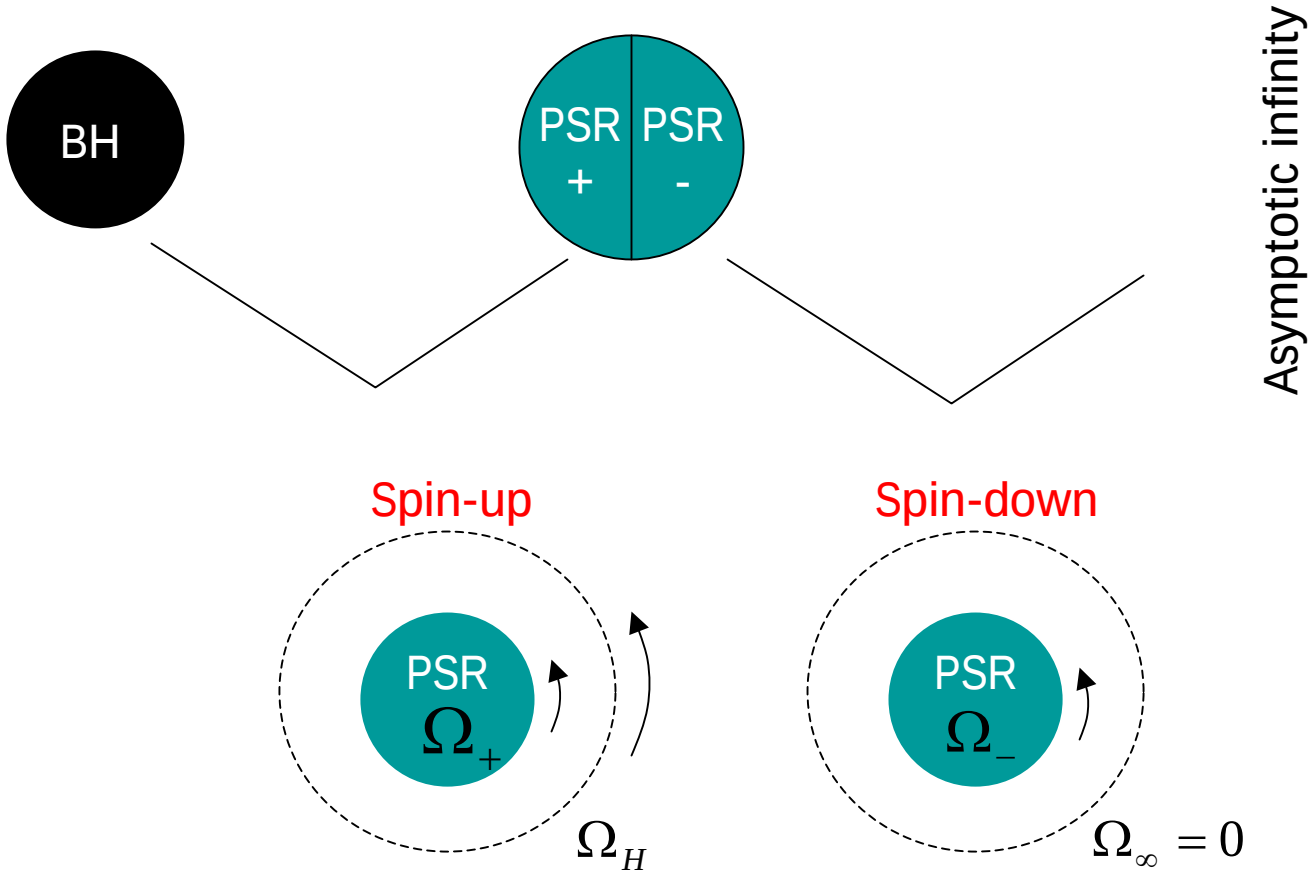
$$eEMF = \nu_p \Omega_H$$



E=p-angular momentum * BH-angular velocity

Van Putten 2000
Hawking 1975
Wald 1974

Suspended accretion by spin-connection black hole-to-torus



The torus catalyzes most of black hole-spin energy, reaches MeV-temperatures and radiates into various channels

