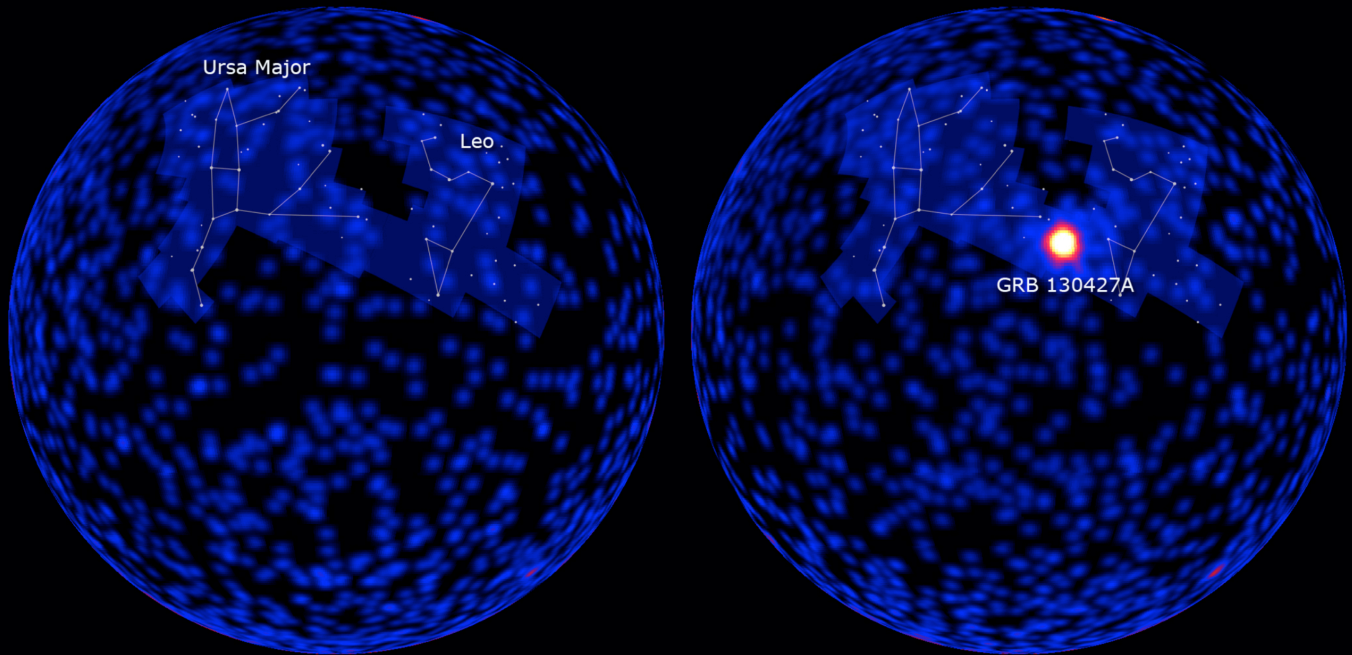
EM non-thermal emission

Gamma-Ray Bursts

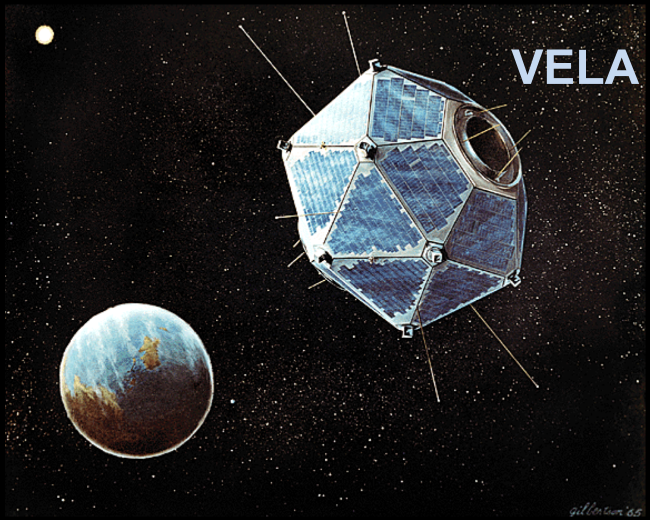


Before and after Fermi LAT observation of GRB 130427A

Brief, sudden, intense flashes of gamma ray radiation which release energy up to **~ 10^{53} erg** (isotropic-equivalent)

Duration: **from few ms to hundreds of s**
Observational band: **10 keV – 1 MeV**
Flux: **10^{-8} - 10^{-4} erg cm^{-2} s^{-1}**

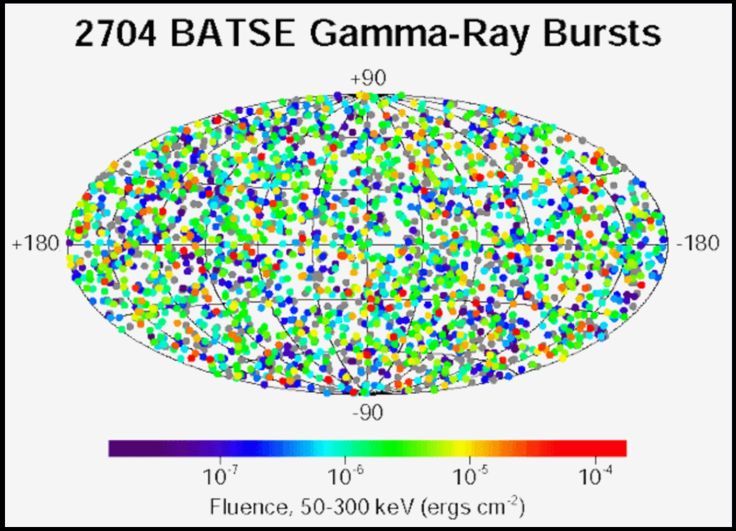
GRBs were discovered serendipitously in the late 1960s by U.S. military satellites looking out for Soviet nuclear testing

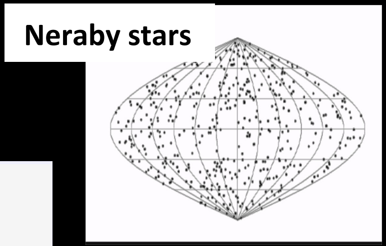


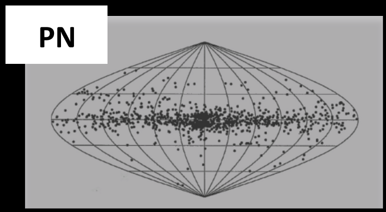
Galactic or cosmological?

