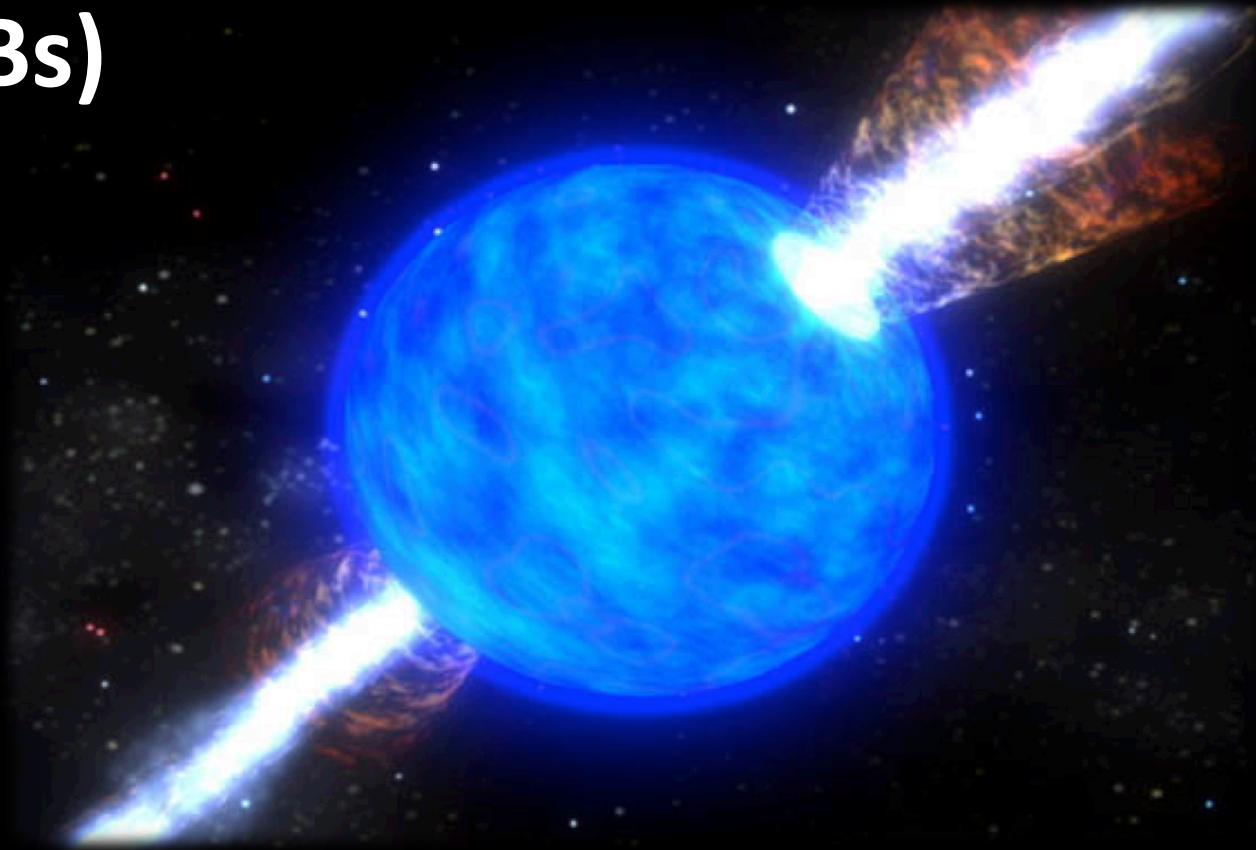


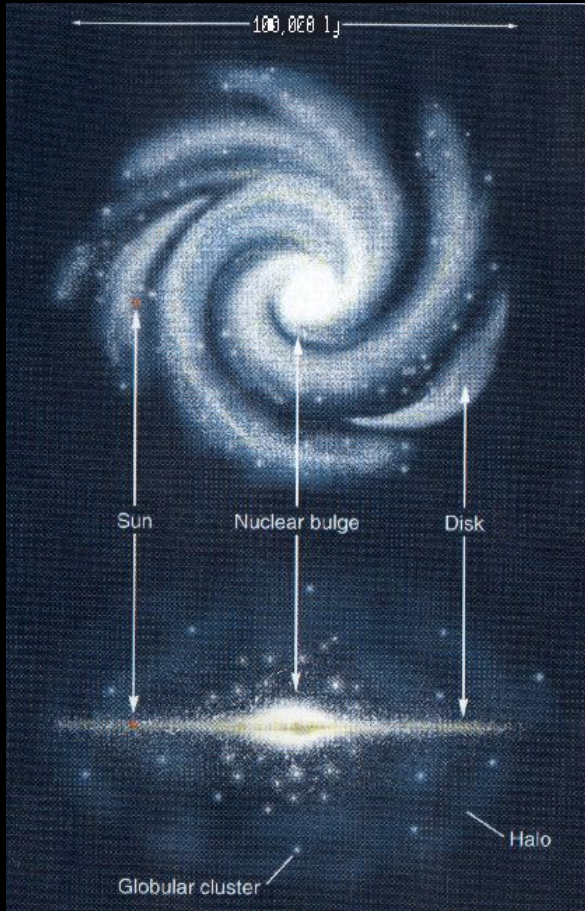
**Gamma-ray
Bursts
(GRBs)**

**Bljeskovi/Eksplozije
gama-zračenja**



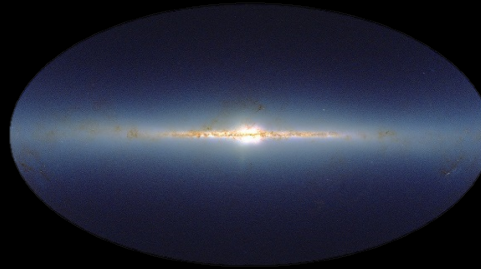
Autor: Miloš Kovačević

Iz posmatračkog ugla

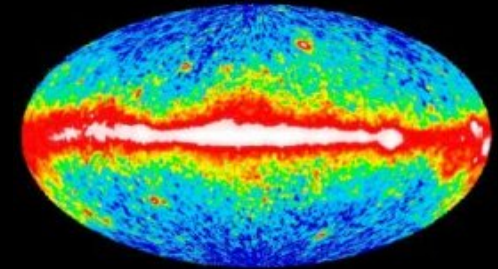


Naša galaksija

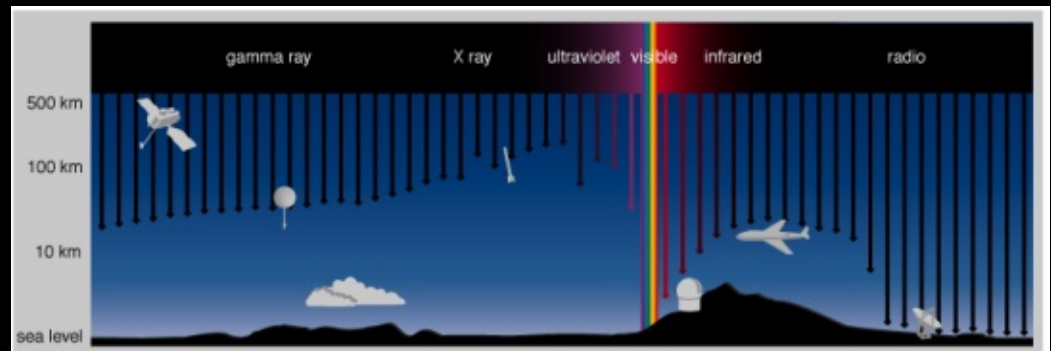
Nebo u 2D (u galaktičkim koordinatama)



infracrveno-optički

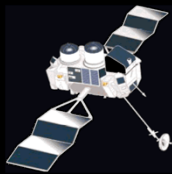