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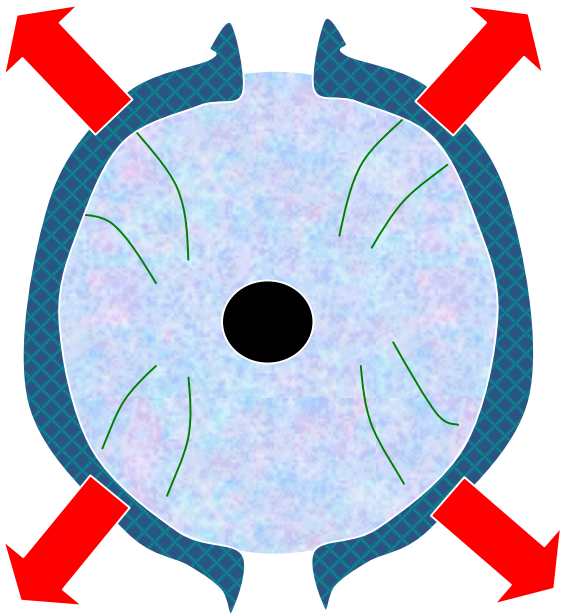
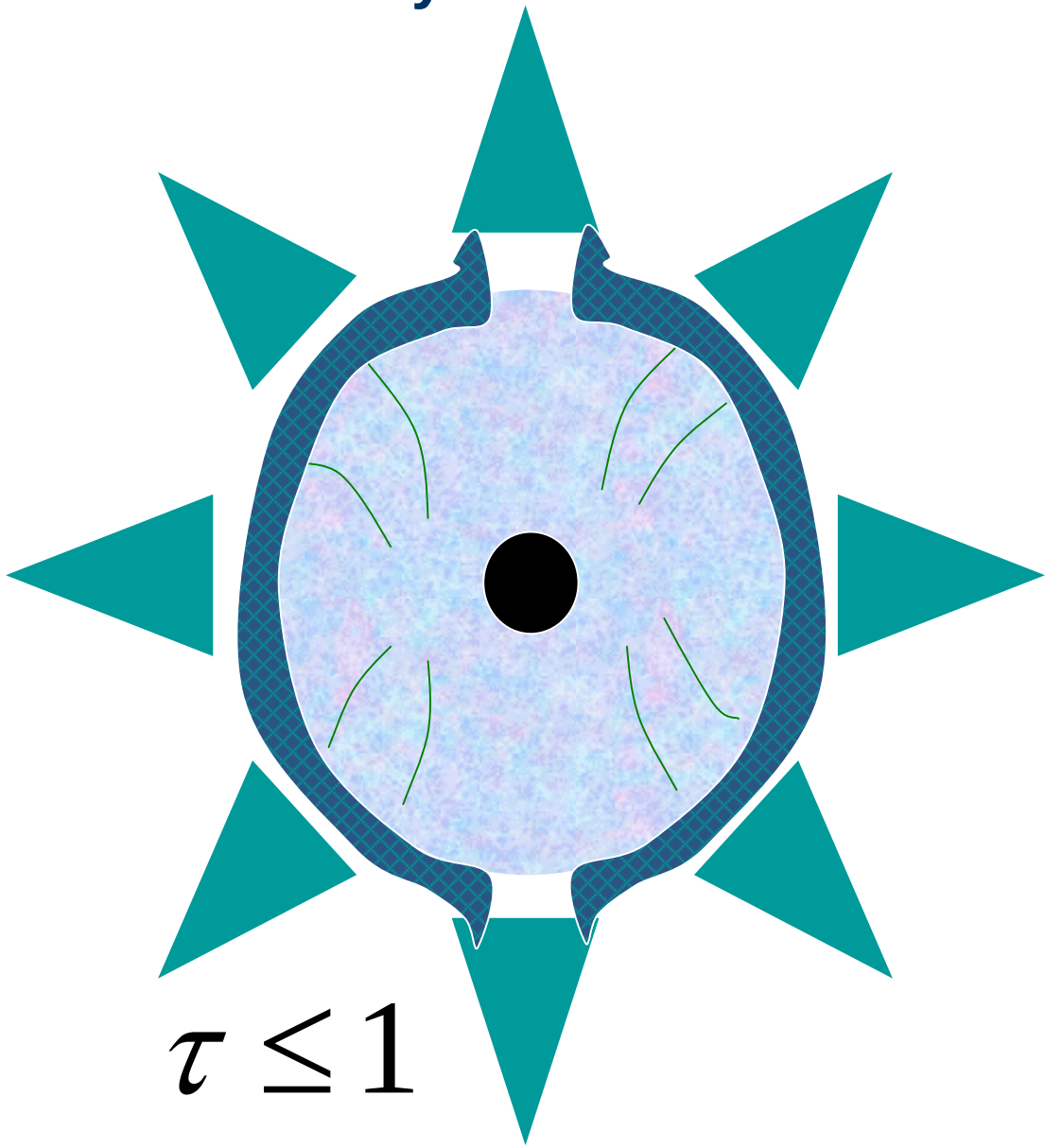
Creating a supernova with X-ray line-emissions