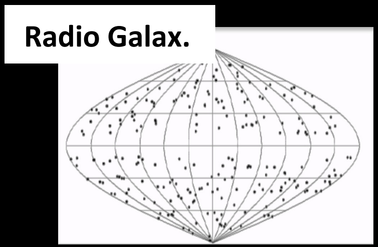
BATSE
20 keV-MeV
(1991-2000)

Isotropic angular distribution





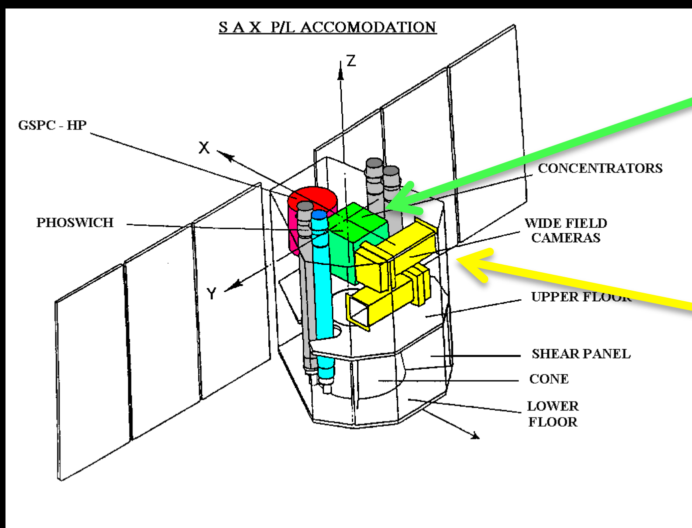




Paczynsky, PASP, 107, 1167

BeppoSAX
(1996-2002)

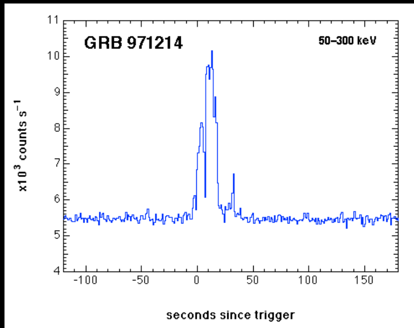
Italian–Dutch satellite for X-ray astronomy resolved the origin of gamma-ray bursts

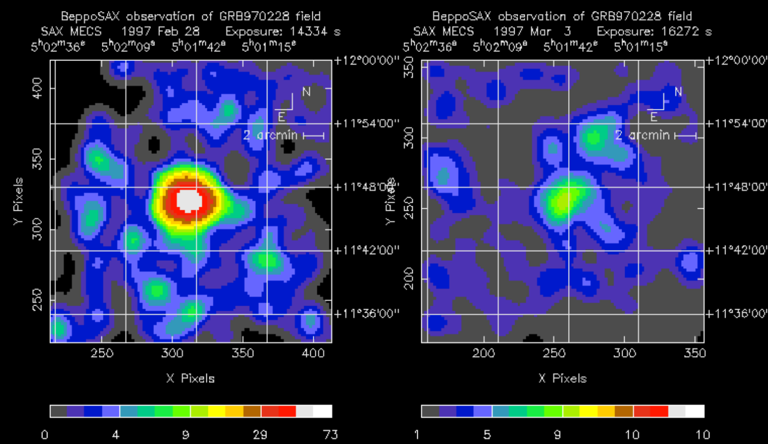


Scintillator for gamma-rays
60-600 keV, poor angular resolution

Wide Field Camera (WFC)
2-30 keV; 20x20 degree FoV
5 arcmin angular resolution

GRB 970228 in the FOV of the WFC

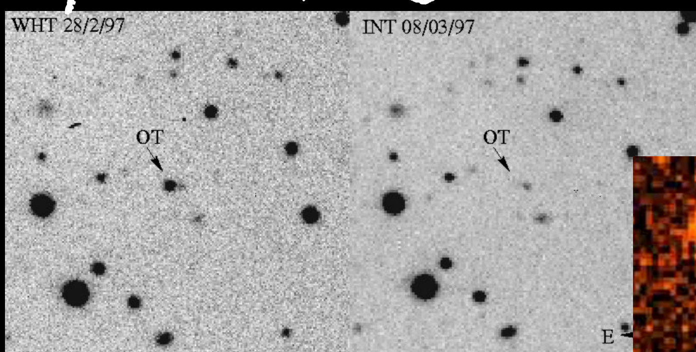




Well localized fading X-ray afterglow!

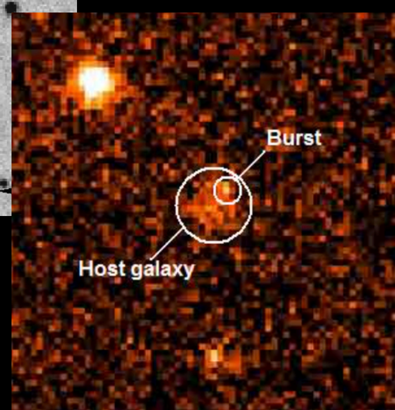
Costa et al., 1997

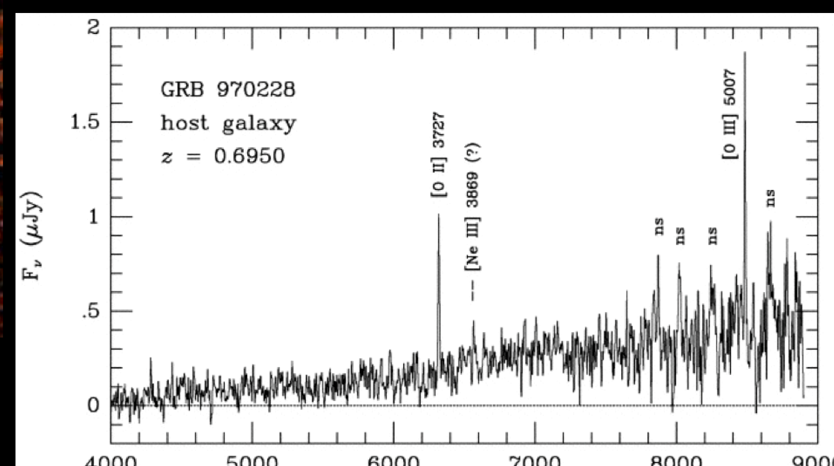
Optical afterglow/host galaxy



z=0.695, D_L=3.6 Gpc

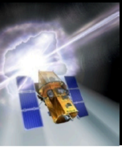
Cosmological redshift





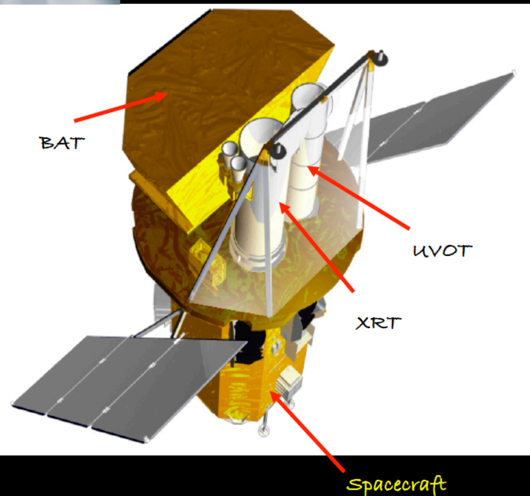
Groot, Galama, van Paradijs, et al IAUC 6584, March 12, 1997

van Paradijs et al., 1997



Swift: "everything in space"

Since Nov. 2004

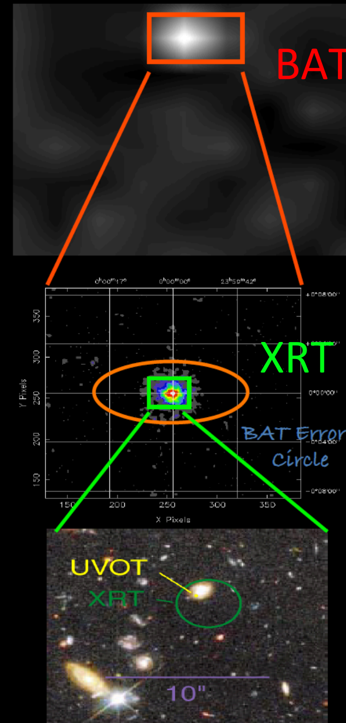


Satellite slews (1 min) and repoints its X ray (XRT) and UV telescopes to observe the error region of the GRB.