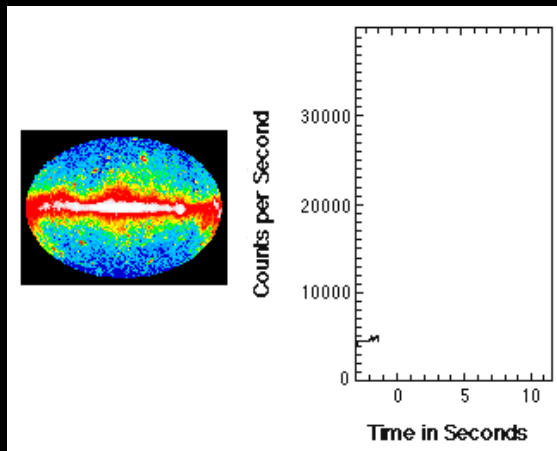
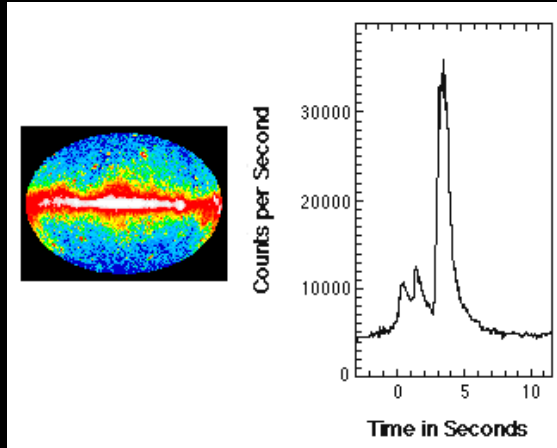


gama

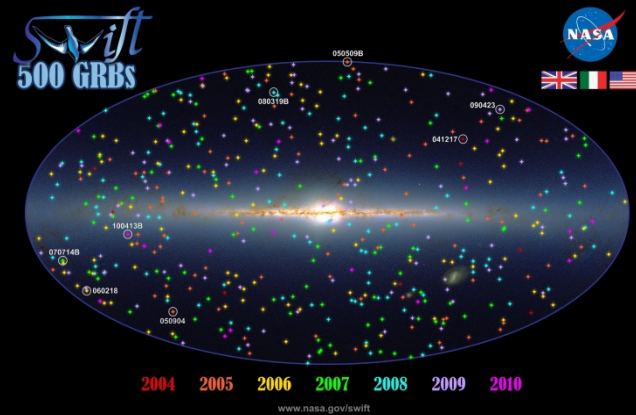


Transparentnost Zemljine atmosfere

Iz posmatračkog ugla



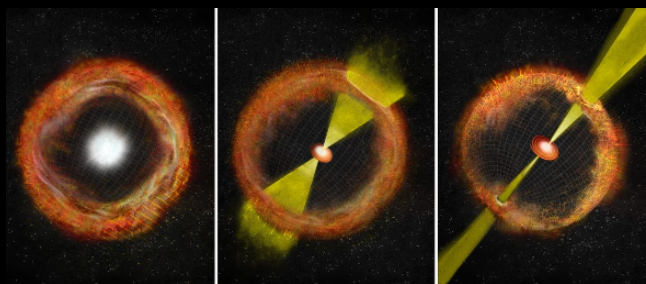
CGRO-BATSE (1991 – 2000)



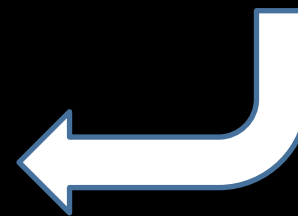
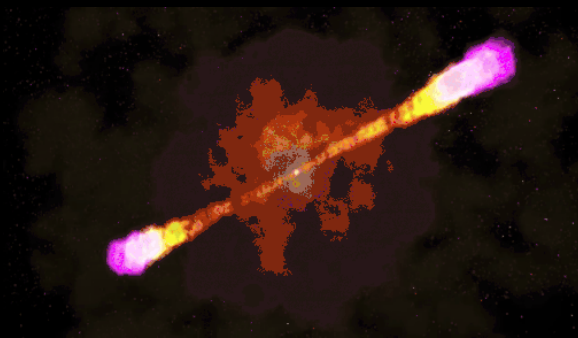
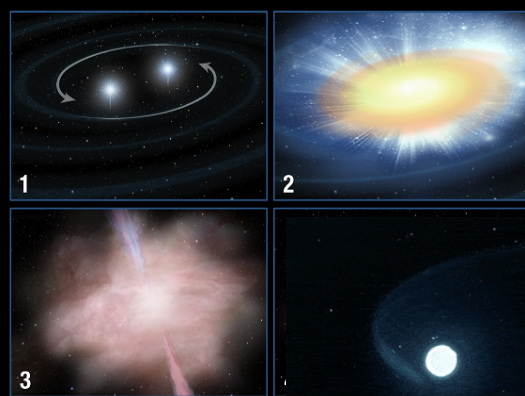
**Swift-BAT (2004 – 2018...)
1 GRB svaka 3 dana**

Kako nastaju?

