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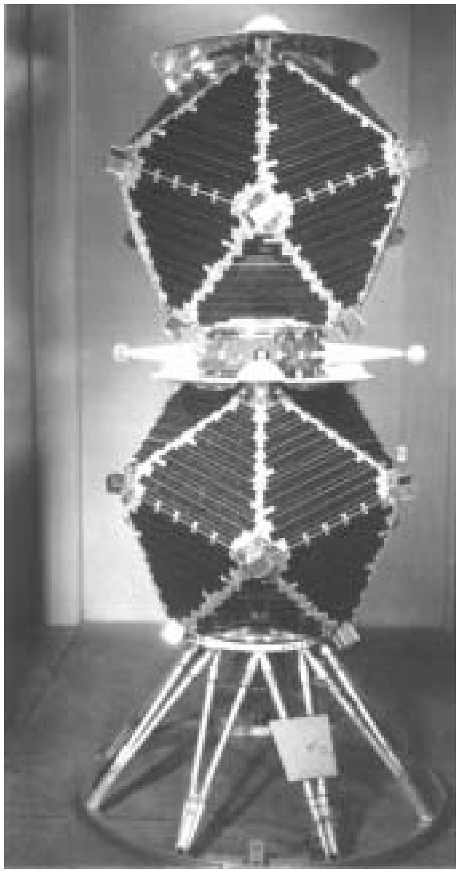
# Black holes, gamma-ray bursts and gravitational waves

Maurice H.P.M. van Putten

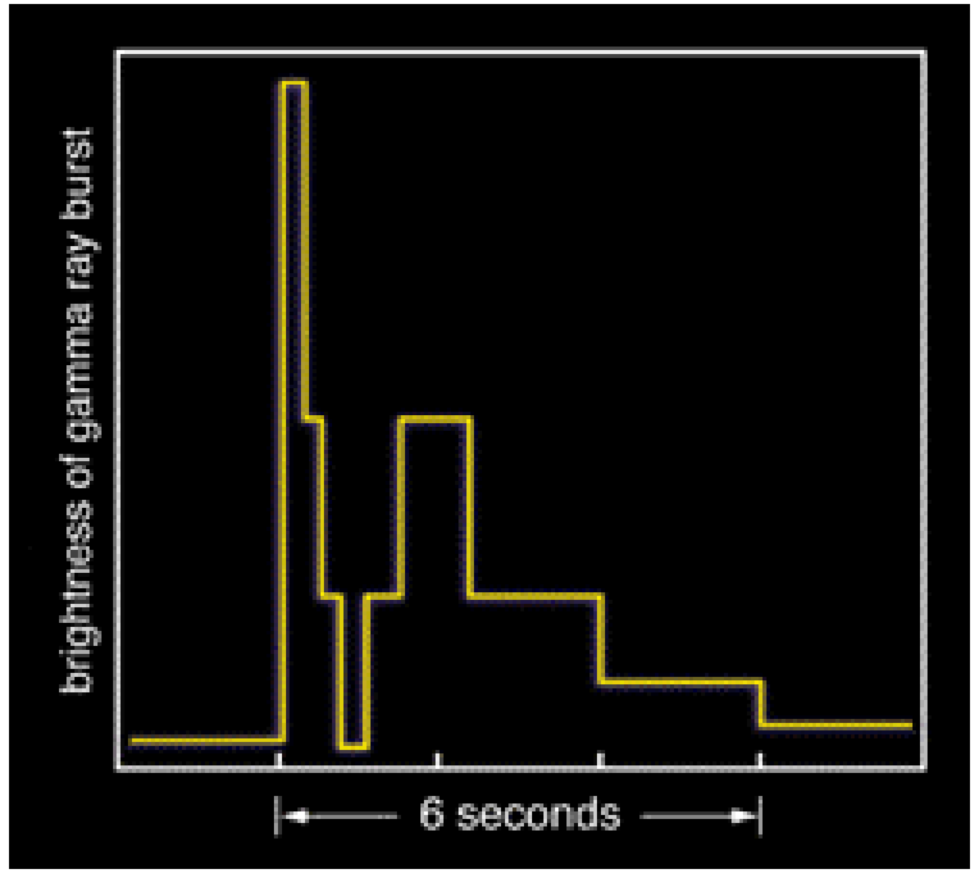
A public lecture

sponsored by ACIGA & AIP 2003

# Vela/Konus (1963-1979)

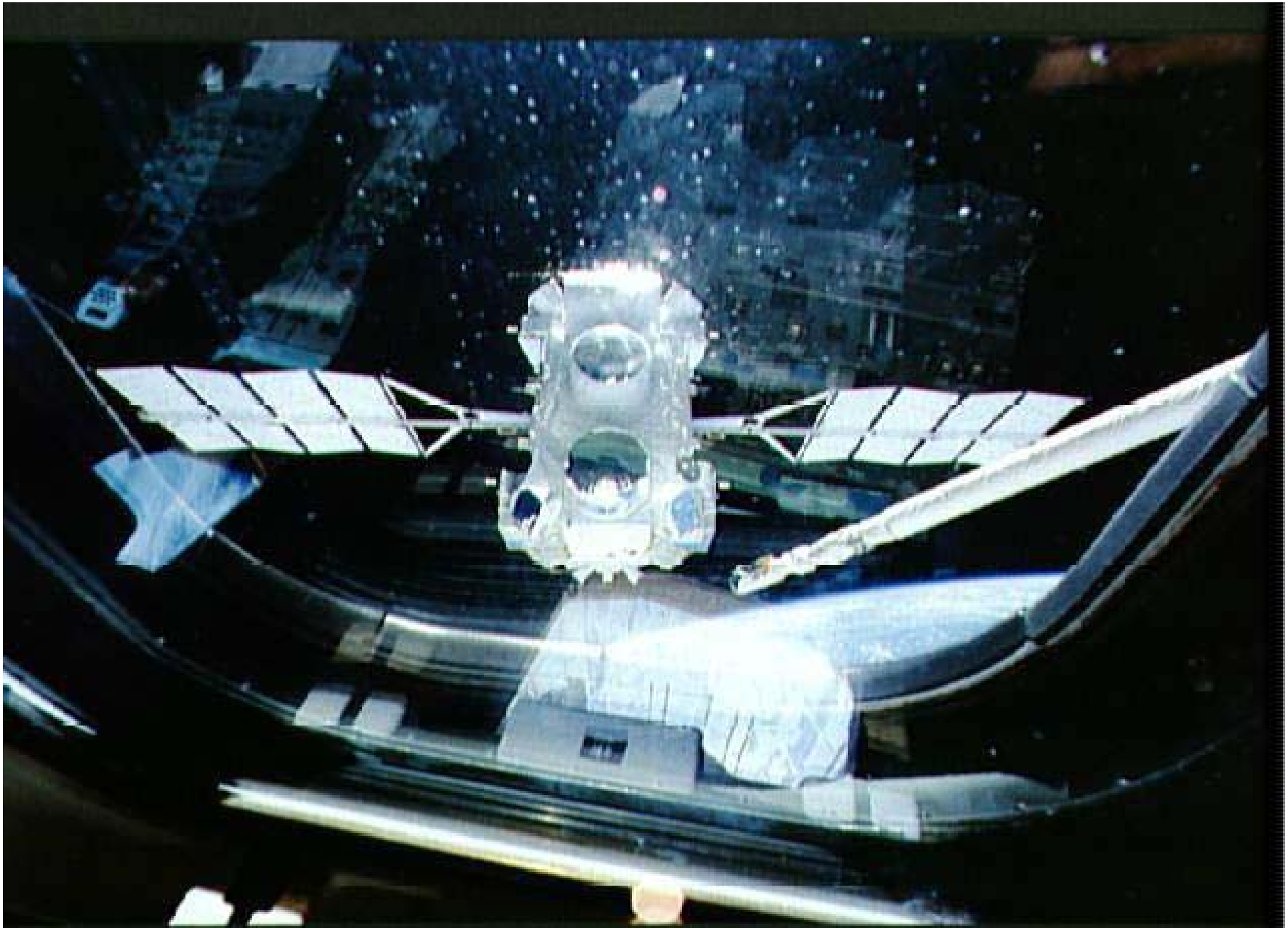


Vela




GRB670702 (Klebesadel & Olson)

# BATSE (1991-2000)



BATSE on the CGRO (NASA)