T<10 sec
θ< 4'
E>15 kev

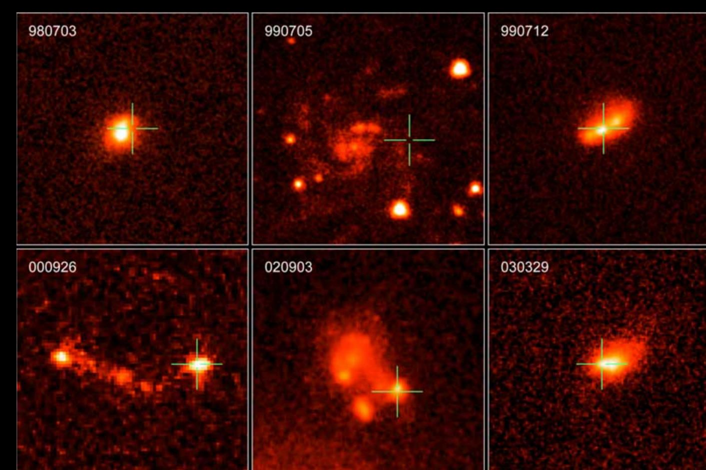
T<100 sec
θ < 5"
E<10 kev

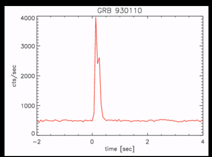
T<300 sec
Optical/NIR



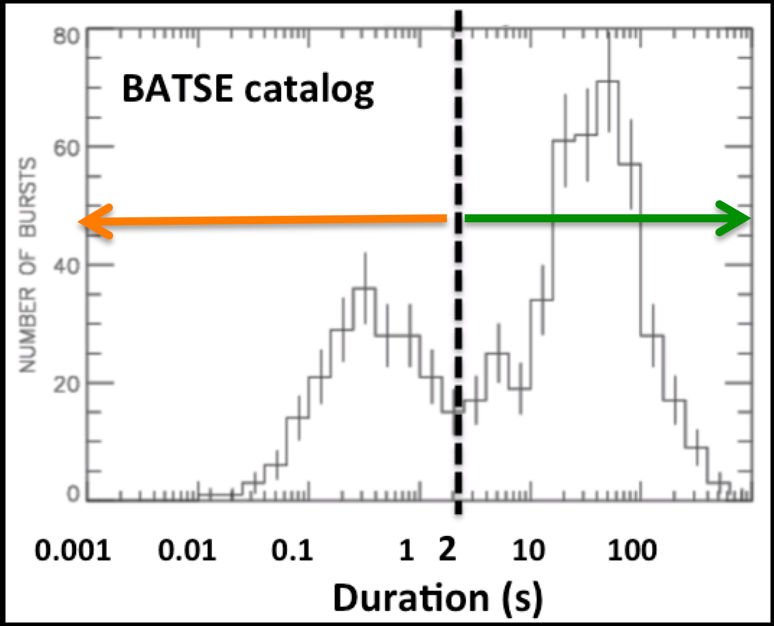
GRBs are extragalctic, cosmological, and occur in galaxies

GRBs host galaxies observed by HST



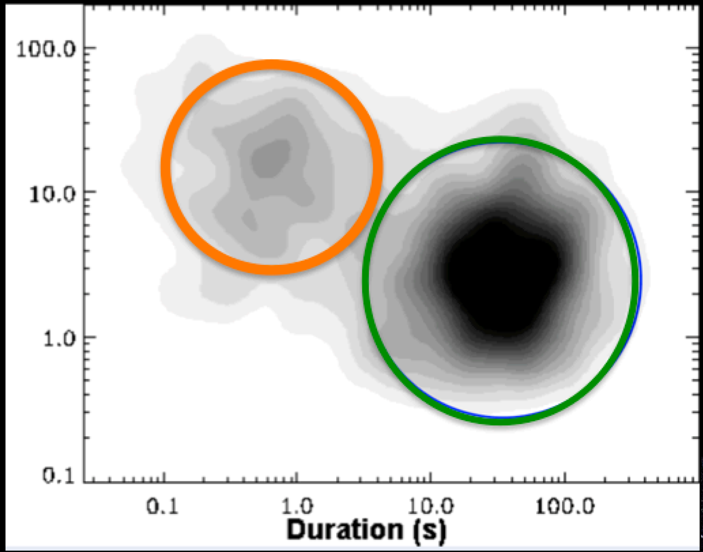


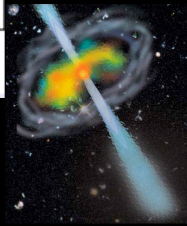
Bimodal duration distribution



Kouveliotou et al. 1993

Hardness ratio





Different Progenitor

Short Hard GRB

- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)
- accretion timescale of disk in binary merger model is short (t ~ 1s)