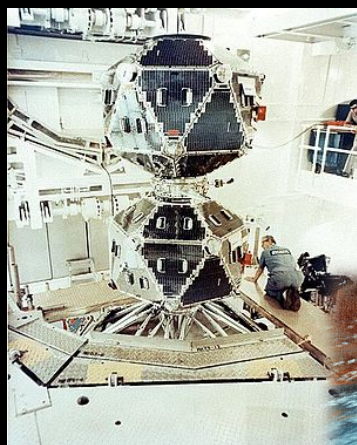
Kraj života masivne zvezde
> GRB & hipernova (jaka supernova)



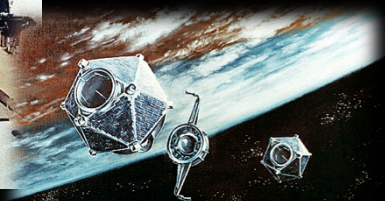
Sudar dve neutronske zvezde
> GRB & kilonova (slaba supernova)



Vela sateliti



12 satelita sa X i gama detektorima lansiranih u periodu 1963 – '70 (SAD)



Internacionalni dogovor o smanjenu nuklearnih testova

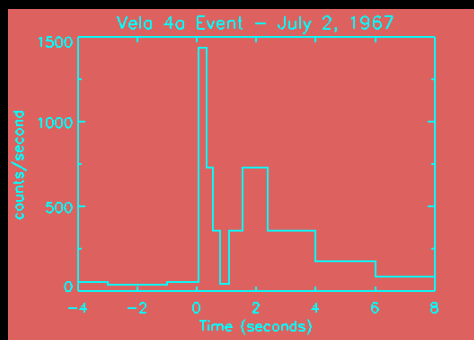
Partial Nuclear Test Ban Treaty

potpisan 1963. izmedju, pre svega, SAD i SSSR.



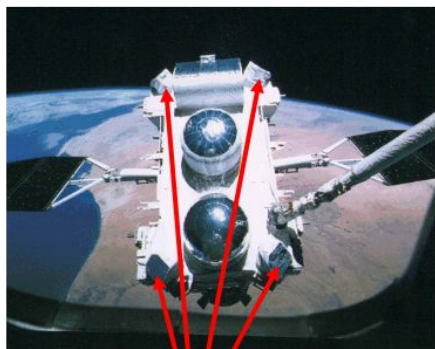
Prvi detektovani GRB

1967. godine (deklasifikovani 1973.)



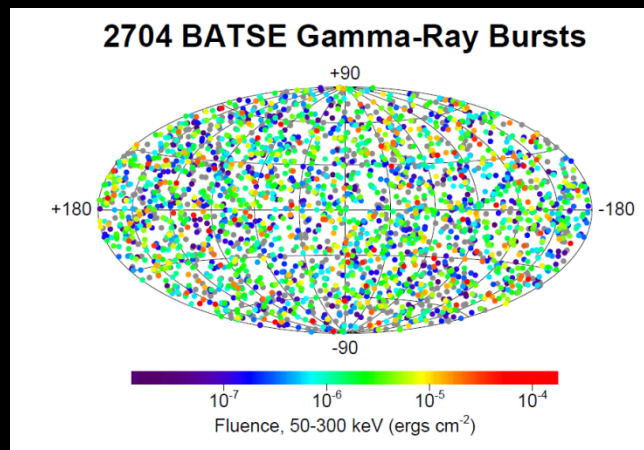
CGRO satelit: *BATSE* detektor(i)...

Compton Gamma-Ray Observatory: Satelit sa X i gama detektorima (1991 – 2000; NASA)

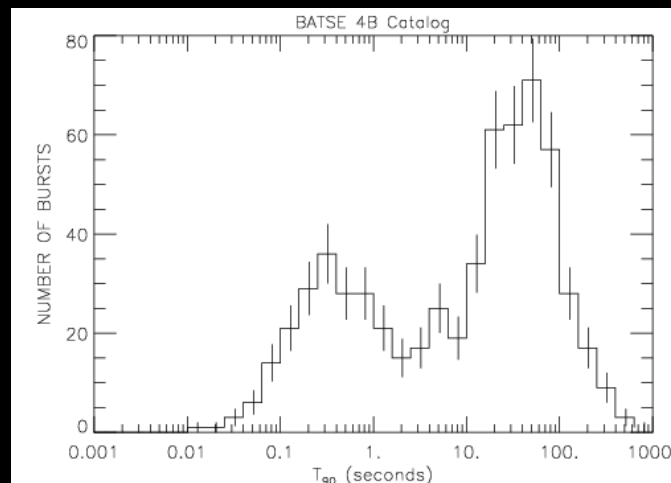


BATSE (Burst and Transient Source Experiment) on the Compton Gamma-Ray Observatory

BATSE: 1 GRB dnevno; lokalizacija 2°-3°; pokriva celo nebo



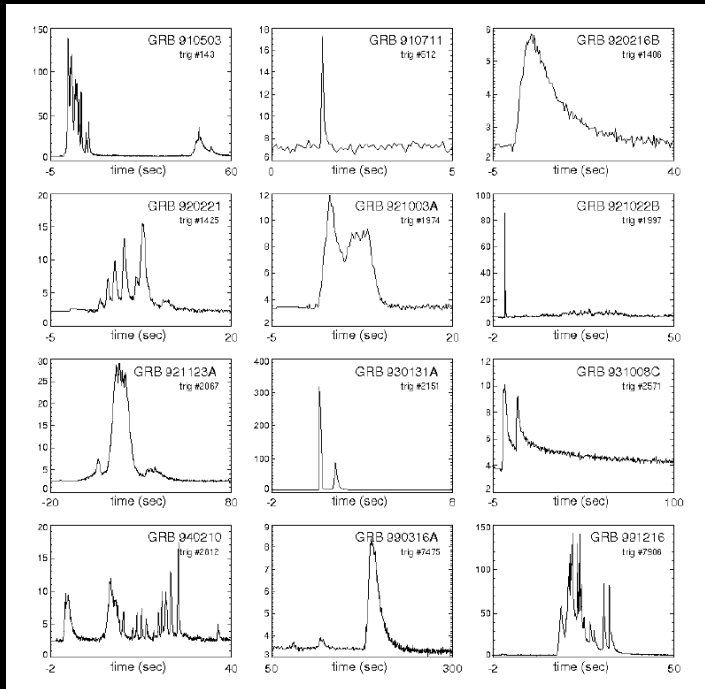
Izotropnost pozicija na nebu
→ vangalakticki objekti