$\tau >> 1$



$\tau \leq 1$

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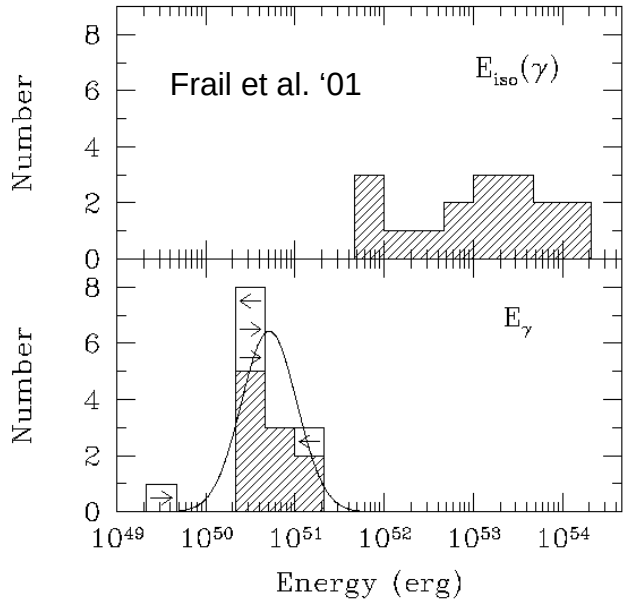
Observed energies:

$$E_{\gamma} \cong 1.5\times10^{-4} M_{Solar} \text{ (Frail et al. 2001)}$$

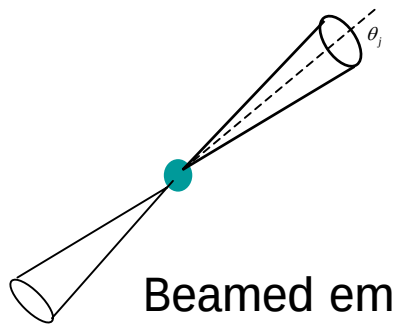
$$E_{SN} \cong 1\times10^{-3} M_{Solar} \text{ (Hoeflich et al.1998)}$$



Modeling GRBs from rotating black holes:

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

$$E_{rot} = 1-4 M_{Solar}$$



Beamed emissions

Where does most of the rotational energy go?

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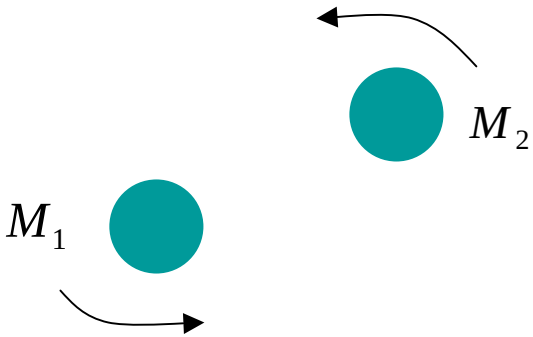
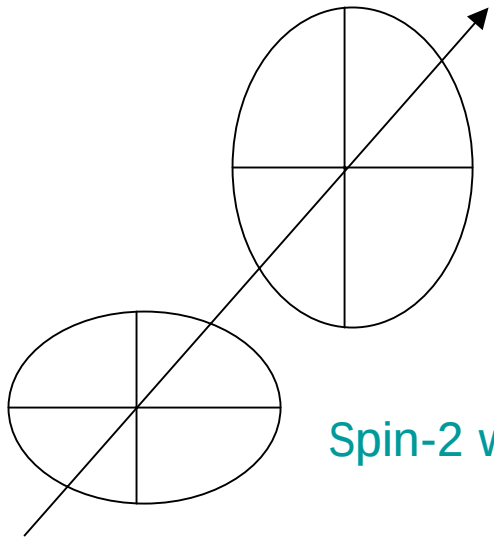
Gravitational radiation