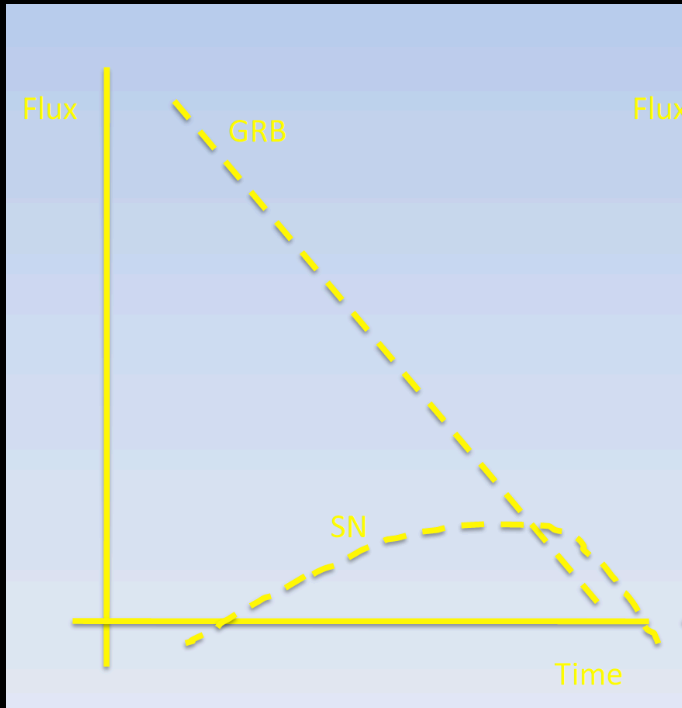
→ **NS-NS NS-BH mergers**

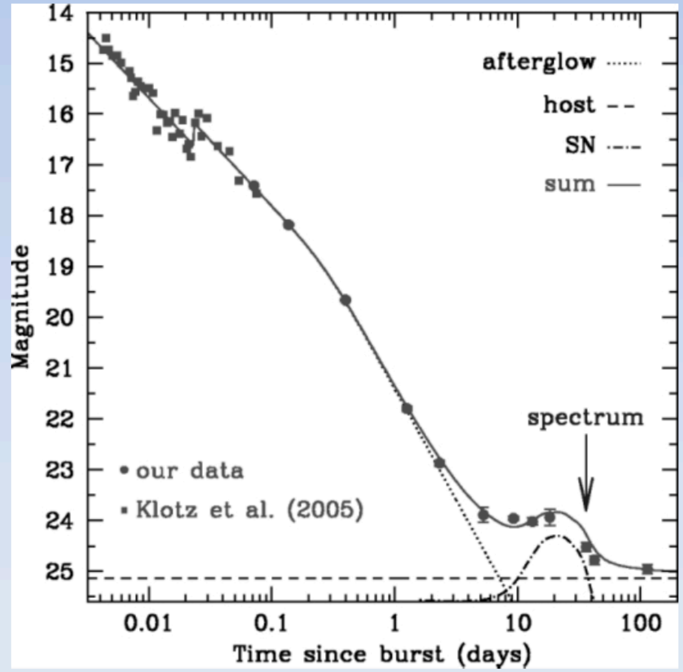
Long Soft GRB

- observed Type Ic SN spectrum
- accretion disk is fed by fallback of SN material onto disk, timescale t ~ 10-100s

→ **Core-collapse of massive stars**

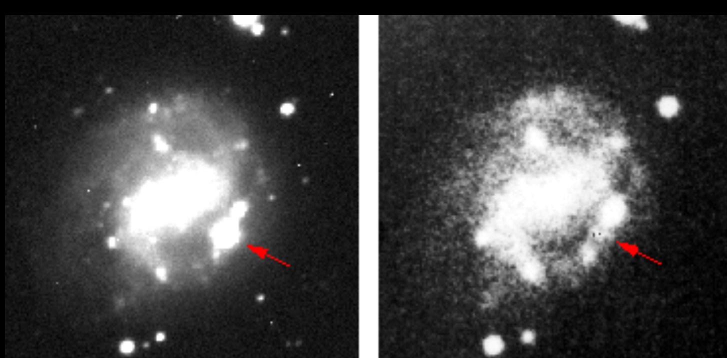
Long GRB and Supernovae





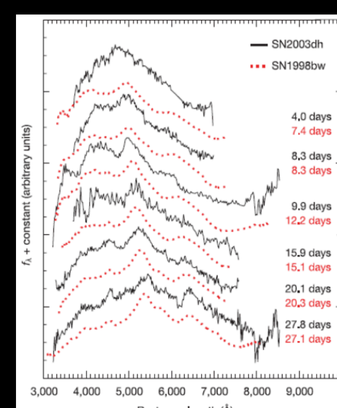
Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Della Valle et al. 2003; Malesani et al. 2004; Soderberg et al. 2005; Pian et al. 2006; Campana et al. 2006; Della Valle et al. 2006, Bufano et al. 2012, Melandri et al. 2012, Schulze et al. 2014, Melnadri et al. 2014 and others…