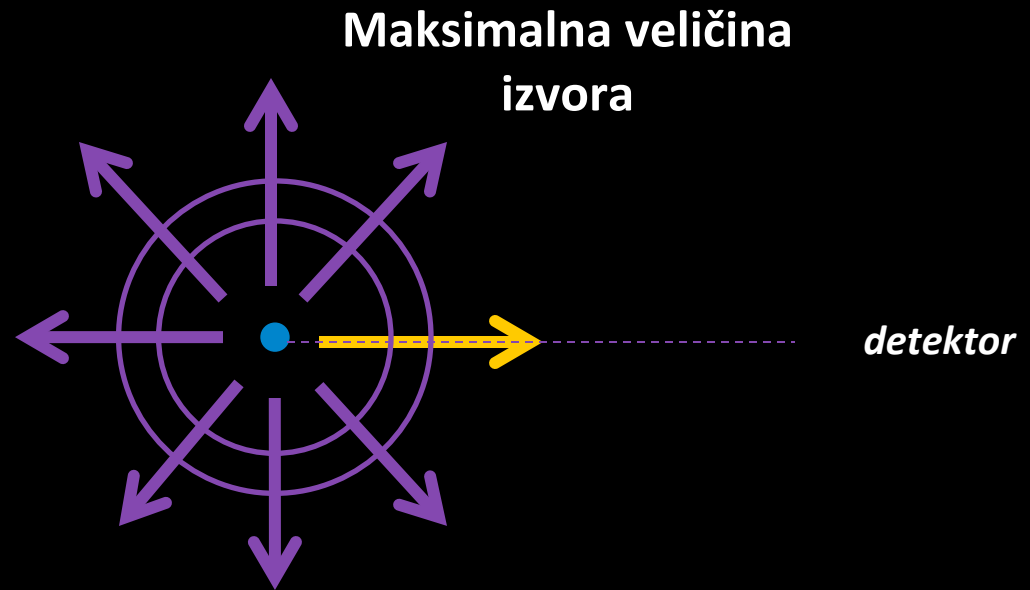
Dužina trajanja GRB
Dve fele: kratki i dugi;
granica oko 2s.

Grupe se razlikuju i po spektru, tj. energijama fotona

Profil

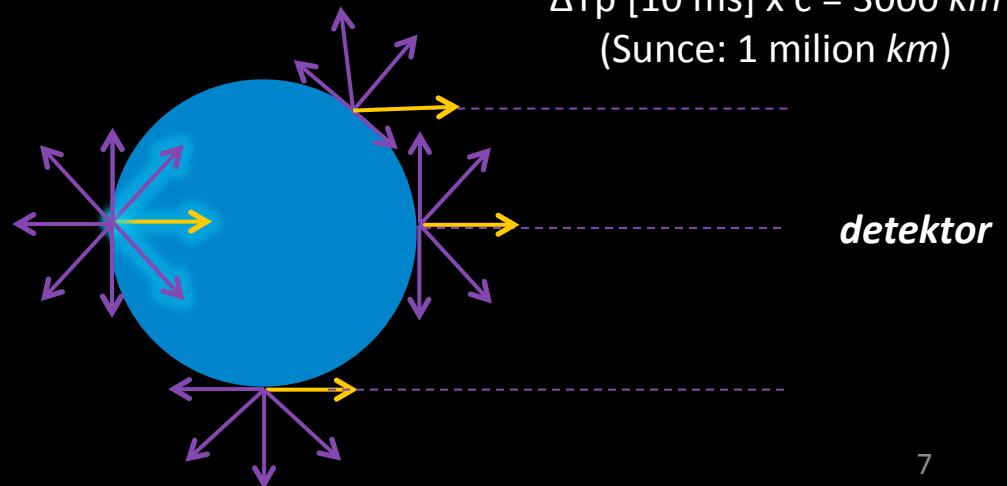


- **Primeri 12 GRB**
- **Svi različiti**
- **Pulsevita struktura (simetrični ili FRED)**
- **Bez periodičnosti (za razliku od npr. pulsara)**
- **$\Delta T_p = \dots 10 \text{ ms} - 10 \text{ s} \dots$**



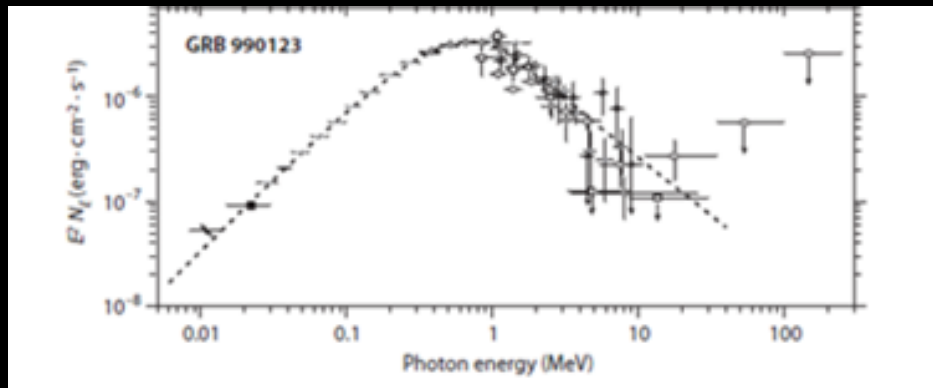
$$\Delta T_p [10 \text{ ms}] \times c = 3000 \text{ km}$$

(Sunce: 1 milion km)



Spektar

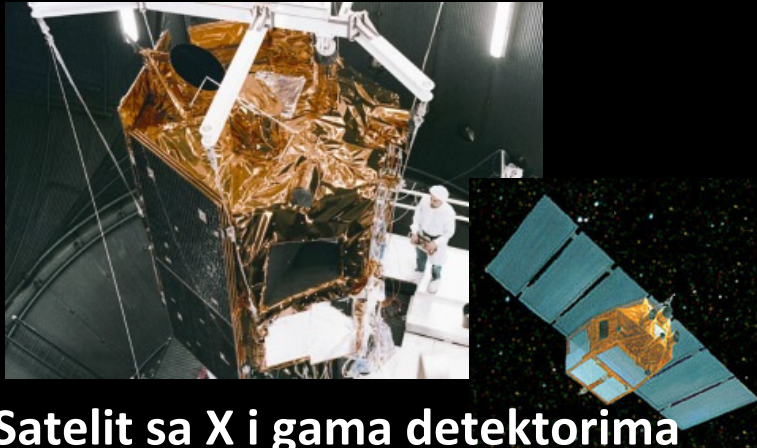
Spektar (BATSE i drugi detektori na CGRO)