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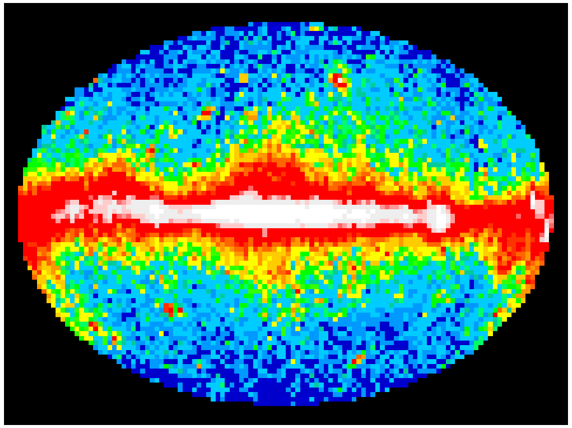
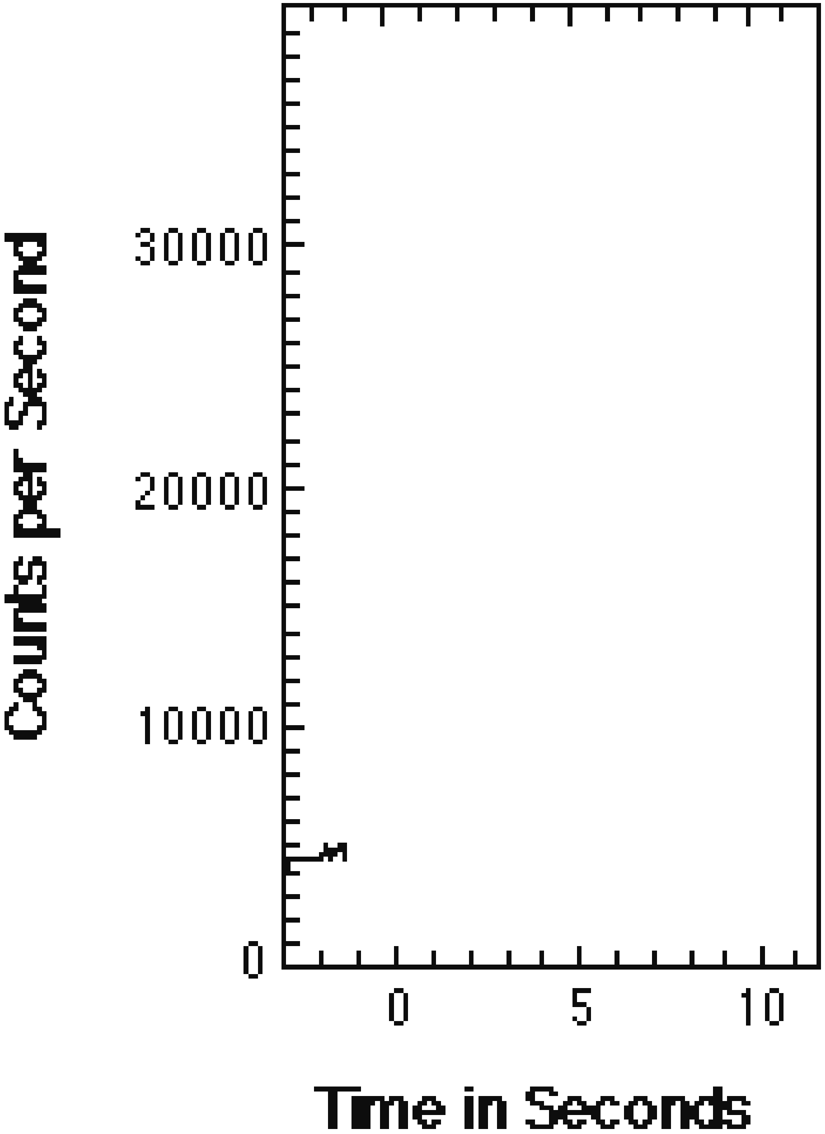
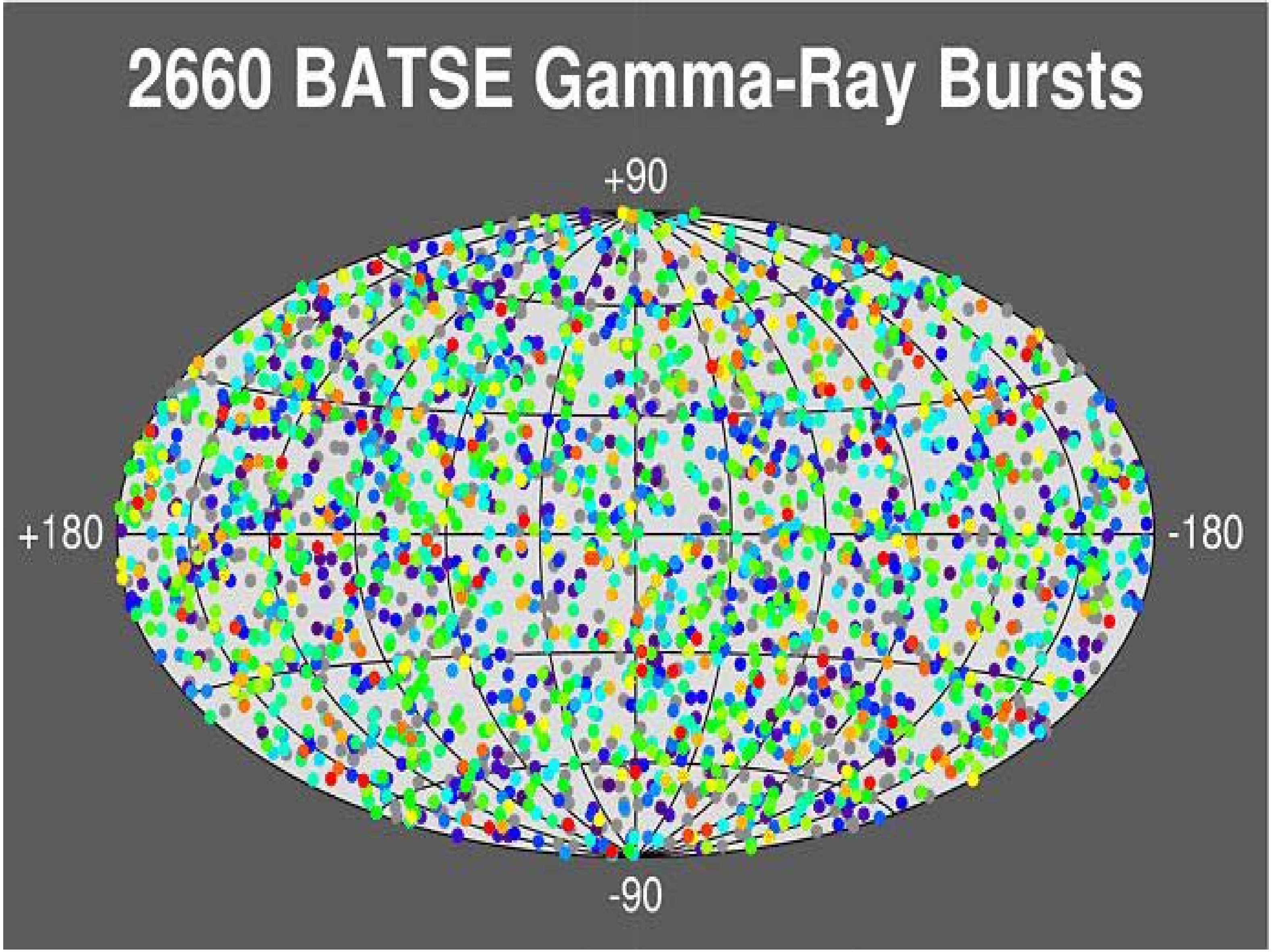