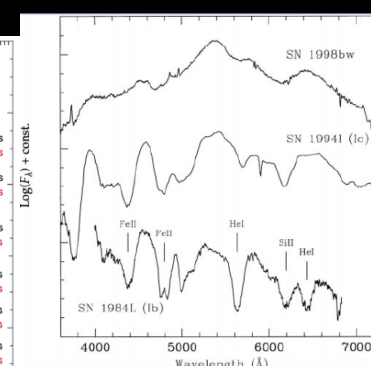
SN 1998bw/GRB 980425
Type Ic supernova



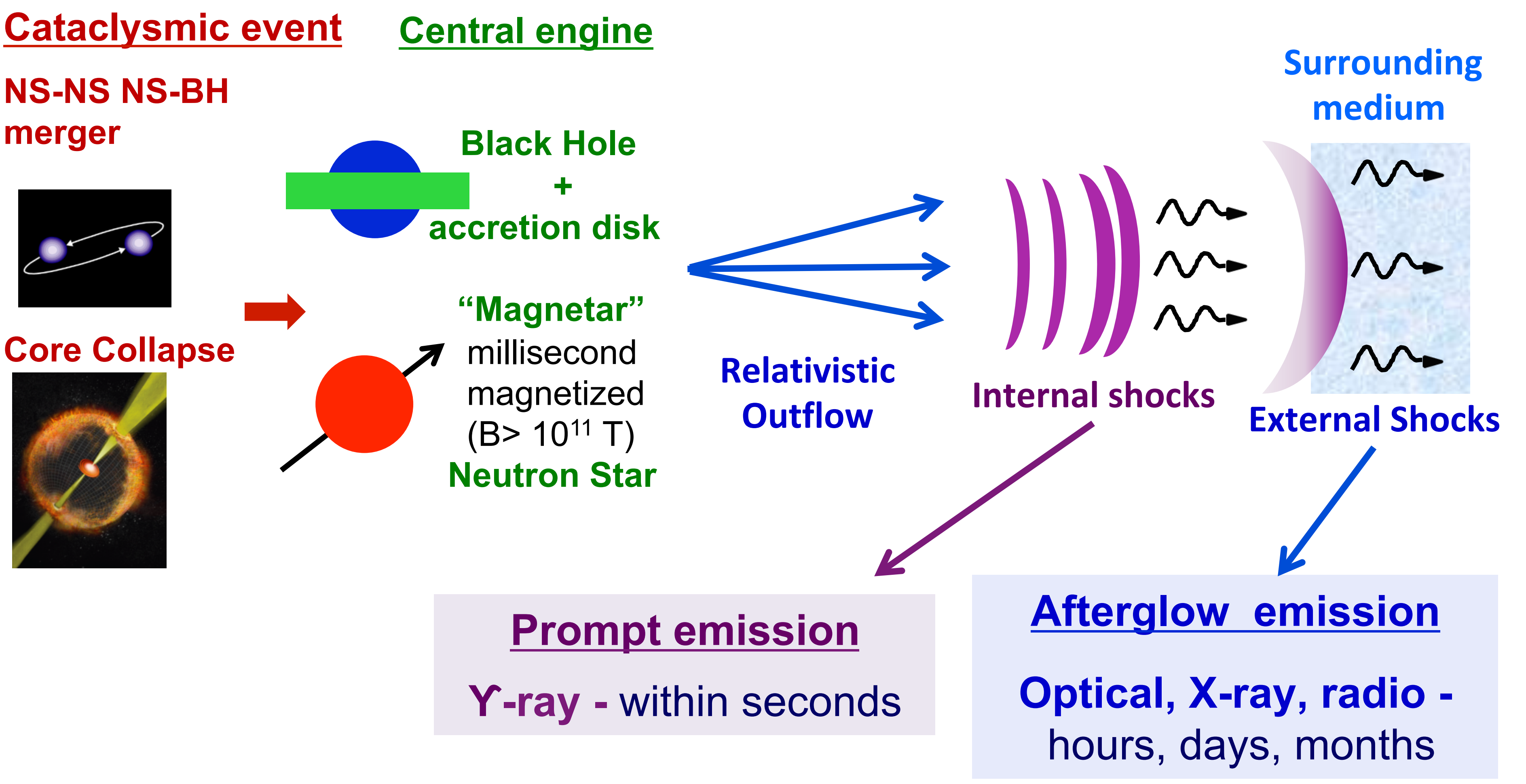
Iwamoto et al 1998; Woosley et al. 1999

Spectra





GRBs emission - Fireball Model

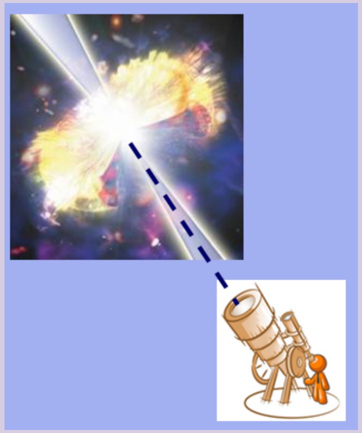


Kinetic energy of the relativistic jet converted into radiation

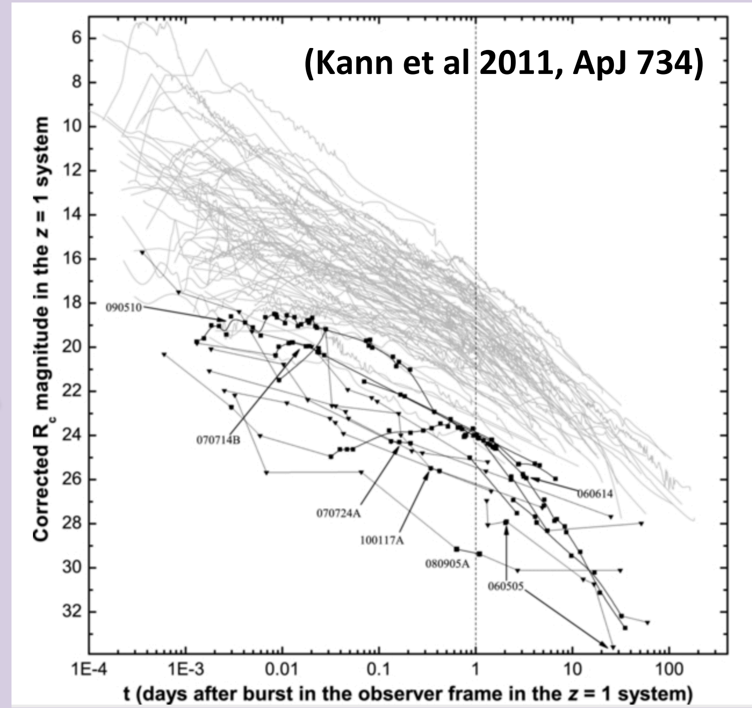
Mjet = 10^{-7}-10^{-5} Mo, $\Gamma \geq 100$, E=10^{48}-10^{51} erg