PSR 1913+16

Hulse & Taylor 1974

$$L_{gw} = 3.2 \times 10^{33} \text{ erg s}^{-1}$$



Spin-2 waves

Theory agrees with observed orbital decay to within 0.1%: Nobel Prize 1993

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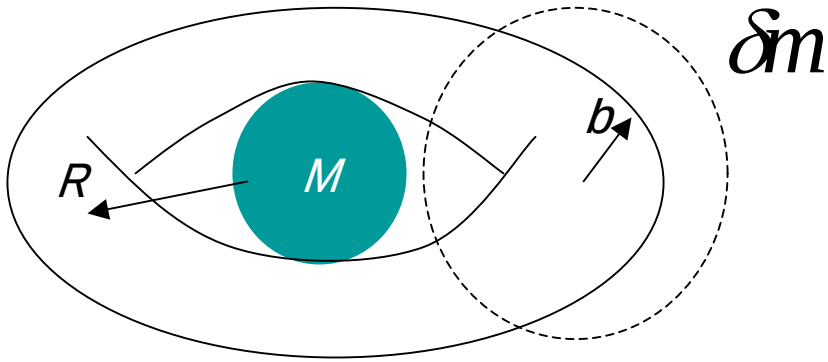
Radiation by mass-inhomogeneities around a BH



Quadrupole mass-moments by Papaloizou-Pringle waves when the torus is slender:

$b/R<0.3260$

Van Putten 2002

Good source of GWs?

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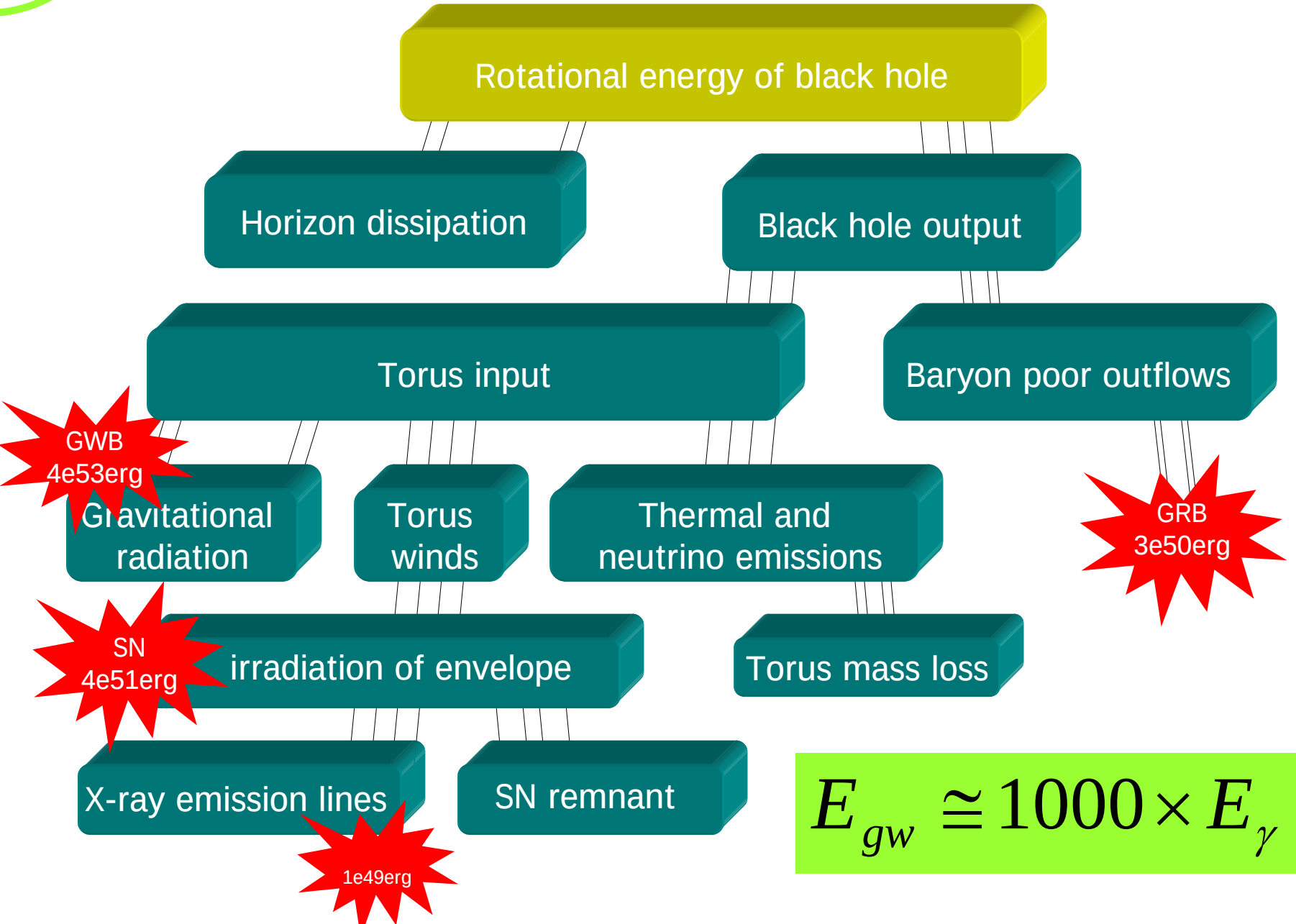
Radiation energies