- Spectral energy distribution
- Količina energije po energijskoj dekadi (gama, X, UV, O, IR, radio)
- Logaritamska skala
- Stepeni zakon → prava

- Band (dvostruki stepeni zakon – E^{stepen})
- Netermalni (nije crno telo) → zona zračenja transparentna/prozirna
- Maksimum u gama domenu
- Maksimum ide ka nižim energijama tokom trajanja jednog pulsa
- Maksimum je u proseku veći za kratke GRB nego duge

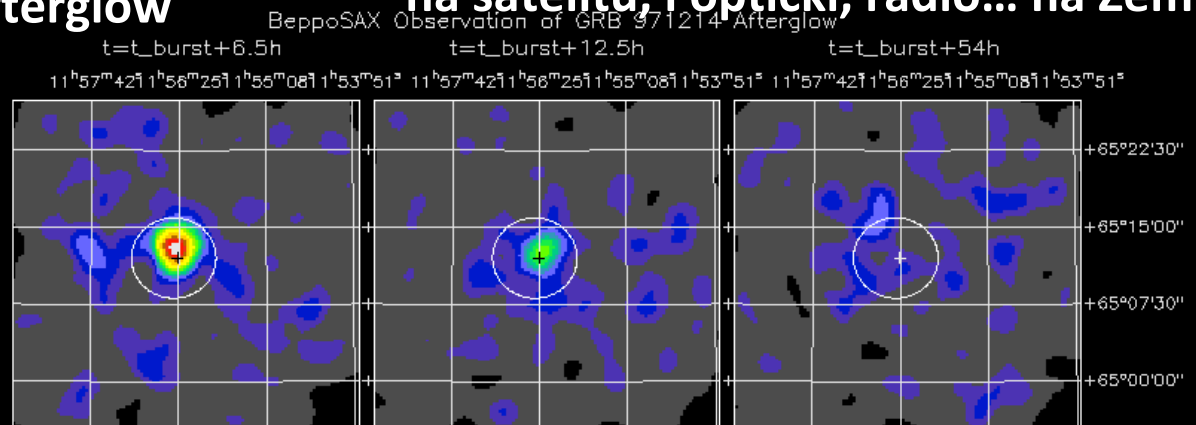
BeppoSAX satelit



Satelit sa X i gama detektorima
(1996 – 2002; Italija, Holandija)
WFC: pokriva deo neba $20^\circ \times 20^\circ$;
Lokalizacija GRB $5'$ [$1^\circ = 60'$]
X-teleskopi: detekcija afterglow

Afterglow/naknadni sjaj
(GRB 970228 – prvi put)

- Nakon glavne emisije
- Mnogo slabiji
- Traje danima
- Gama, X, O, mikro, radio – stepeni sp.
- Detektuju ga teleskopi (detektori fokusirani na deo neba); X-teleskopi na satelitu, i optički, radio... na Zemlji



Udaljenost

GRB 970228



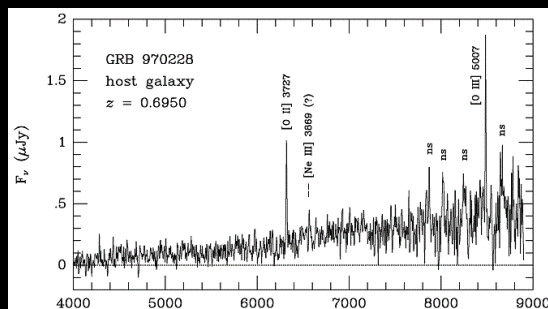
GRB u galaksijama
(van centra)

← spektralne linije

$z = 0.7$

8 milijardi svetlosnih godina

detektor



○ 1997 – 2018...

• Dugi GRB:

$z_{\min} < 0.01$ (100 miliona sv. god.)

• Kratki GRB:

$z_{\min} = 0.1$ (1 milijarda sv. god.) *

• GRB:

$z_{\max} = 8, 9$ (30 milijardi sv. god.)

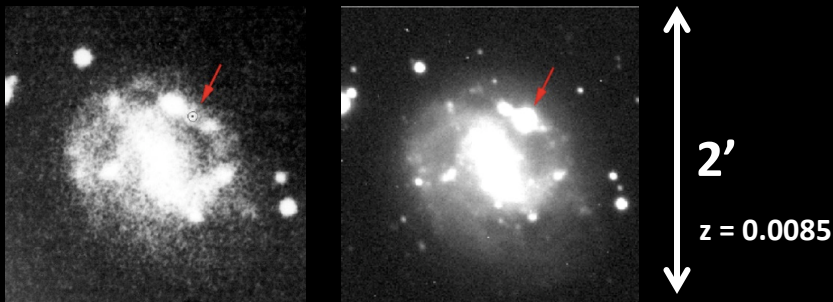
• Zemlja – Sunce: 8 sv. min.

• Najbliza zvezda: 4 sv. god.

• Mlecni Put: 100.000 sv. god.

GRB – Supernova veza

GRB 980425 – SN 1998bw
(prvi potvrđjeni par)



tokom GRB

*SN
par dana kasnije*

GRB nisu u centru galaksija
& povezani su sa SN
→ stelarni fenomeni
(kraj zvezde)
(za razliku od AGN/AGJ)

- 1998 – 2018...
20-50 potvrđenih parova
(energične SN tipa Ib/c)
- ❖ Samo dugi GRB:
 - $z_{\min} < 0.01$ (100 miliona sv. god.)
 - $z_{\max} = 1$ (1 milijarda sv. god.)
[ograničenost teleskopa]
 - GRB $E_{\text{iso}} = 10^{48} - 10^{54}$ erg
 - Pretpostavlja se da veliku većinu dugih GRB prati SN (hipernova)
- ❖ Kratki GRB:
makronova/kilonova
GRB 130603, GRB 170817

Energija

Fluks & udaljenost
& korekcije zbog širenja svemira
→ (izotropna) energija E_{iso}

GRB 970228: $E_{\text{iso}} = 10^{52}$ erg
[1J = 10^7 erg]

! E_{iso} - samo fotoni/EM-zračenje

○ 1997 – 2018...

• Dugi GRB:

$$E_{\text{iso}} = 10^{48} - 10^{55} \text{ erg}$$

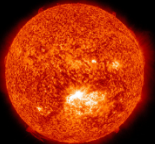
• Kratki GRB:

$$E_{\text{iso}} = 10^{49} - 10^{53} \text{ erg}$$

GRB:

$$L_{\text{max}} = 10^{53,54} \text{ erg / s}$$

Koliko je 10^{54} erg?