Optical afterglows of on-axis GRBs

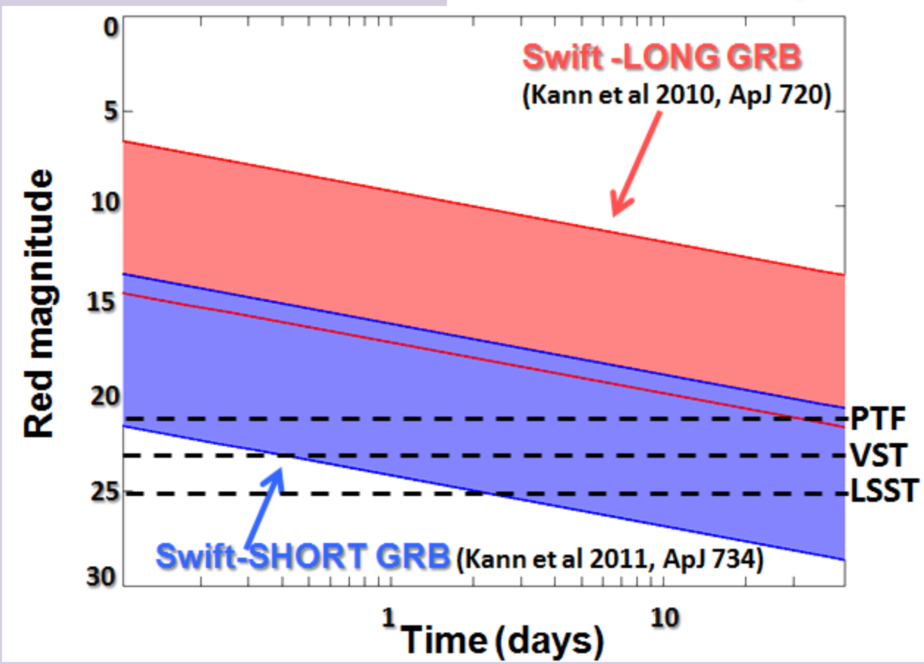
On-axis GRBs



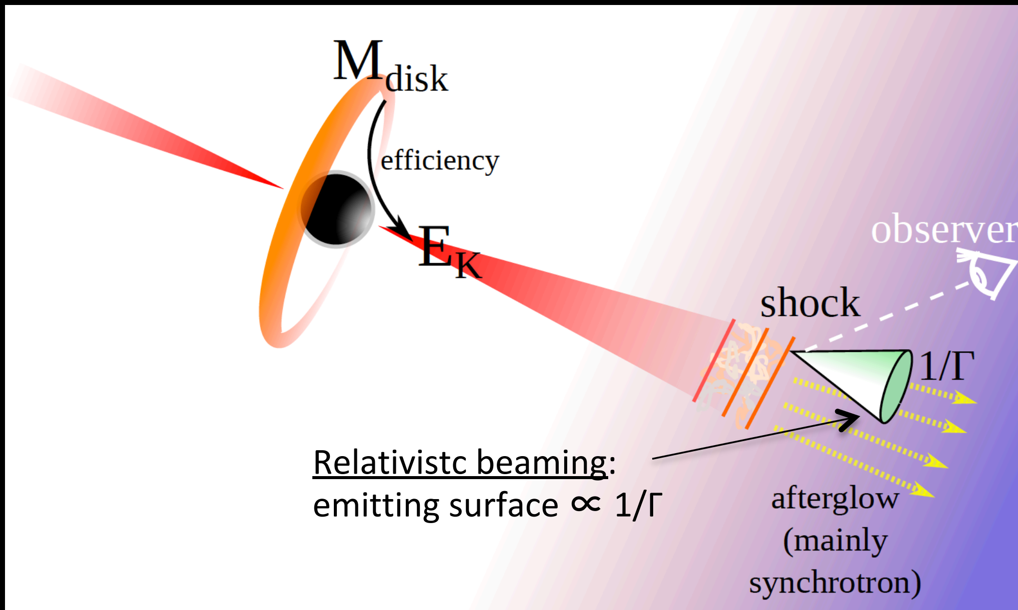
Observed GRB optical afterglows



Source at 200 Mpc

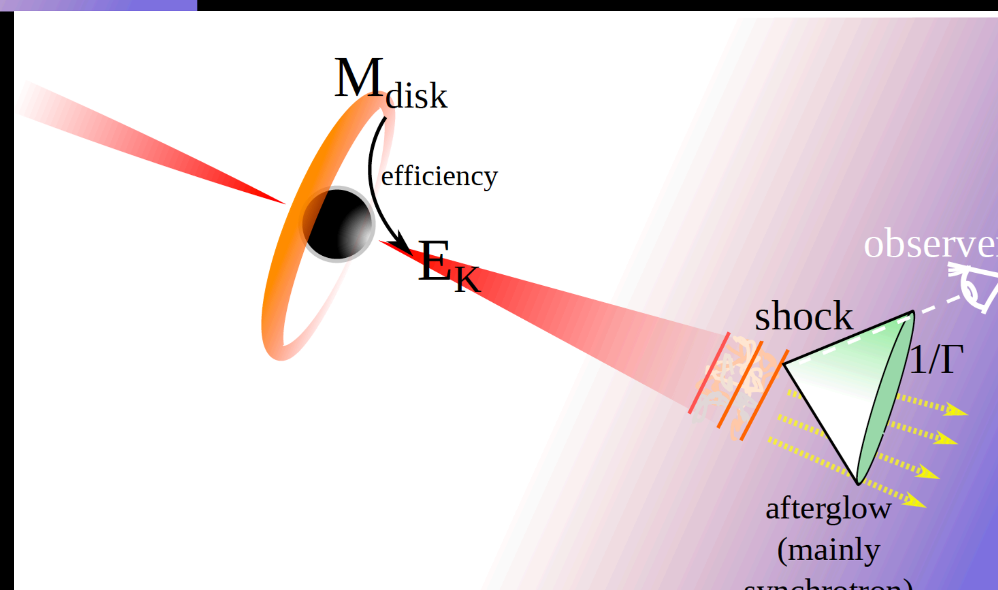


On average the optical afterglow decays as a **power law** $\mathbf{time^{-\alpha}}$ with **α in the range 1 to 1.5**

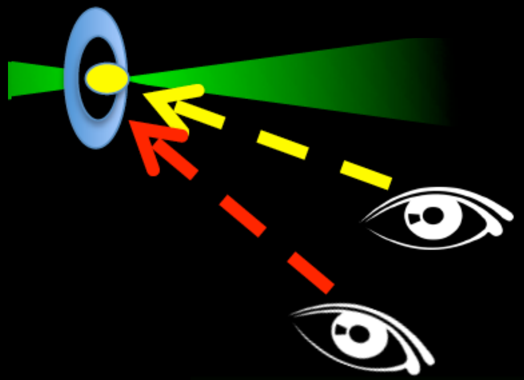


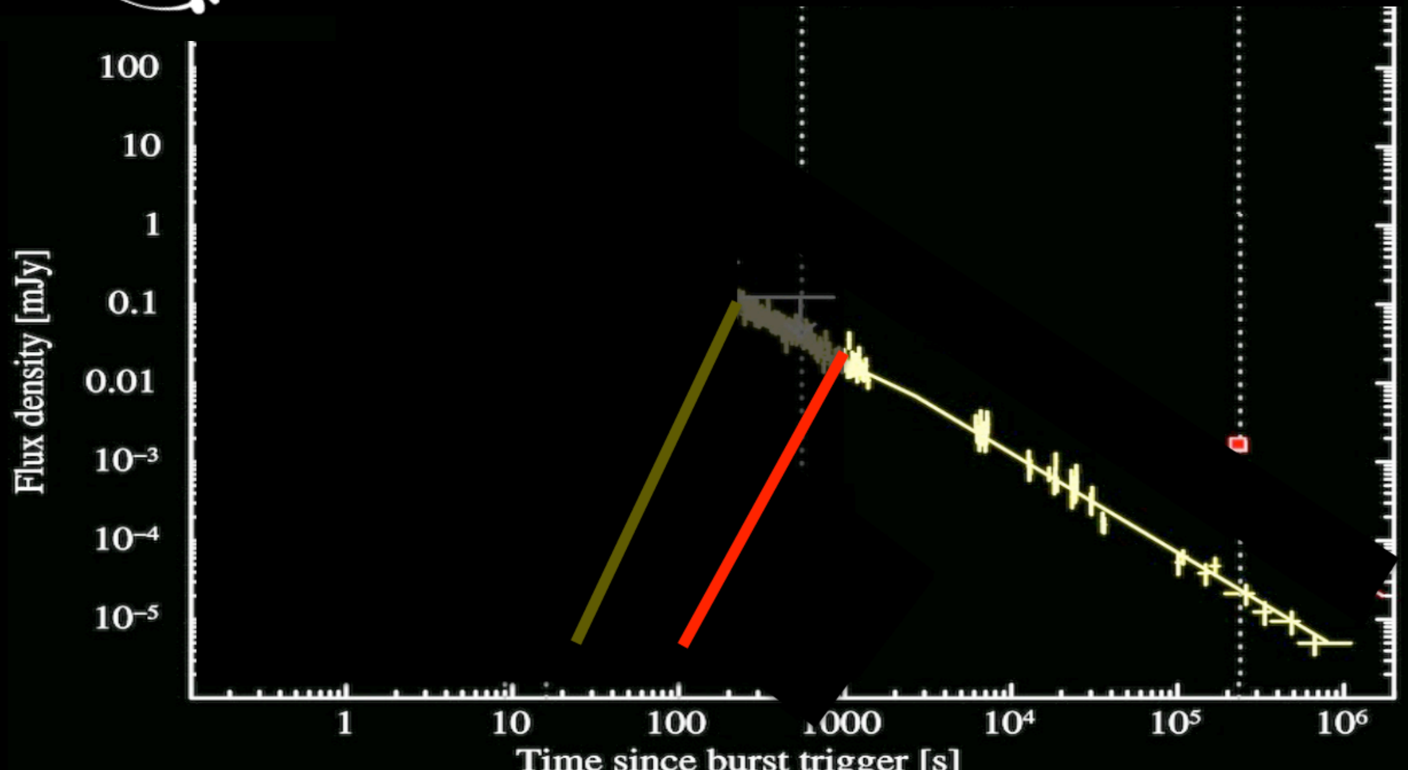
Early EM emission detectable only by on-axis observers