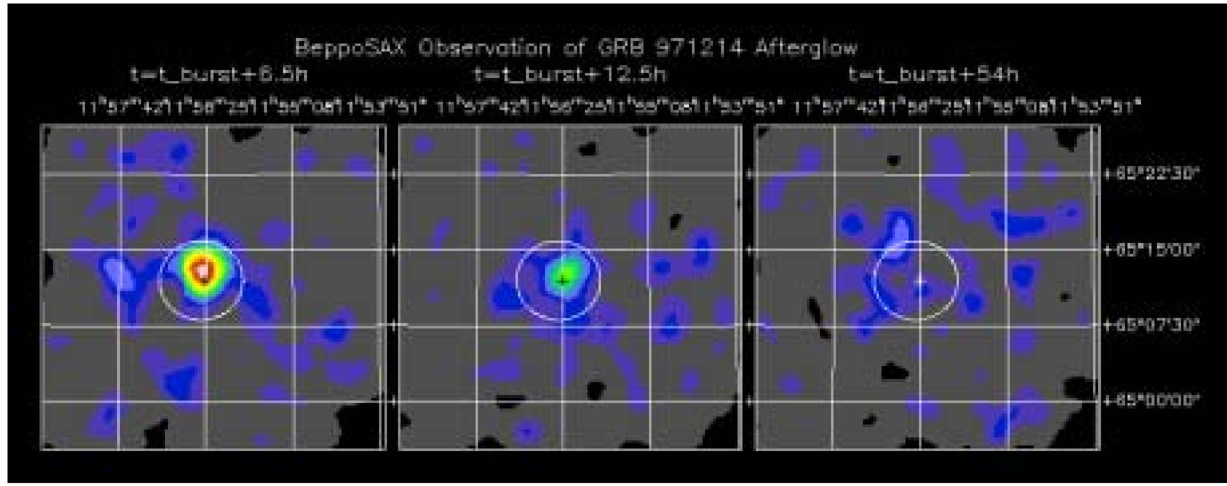

BATSE Group, NASA
http://image.gsfc.nasa.gov/docs/science/know_l1/bursts.html

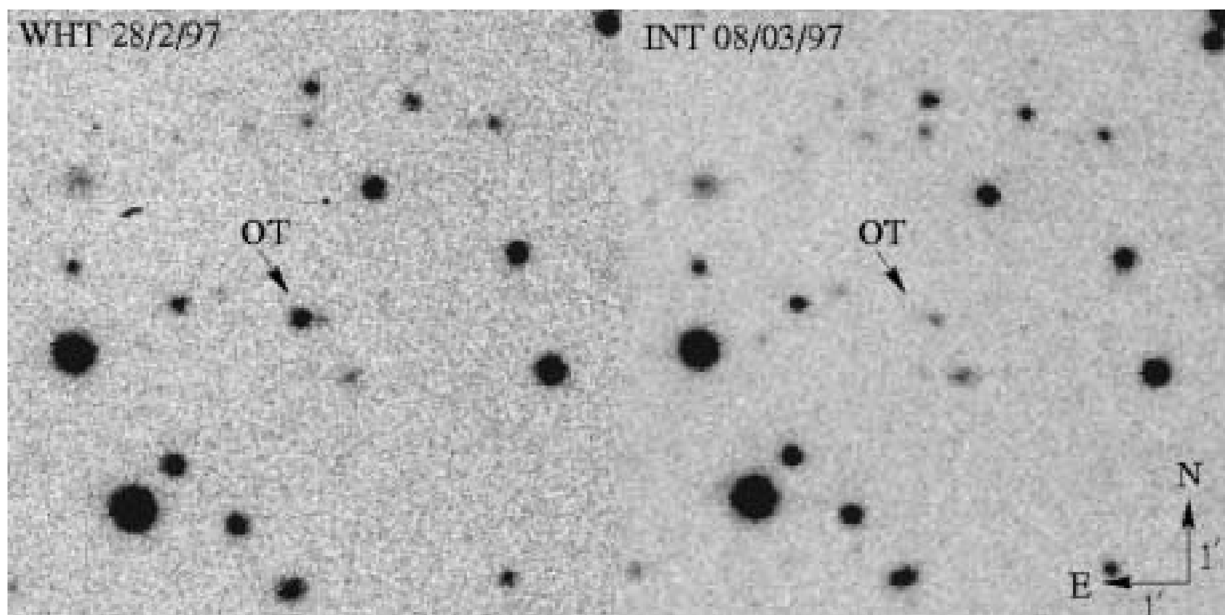



Cosmological origin: isotropic energy emissions up to 1MSolar

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

GRB971214 z=3.418




GRB970228 z=0.695

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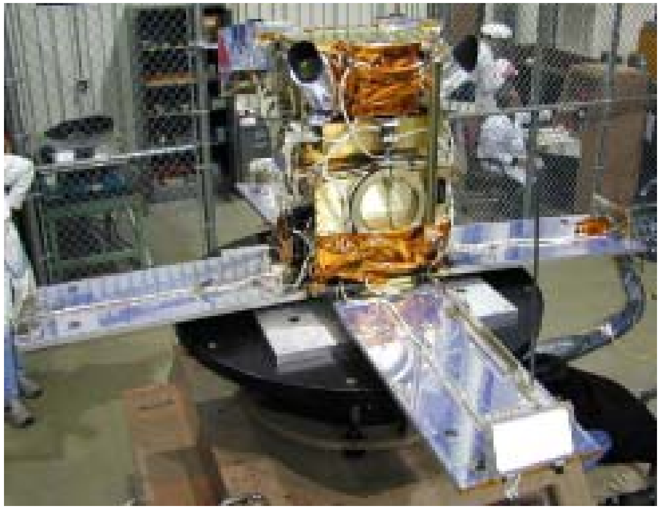
# GRBs with known redshifts

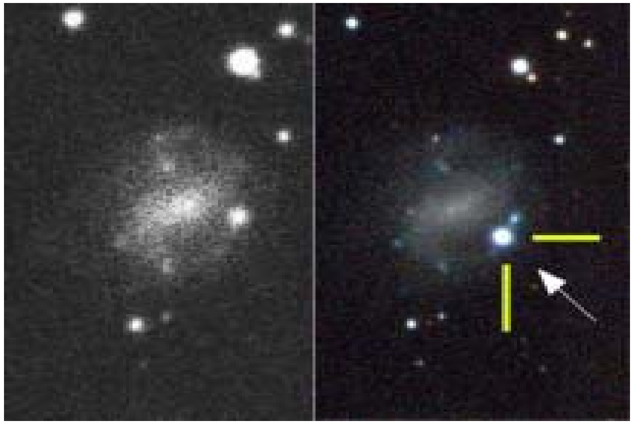


HETE-II

| 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 |
| 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 <- very nearby! |

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)

# GRB association to supernovae



SN1998bw (ESO, 1998)
Galama et al. 1998

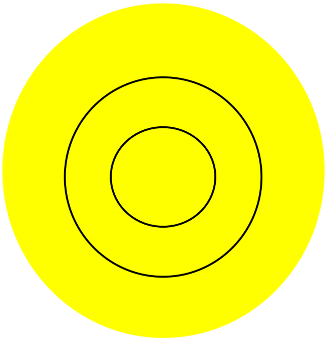
GRB030329/SN2003dh
(z=0.168, D=800Mpc)

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

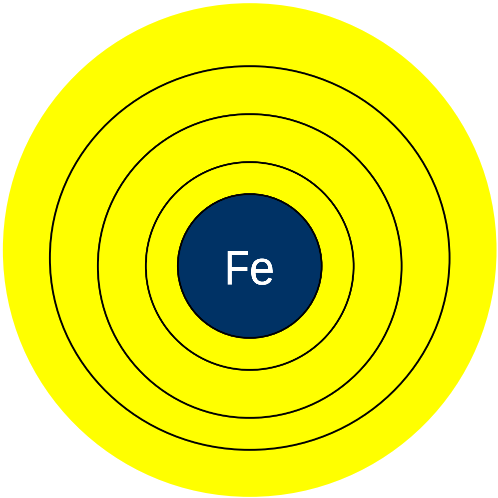
Stanek, K., et al., 2003
(also: Garnavich et al. 2003,
Hjorth et al. 2003)

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

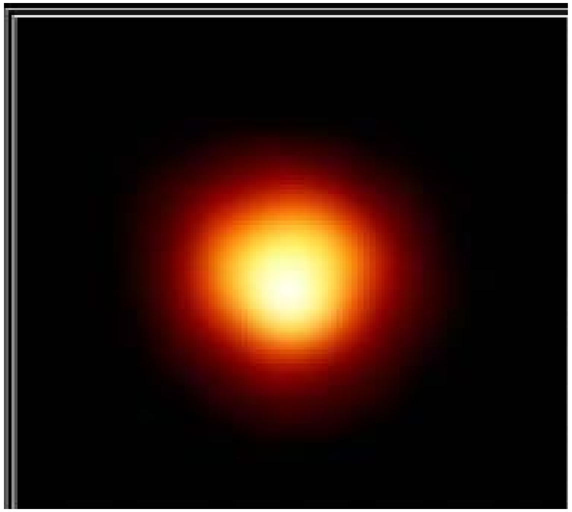
Beyond Chandrasekhar limit, further collapse into a neutron star (Landau)

Shock rebounce produces a supernova plus a burst in neutrinos

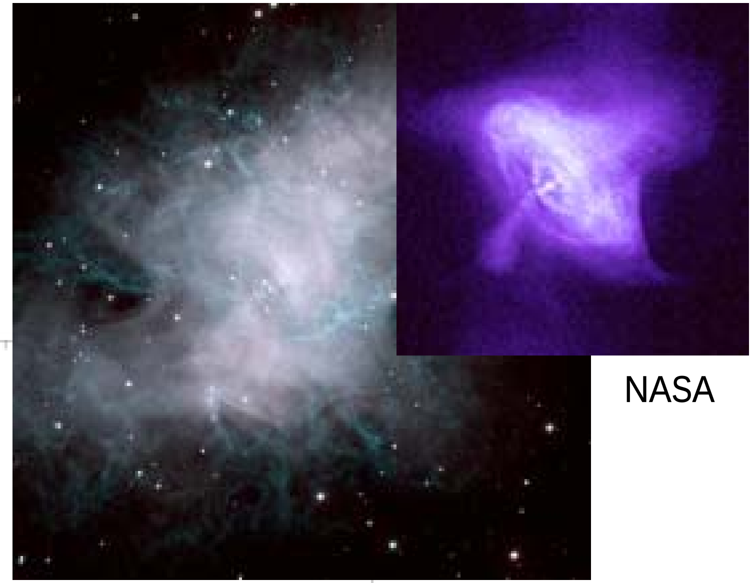
Exceeding the neutron star mass limit leaves a black hole – the most compact object