$M_{\text{sunce}} = 10^{30} \text{ kg}$

$\xrightarrow{E = mc^2}$ 10^{54} erg

Supernova
(neutronska zvezda)



$$E_{\text{tot}} = 10^{53} \text{ erg}$$

$$E_{\text{kin}} = 10^{51} \text{ erg}$$

$$E_{\text{ph}} = 10^{49} \text{ erg}$$

SN 2015L
(najintenzivnija SN ikad)

$$E_{\text{ph}} = 10^{52} \text{ erg}$$

tokom 4 meseca

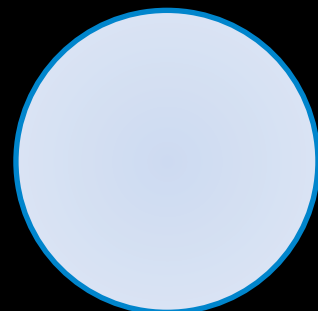
$$L_{\text{max}} = 10^{45} \text{ erg / s}$$

Compactness problem / kompaktnosti



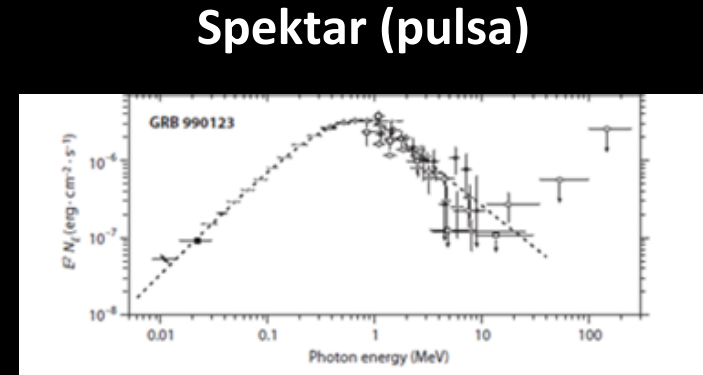
Kratak puls

Maksimalna
velicina izvora
→



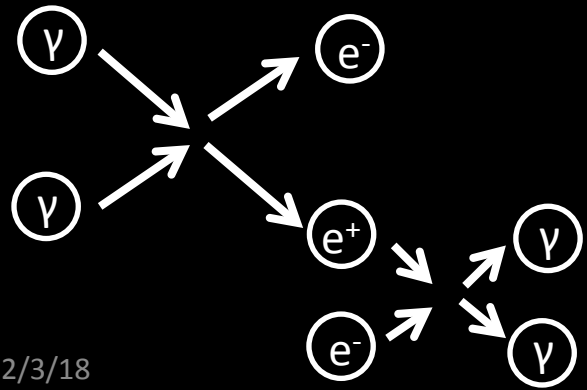
Transparentno ←

Broj fotona
(koncentracija)
 $E_\gamma > 0.5 \text{ MeV}$



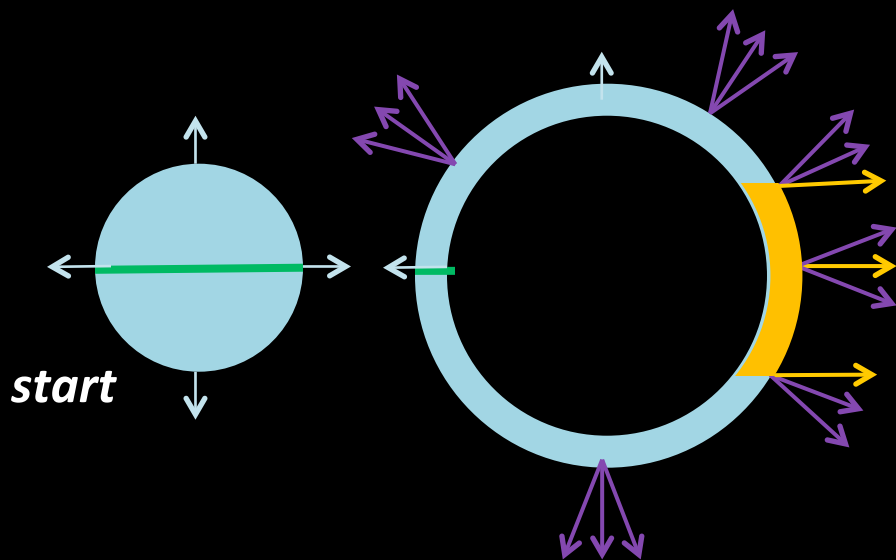
Spektar (pulsa)

E_{iso} (pulsa)

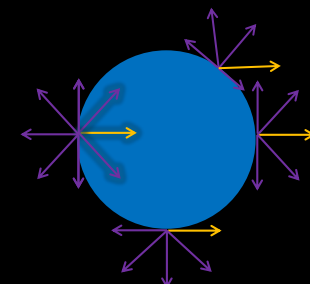


- foton-lepton plazma; optička gustina = 10^{15}
- Veoma netransparentno!
- Zračenje samo sa površine (dosta slabije)!
- Spektar crnog tela (termalni)!

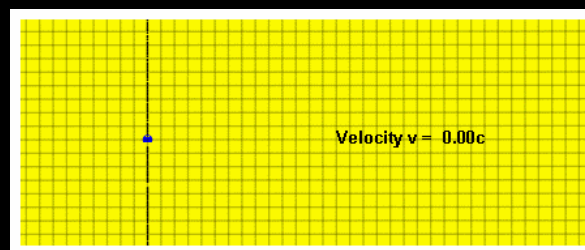
(Ultra)relativističko kretanje



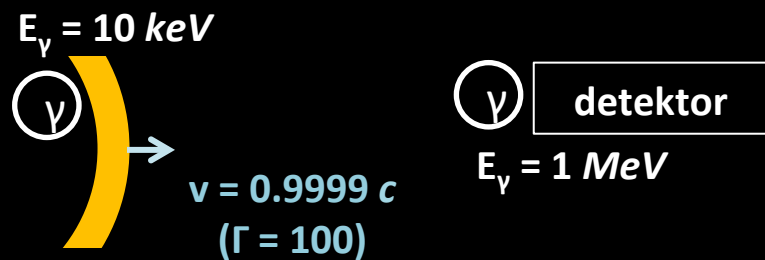
Fokusiranje
zracenja



Staticki izvor



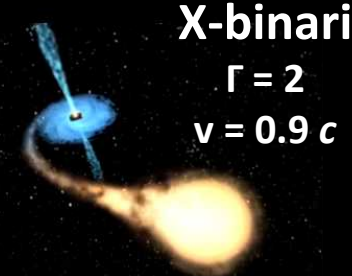
Photon boosting /
povećanje energije
fotona



optička gustina = 1 $\rightarrow \Gamma = 100, \Gamma_{\max} = 1000$
 $\Gamma = 1/$; $v = 0.9999, 0.999999 c$