$$E_{gw} \cong 1000 \times E_{\gamma}$$

LIGO Hanford site, WA

An ACIGA-LIGO Collaboration

+ similar LIGO Livingston, LA
+ similar VIRGO in Pisa, Italy

The Australian International Gravitational Observatory (AIGO)

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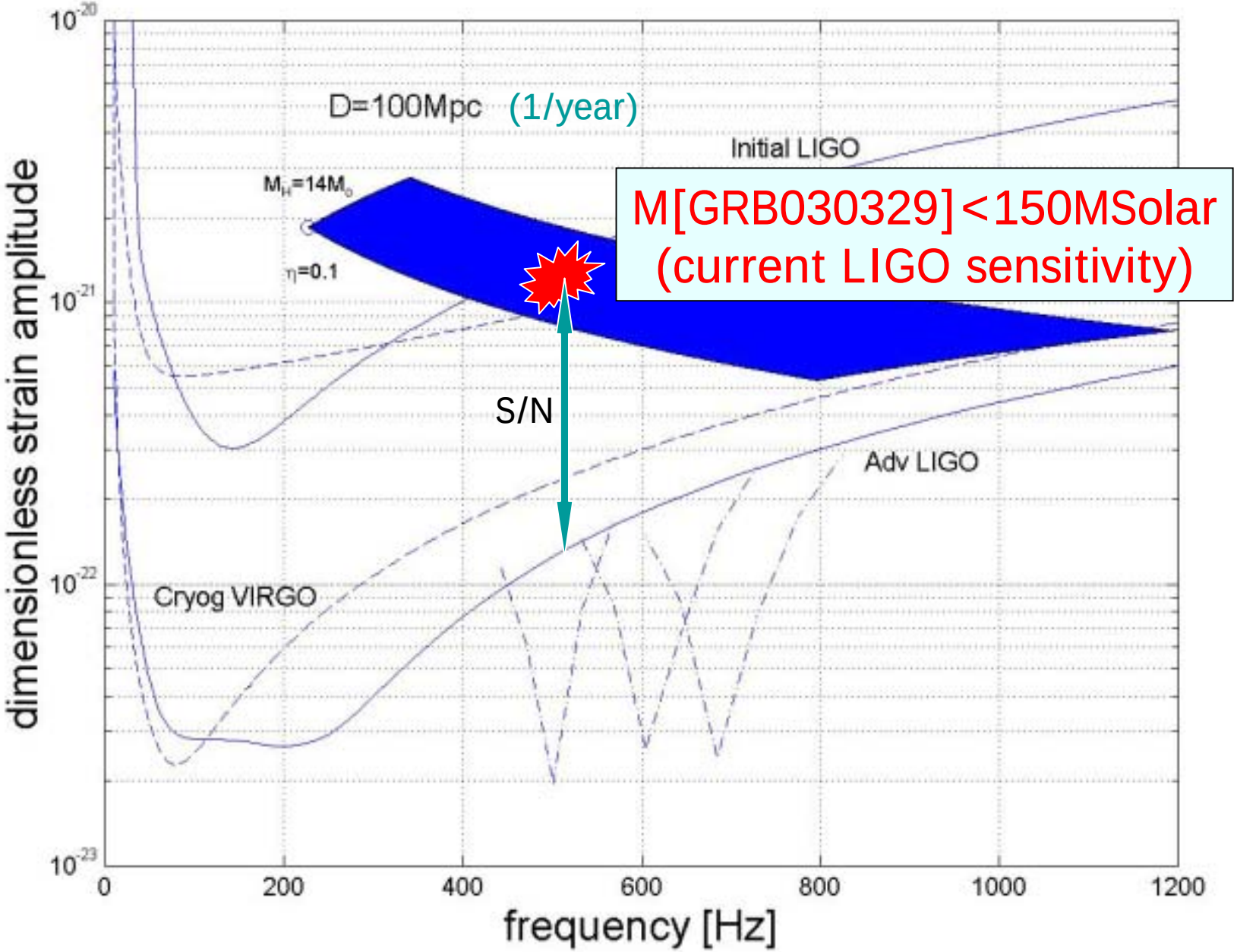
D=100Mpc (1/year)
Initial LIGO
M_H=14$M_\odot$
η=0.1
M[GRB030329]<150MSolar
(current LIGO sensitivity)
S/N
Adv LIGO
Cryog VIRGO
dimensionless strain amplitude
frequency [Hz]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
0
200
400
600
800
1000
1200