# Compact objects formed in supernovae of massive stars

Betelgeuse: 20 MSolar

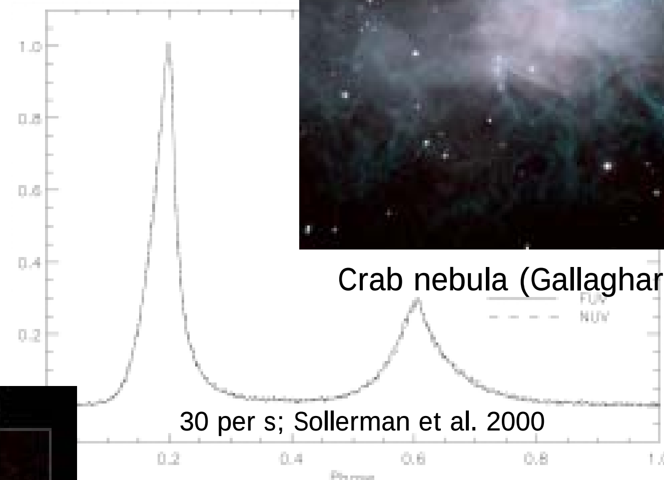


Dupree & Gilliland 1999

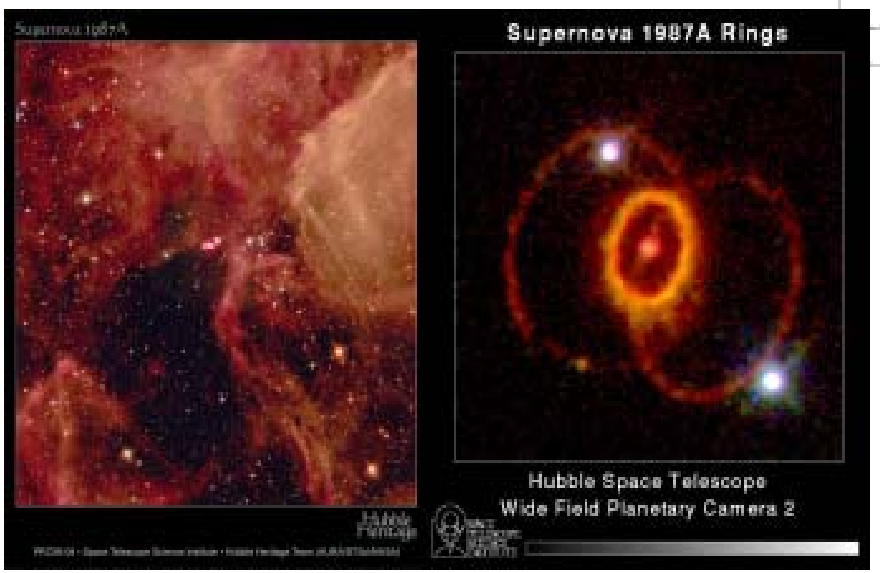


NASA

Crab nebula (Gallaghar et al. 2000)




30 per s; Sollerman et al. 2000



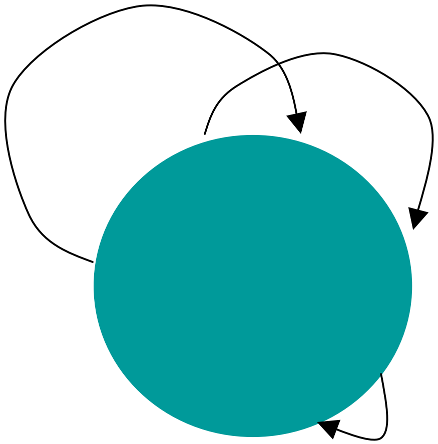

*A black hole?*

# 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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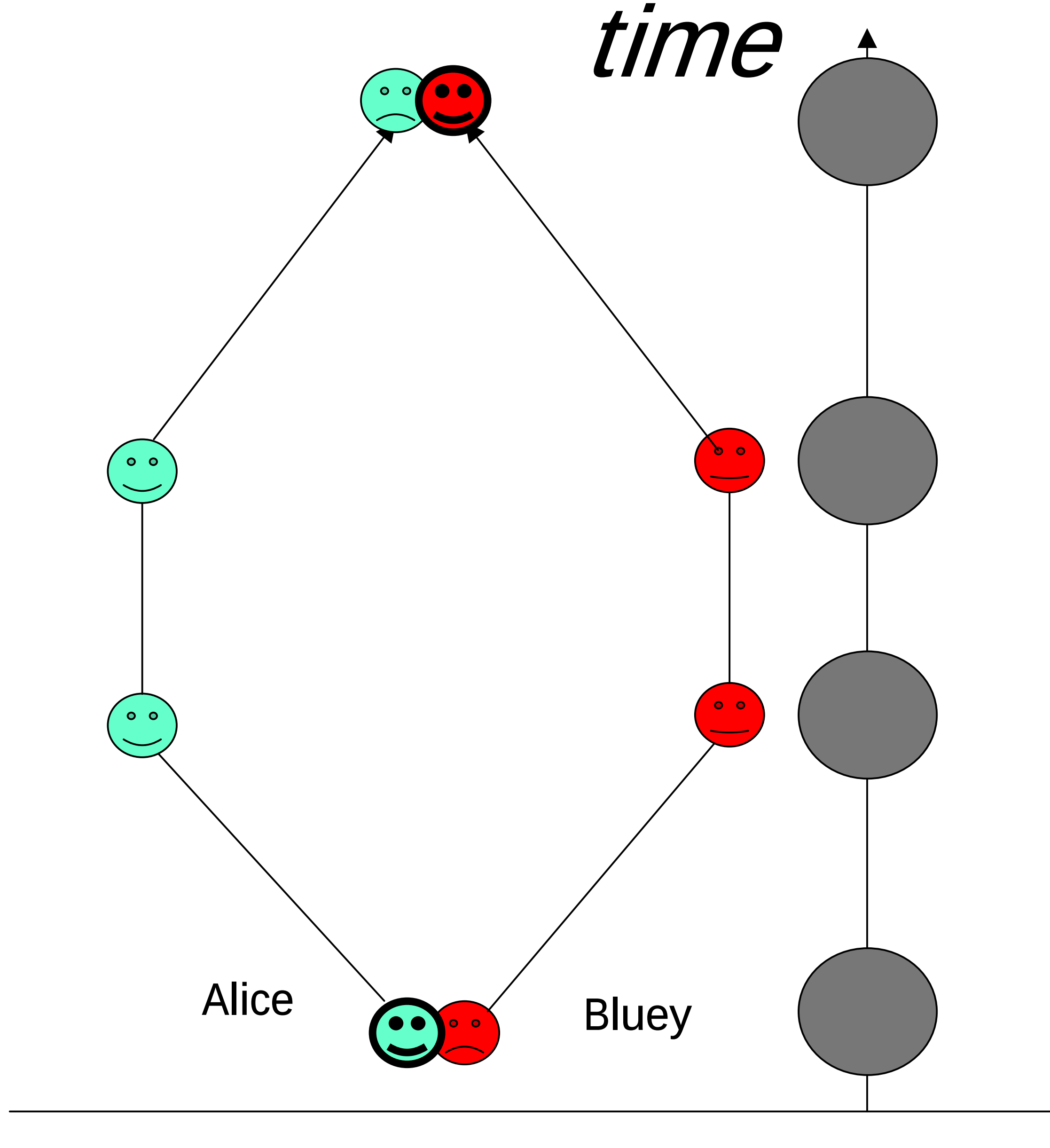
# Age reversal between Bluey and Alice




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

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

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

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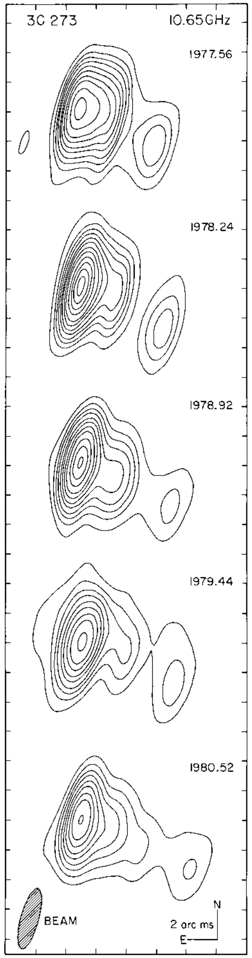
"Bluey freezes" at Schwarzschild radius $\frac{2GM}{c^2}$

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

'Frozen stars' are compact and black : black holes

# Rotating black holes as active nuclei in the universe




Quasar 3C273
(Pearson et al 1981)