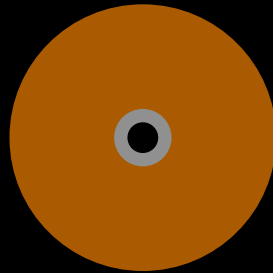
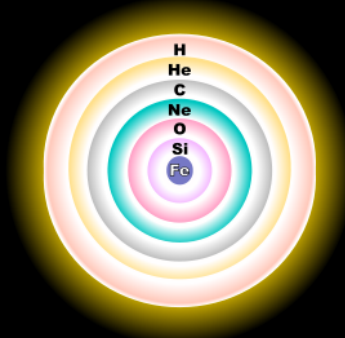
AGN/AGJ
 $\Gamma = 2-20$
 $v = 0.99 c$



X-binari
 $\Gamma = 2$
 $v = 0.9 c$

Crna rupa & jet/mlaz

Zvezda pre supernove



Gvozdeno jezgro,
 $R = 10.000 \text{ km}$ (+ rotacija)

(proto) Neutronska zvezda,
 $R = 30 \text{ km}$

Crna rupa, $R = 6 \text{ km}$ (+rotacija)

$$E_{\text{tot}} = 10^{53} \text{ erg}$$

$$(E_{\text{ph}} = 0.001 E_{\text{tot}})$$

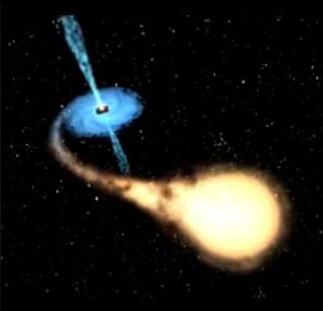
$$E_{\text{tot}} > 10^{53} \text{ erg}$$

$$(E_{\text{iso}} = 10^{54,55} \text{ erg})$$

AGN

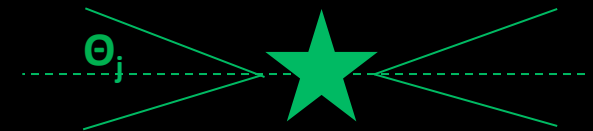


X-binari



Akumuliranje materije na crnu rupu
 → jet-ovi/mlazevi

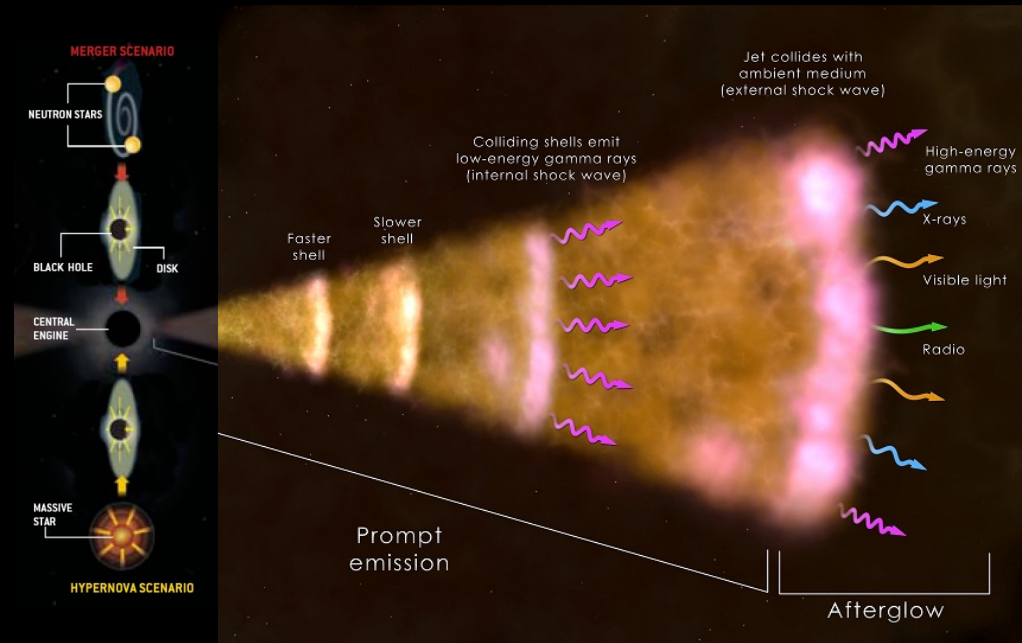
GRB



$$\Theta_j = \dots 3^\circ - 10^\circ \dots$$

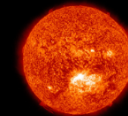
$$\rightarrow E_{\text{ph}} = 0.01 E_{\text{iso}}$$

Fireball / vatrena lopta model



Afterglow:

- Kada se svi fireball-ovi spoje i sudare sa kontinualnim i retkim ISM ($r = 10^{11}$ km) (interstelarnim medijumom)
- Slabije zracenje koje traje danima u svim delovima spektra



$$R_{\text{sunce}} = 10^6 \text{ km}; c = 10^5 \text{ km/s}$$

Centralni motor:

- $E_{\text{tot}} = 10^{54}$ erg:
neutrine + GW +
- niz Fireballs ($E_{\text{fbs}} = 10^{52}$ erg):
foton-lepton-(malo)protona plazma
- $T_{\text{fb}} = 1 \text{ MeV}$
- $R_{\text{fb}} = 10\text{-}100 \text{ km}$

Fireball evolucija:

- Fokus u jet/snop \rightarrow deo sferne ljuske debljine R_{fb}
- $E_u \rightarrow E_k$ protona $\Gamma = 100$ ($r = 10^3$ km); Fb se hladi
- Transparentnost ($r = 10^7$ km); fotoni napuste Fb (mala E_{ph})
- Sudari dve fireball ($r = 10^9$ km)
- \rightarrow Ubrzanje elektrona + magnetno p.
- \rightarrow sinhrotronsko zracenje ($E_{\text{ph}} = 10^{51}$ erg; netermalni s.)
- \rightarrow Usled fokusa $E_{\text{iso}} = 10^{53}$ erg