EM emission detectable also by off-axis observers



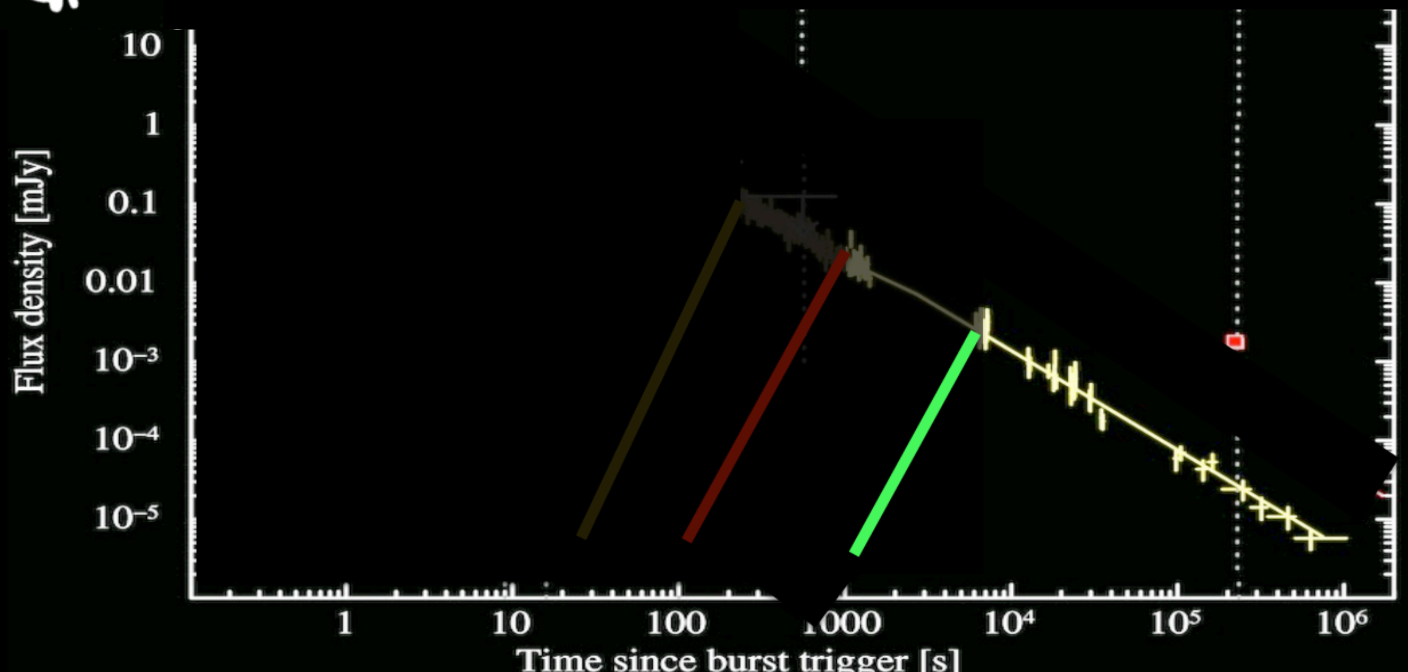
Credit: Salafia





Credit: Ghirlanda

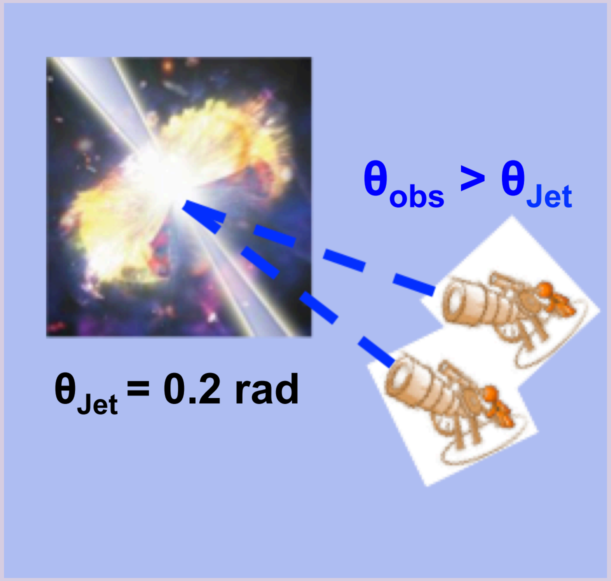
More off—axis:
(a) the emission peaks later
(b) the flux at peak is fainter