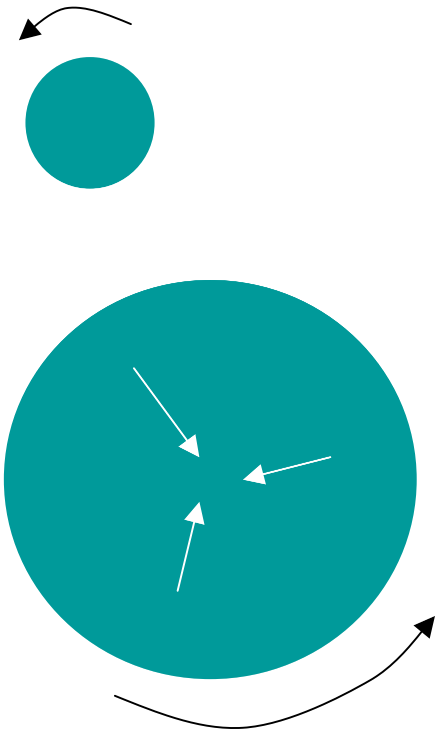
Supermassive BHs


Mirabel & Rodriques 1992

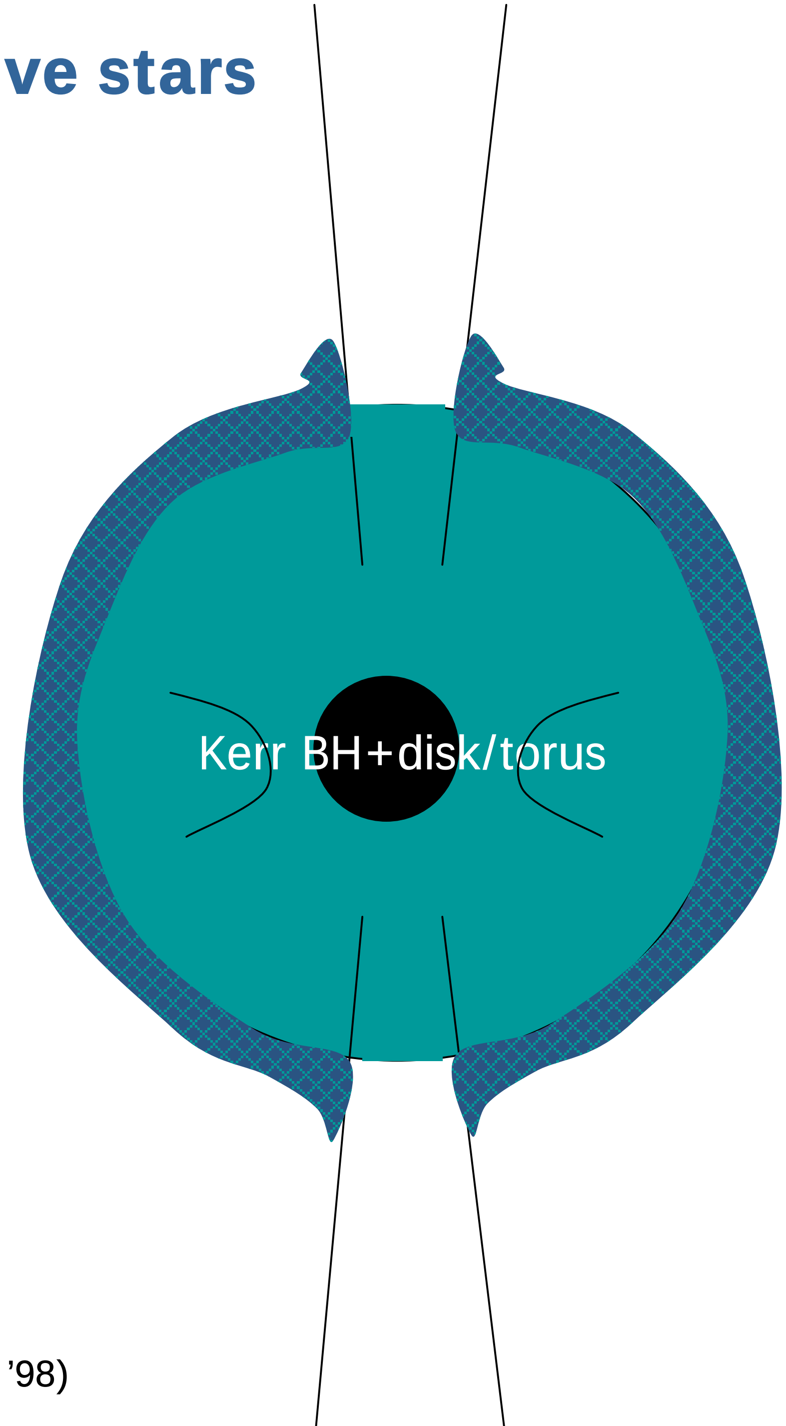
Stellar mass black holes

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

# Kerr BH in core-collapse of massive stars in binaries

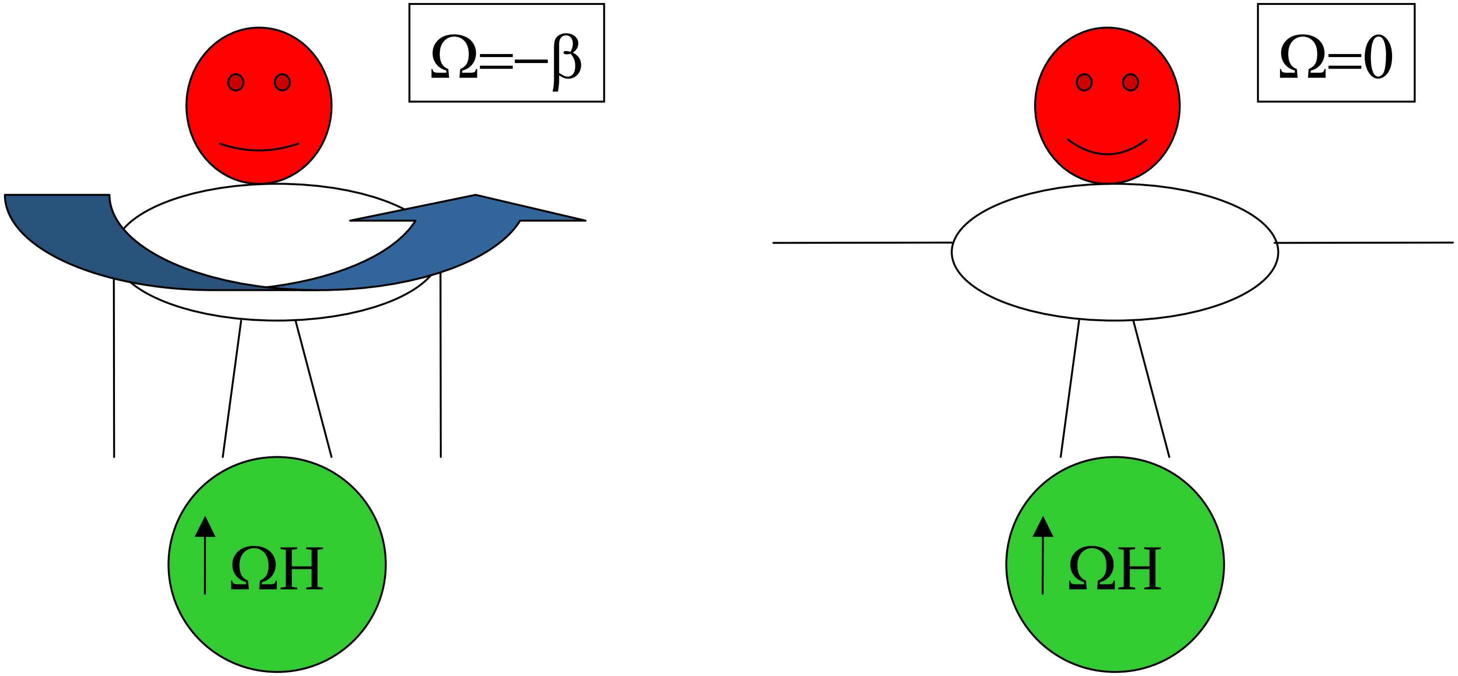


Core-collapse in binary
Woosley(1993)
Paczynski(1998)
Brown et al.(2000)