Swift & Fermi



○ Swift

- Satelit sa gama, X i UV detektorima (2004 – 2018...; NASA i drugi)

Brza i precizna lokalizacija

- GRB 050509b:

prva lokalizacija kratkog GRB

($z = 0.225$)

- Swift lokalizovao skoro sve kratke GRBs i vecinu dugih

○ Fermi

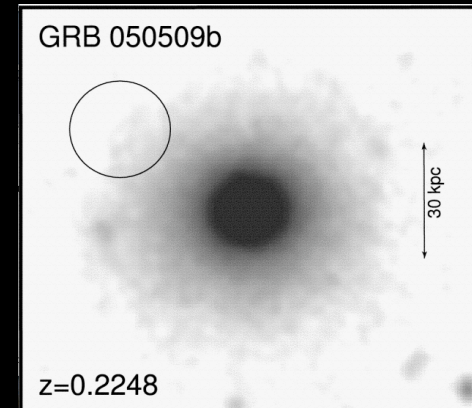
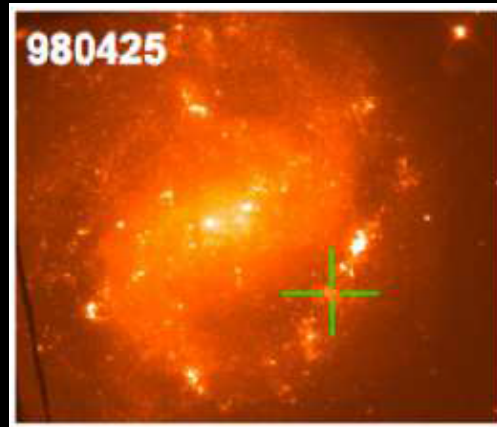
- Satelit sa gama i X detektorima (2008 – 2018...; NASA i drugi)

- Veliki energijski opseg

○ Sve je javno!

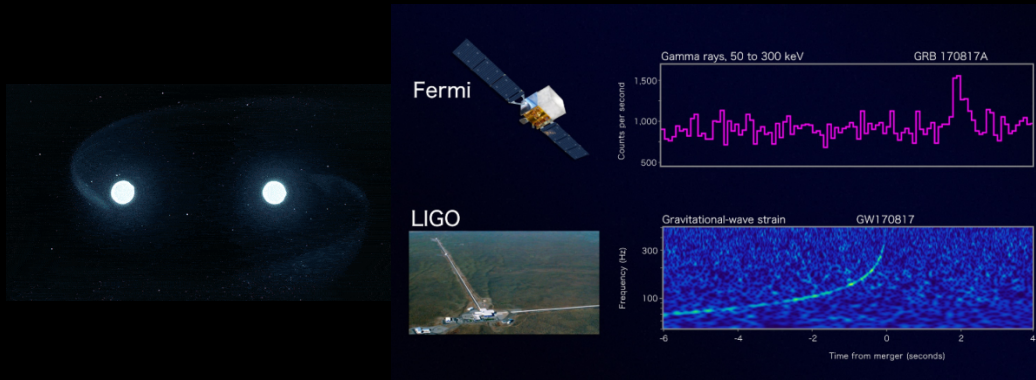
(sirovi podaci, katalozi, softver... na NASA serveru)

Lokacije dugih i kratkih GRBs u galaksijama



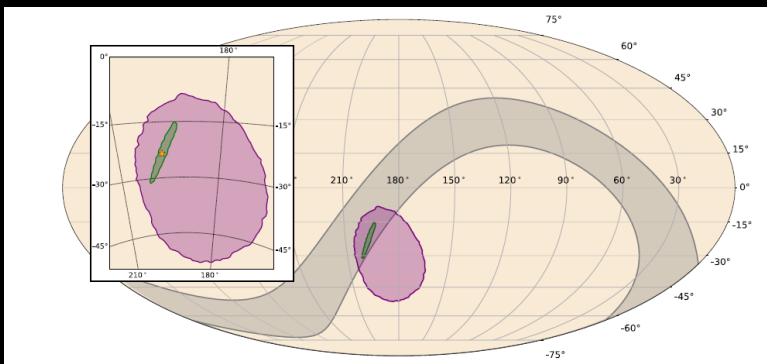
- Galaksije dugih GRBs:
 - nepravilne, patuljaste, spiralne - svetliji delovi
(star forming regions / regije s formiranjem zvezda)
 - Masivnije zvezde – kraće žive
→ Kraj života masivnih zvezda (+ Supernove tipa Ib/c)
- Galaksije kratkih GRBs:
 - Uglavnom elipticne (starije)
 - Bez preferencije mesta
 - Poneki veoma udaljeni od centra
→ Stare zvezde
→ Sudari 2 neutronske zvezde (+ kilonova, odsustvo regulrane SN)

GW 170817 - GRB 170817



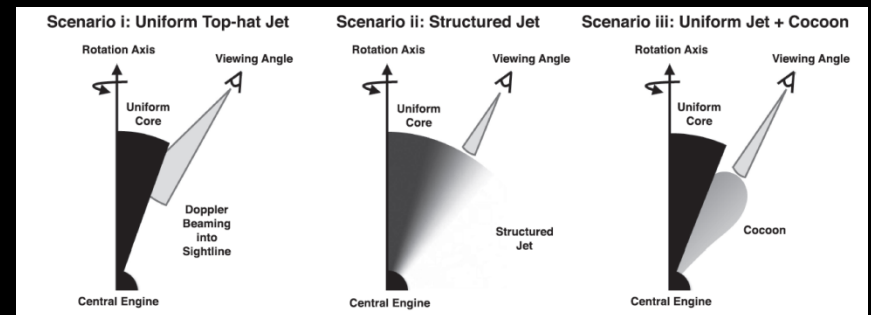
- 2 *LIGO* i *Virgo* GV detektori: signal 100s; 2015 – 2018... 7 GV, prvi put 2 NS ($85 < d < 160 \text{ Mpc}$)
- 2s nakon kraja GV *Fermi-GBM* kratki GRB
- 11 sati nakon opticka detekcija → Galaksija $d = 130 \text{ Mpc}$ ($z = 0.01$)
- kilonova

- GRB: $z = 0.01$ ($z_{\min} = 0.1$);
 $E_{\text{iso}} = 10^{46,47}$ ($E_{\text{iso, min}} = 10^{49}$) erg



{Abbott et al (2017), ApJ}

X, radio posmatranja i dalje traju



{Abbott et al (2017), ApJ}