LIGO

Simulation: instantaneous S/N-ratio = 0.15

D1

LIGO

Simulation: instantaneous S/N-ratio = 0.15

LIGO

Simulation: instantaneous S/N-ratio = 0.15

D1 D2 D1*D2

LIGO

Credits...

Collaborators:

Amir Levinson (Tel Aviv)
Hyun Kyu Lee (Hanyang U)
Chul H. Lee (Hanyang U)
Hongsu Kim (SNU)
Tania Regimbau (MIT-LIGO)
Gregory M. Harry (MIT-LIGO)
Michele Punturo (VIRGO, INFN)
Eve C. Ostriker (U Maryland)
David Coward (UWA)
Ronald Burman (UWA)

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Conclusions

Observations: GRBs originate in supernovae of massive stars – this solves the GRB-mystery!

The inner engine of GRB-SNe remains to be observed

Theory: GRB-SNe from rotating black holes:

- Kerr black holes in core-collapse of massive stars in binaries (Woosley, Paczinski, Brown)
- Kerr black holes may be luminous by shedding large amounts of energy in angular momentum

GRBs produced by spin-orbit interactions around rotating black holes
Powerful torus emissions produced by black hole-spin energy

Van Putten 2000
Hawking 1975
Wald 1974

We have determined:

Most of black hole-luminosity is catalyzed into gravitational radiation (0.2MSolar@500Hz)
A minor output produces an aspherical supernova (0.1% in kinetic energy)
A small fraction GRB-emissions (0.01%)

Upcoming gravitational wave-experiments (2008-) promise to be exciting:

LIGO Hanford

VIRGO Pisa

first-ever detections of gravitational radiation
observe the Universe in gravitational waves (new sources, relic waves early universe,...)
probe inner engines of GRB-SNe
observe ‘life’ the process of spin-down of Kerr black holes within one minute
test general relativity,...

ACIGA-LIGO
Gingin

Questions/discussion:

1. Audience: Type of SNe associated with GRBs
2. Ian MCarthur (UWA): Origin of beaming
3. Igor Bray (IAP): status of gravity
4. van Putten: TeV-gravity in early universe

Formation of active nucleus and beamed outflows