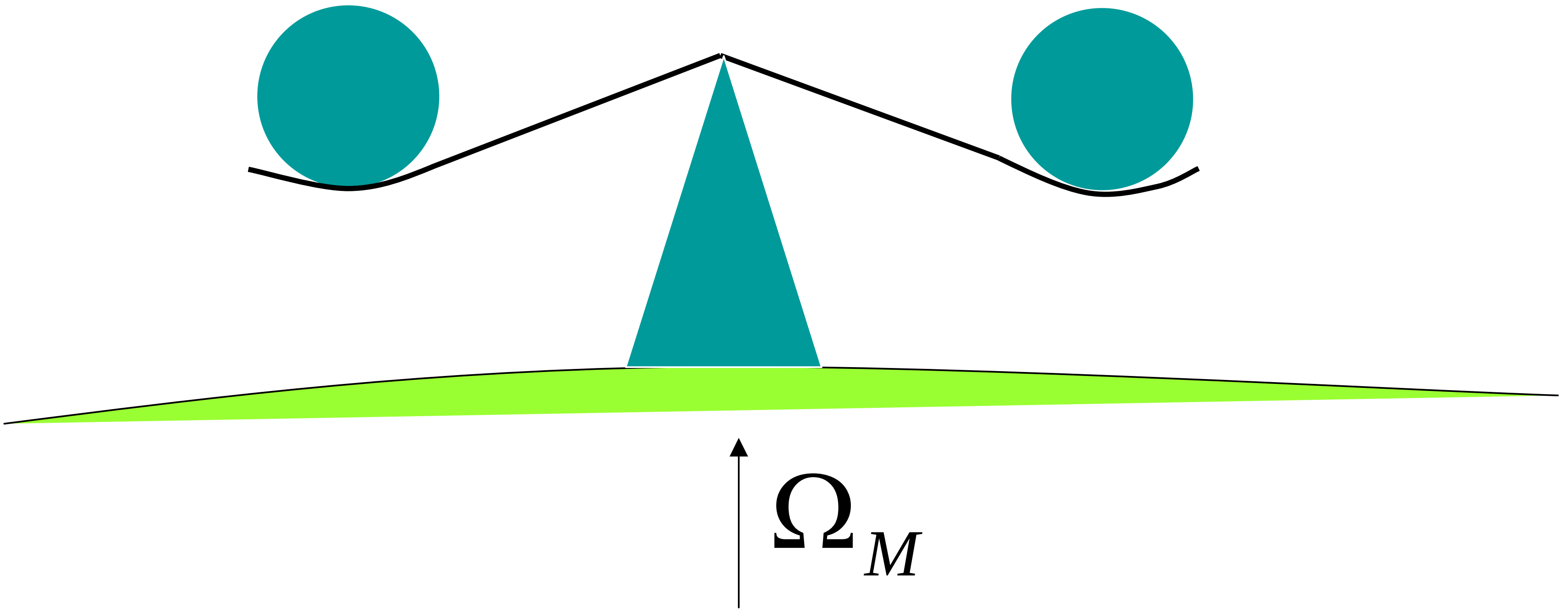



Jet penetrating remnant stellar
envelope (McFadyen & Woosley '98)

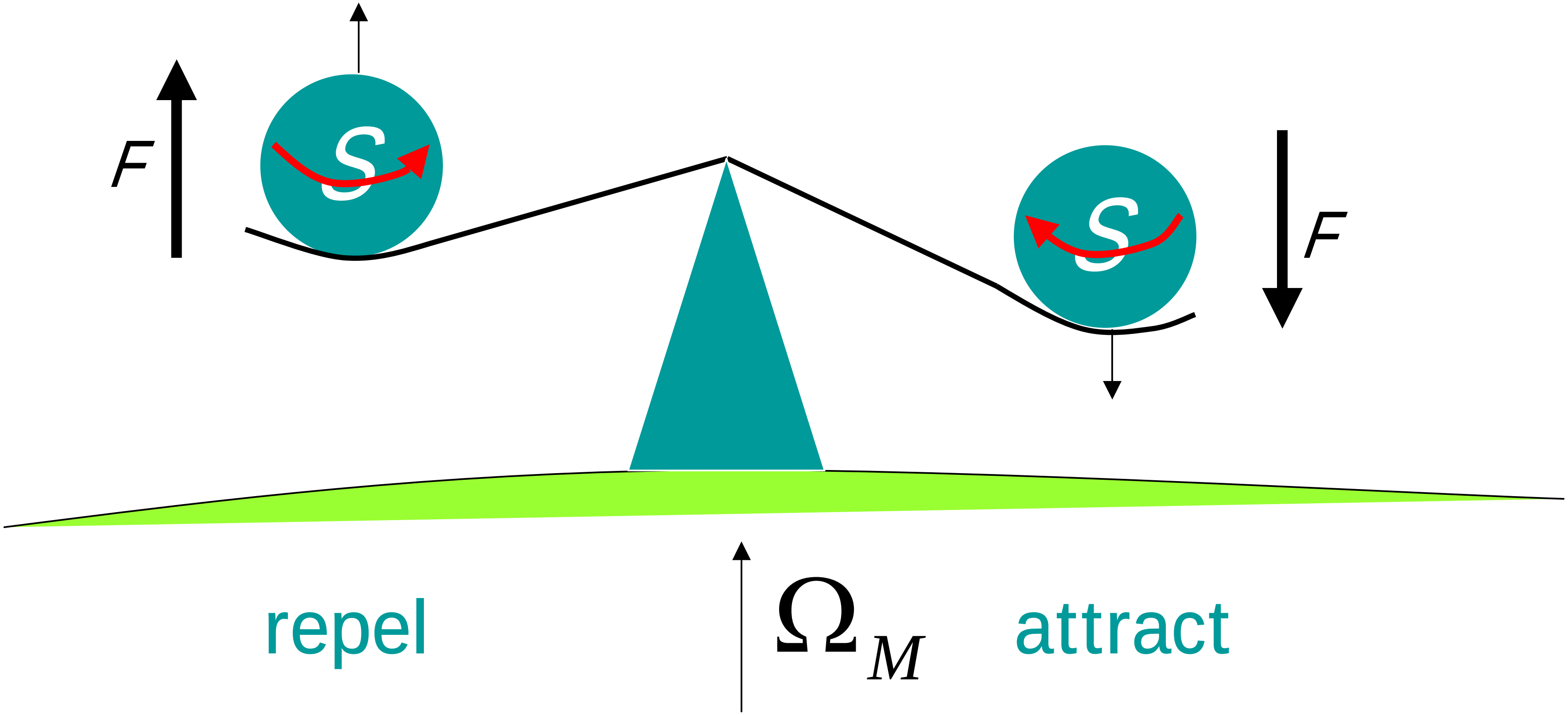
# Rotating black holes: frame-dragging (Kerr 1963)



# 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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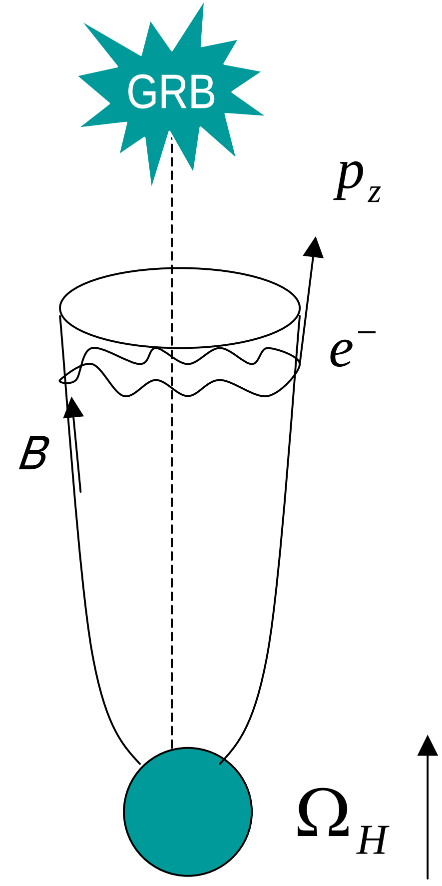
# GRB from spin-orbit coupling to charged particles

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

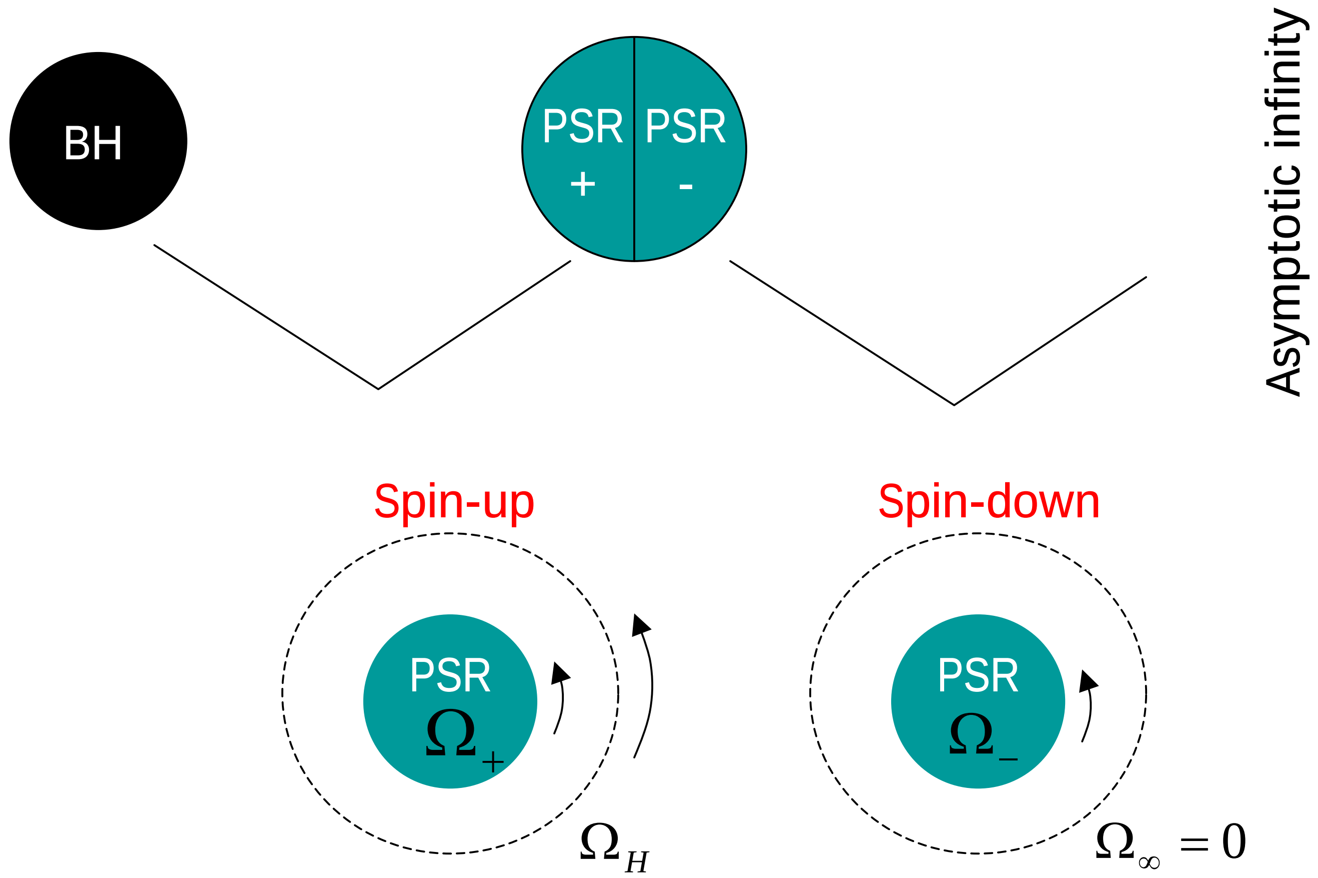
$$eEMF = \nu_p \Omega_H$$

*E*=p-angular momentum * BH-angular velocity



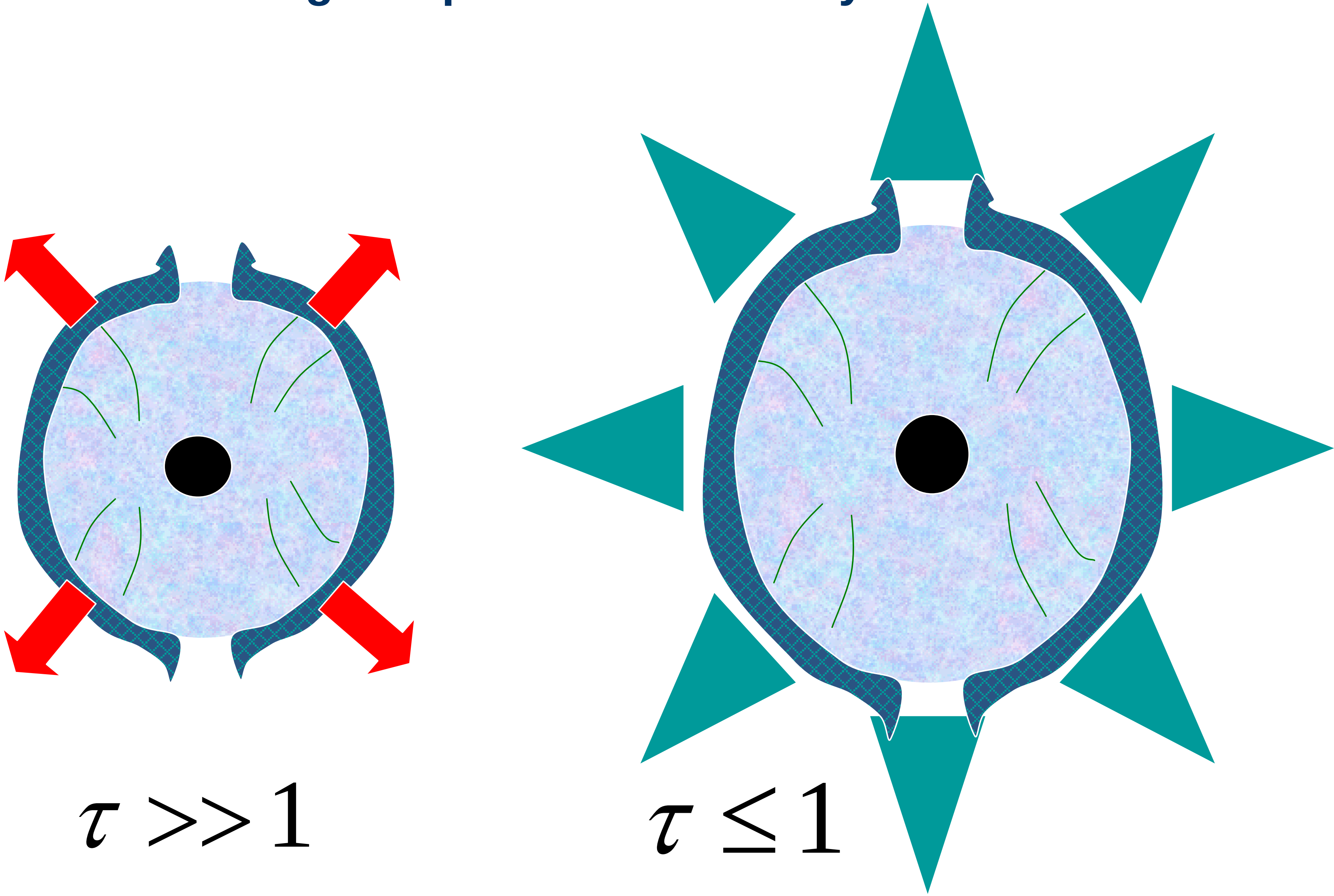

Van Putten 2000
Hawking 1975
Wald 1974

## 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

# Creating a supernova with X-ray line-emissions



$\tau >> 1$

$\tau \leq 1$

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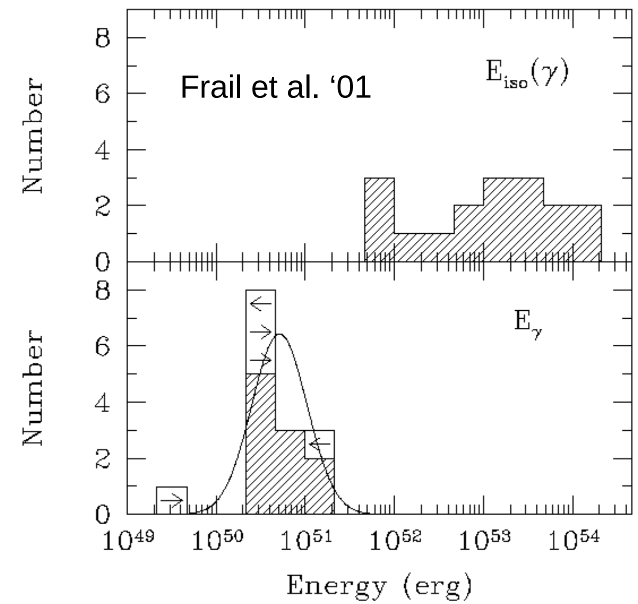
## Observed energies:

$$E_{\gamma} \cong 1.5 \times 10^{-4} M_{Solar} \text{ (Frail et al. 2001)}$$

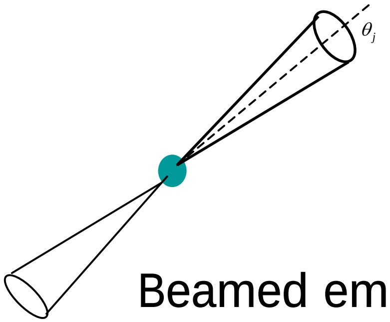
$$E_{SN} \cong 1 \times 10^{-3} M_{Solar} \text{ (Hoeflich et al. 1998)}$$




## 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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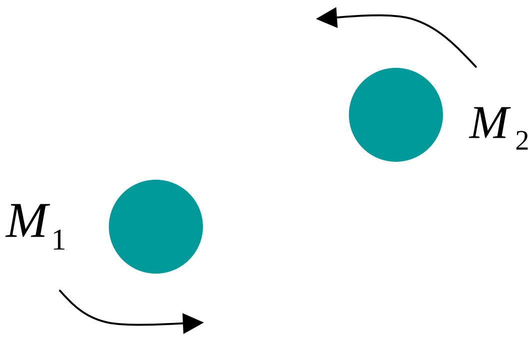
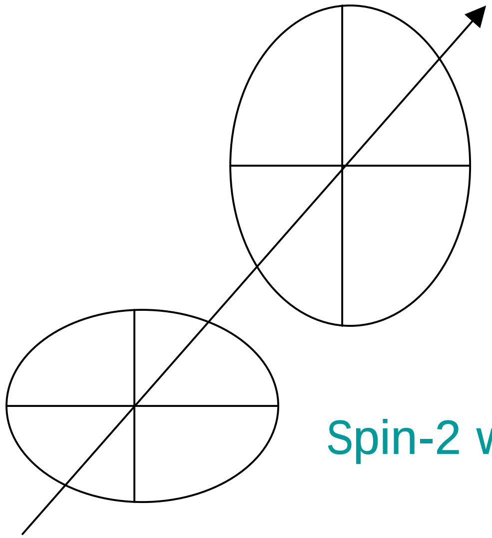
# Gravitational radiation

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




PSR 1913+16

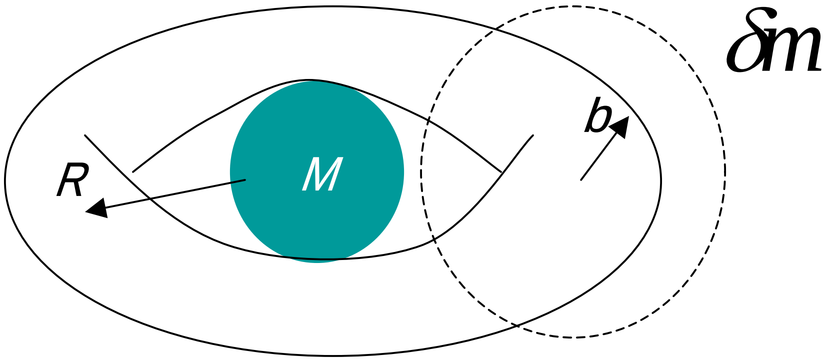
Hulse & Taylor 1974



Spin-2 waves

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

# 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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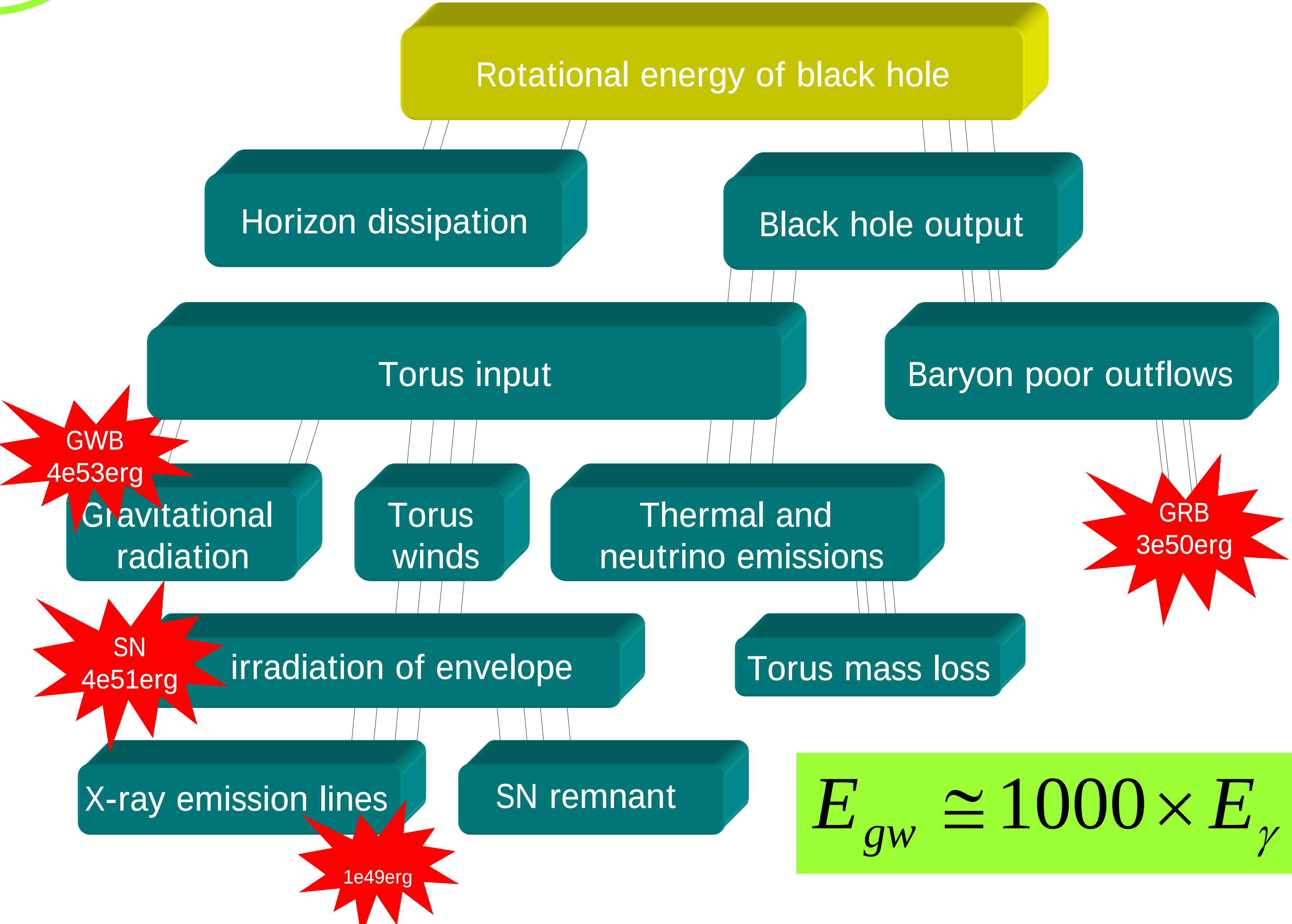
# Radiation energies




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

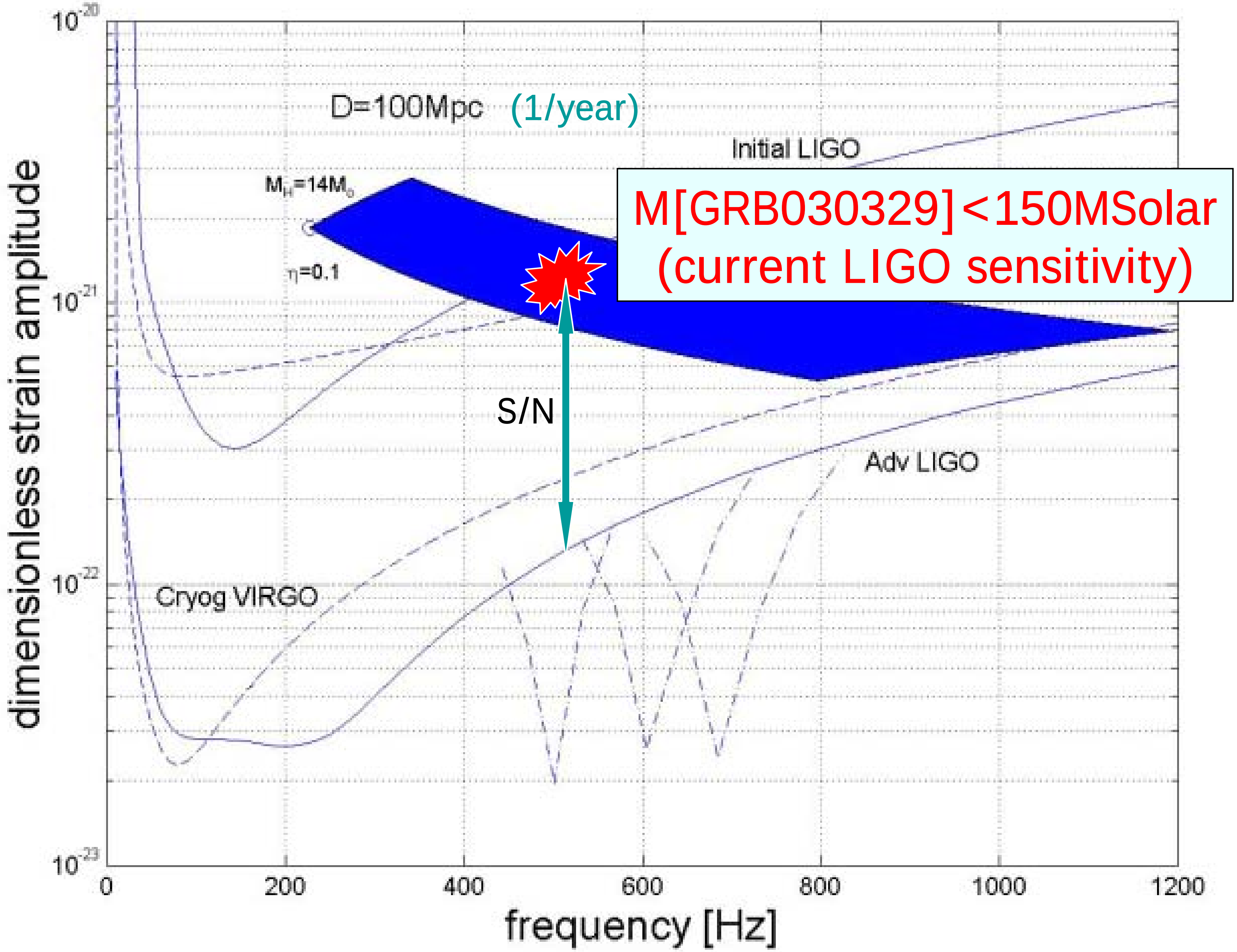
LIGO Hanford site, WA

An ACIGA-LIGO Collaboration

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

The Australian International Gravitational Observatory (AIGO)

LIGO



D=100Mpc
(1/year)
Initial LIGO
M[GRB030329]<150MSolar
(current LIGO sensitivity)
M_H=14M_o
η=0.1
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

# Simulation: instantaneous S/N-ratio = 0.15

D1

LIGO

# Simulation: instantaneous S/N-ratio = 0.15

D1

D2

LIGO

# Simulation: instantaneous S/N-ratio = 0.15

D1 D2 D1*D2

# 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)

# 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