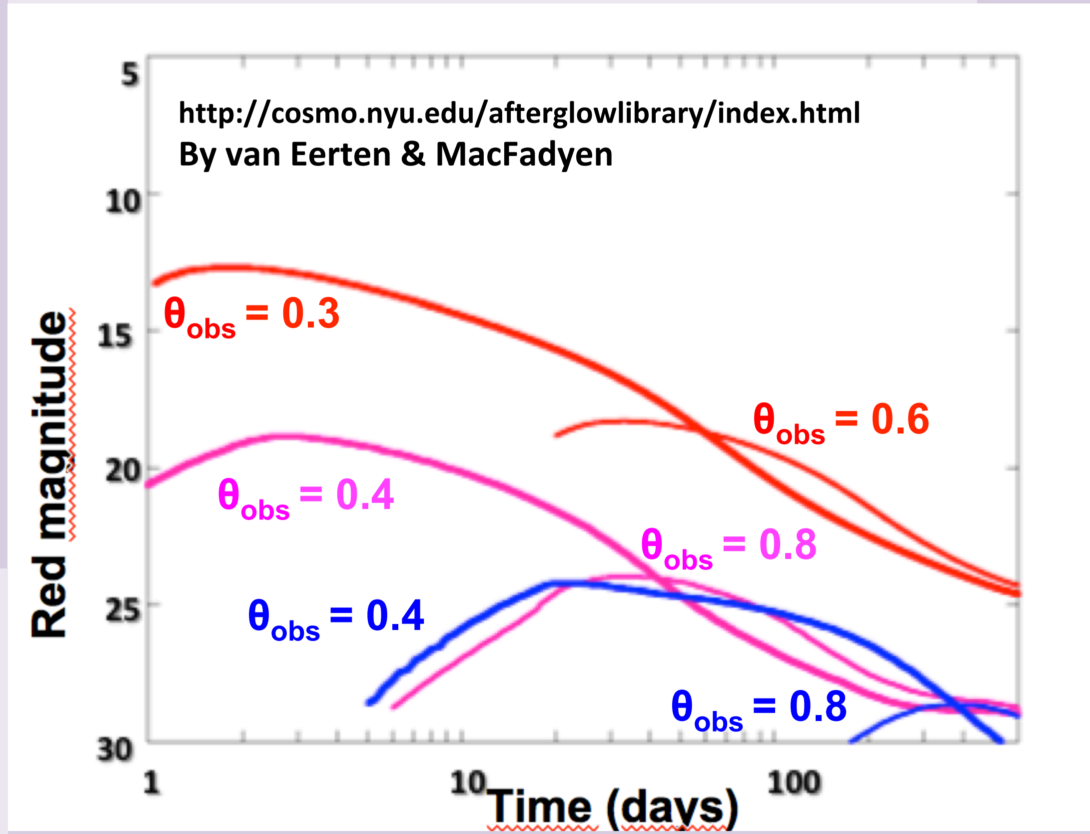
Credit: Ghirlanda

Optical afterglows of Off-axis GRBs

Off-axis GRB



Modelled afterglows - Source at 200 Mpc



LONG bright GRB

E_jet = 2e51 erg, n = 1 cm^{-3}

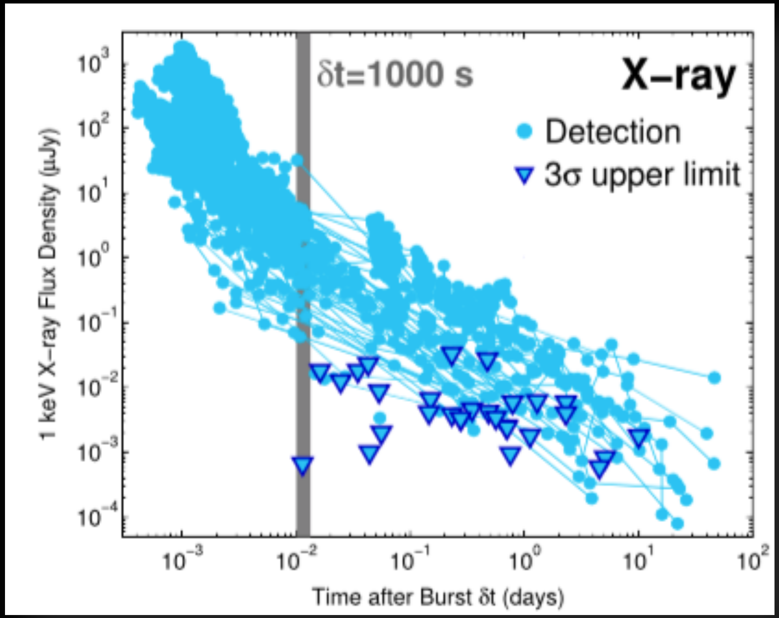
LONG faint/ SHORT bright GRB

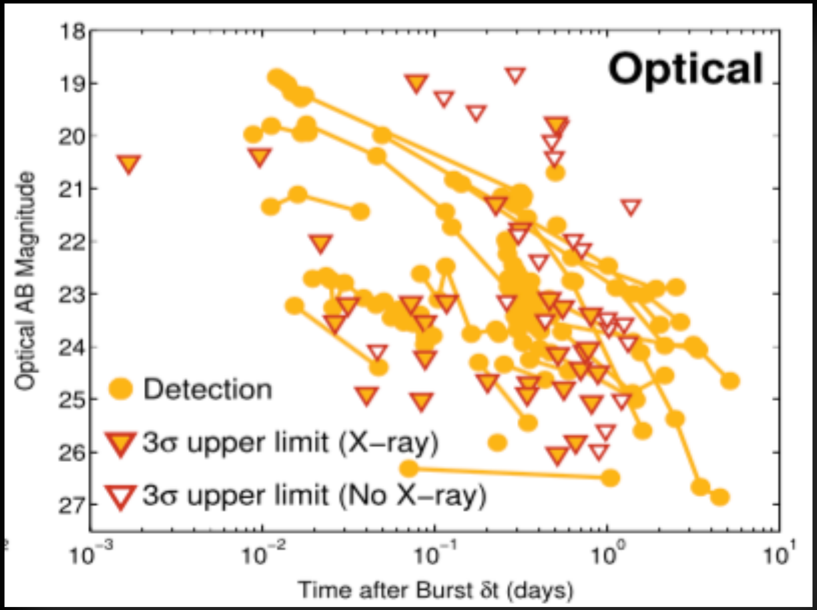
E_jet = 1e50 erg , n=1 cm-3

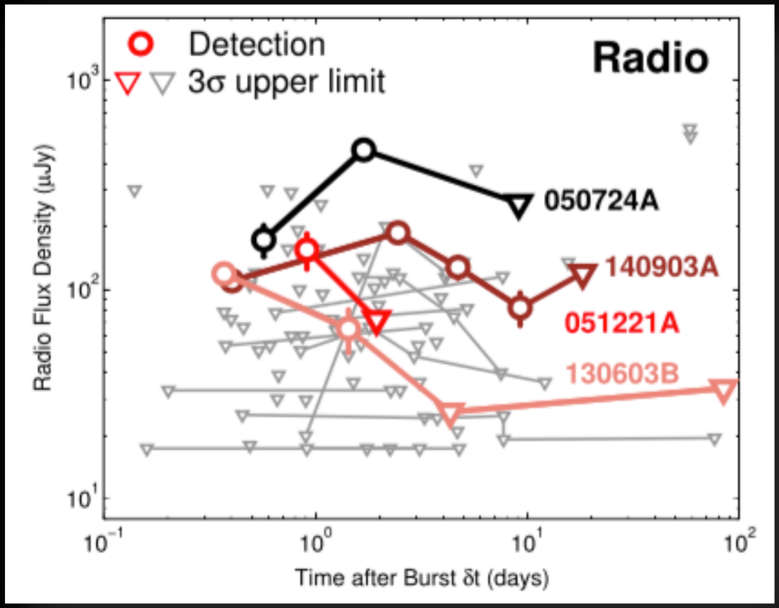
SHORT GRB

E_jet = 1e50 erg , n=10^{-3} cm^{-3}

Short GRB afterglows in numbers





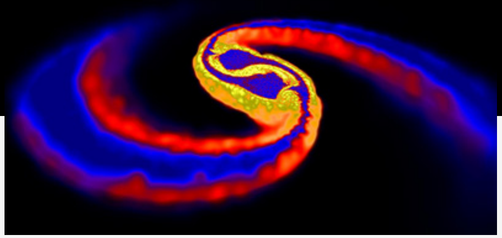


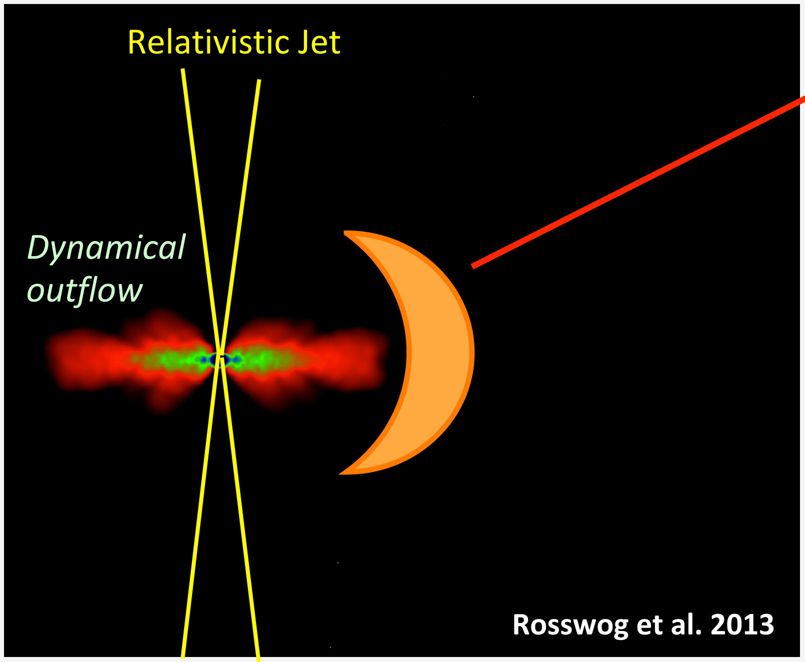
- About 140 SGRBs detected since 2005
- Afterglow detection percentage :
  - 90% in X-rays
  - 40% in opt
  - 7% in radio
- About 30 with redshift
- z_{min}=0.12 → 560 Mpc
- Energy =10^{48-52} erg

Fong et al. 2015

Thermal-emission

Kilonova





Tidal-tail ejecta → r-process

Neutron capture rate much faster than decay, special conditions: T > 10^9 K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

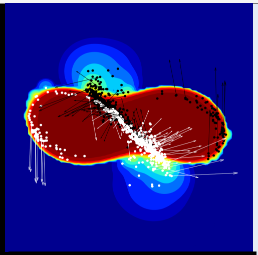
↓

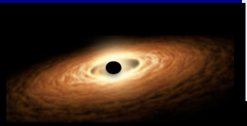
radioactive decay of heavy elements

↓

Power short lived RED-IR signal (days)

Li & Paczynski 1998; Kulkarni 2005 Metzger et al. 2010; Tanaka et al. 2014; Barnes & Kasen 2013





Shock-heated ejecta, accretion disc wind outflow, secular ejecta

→ Weak interactions: neutrino absorption, electron/positron capture

→ Higher electron fraction, no nucleosynthesis of heavier element

→ Lower opacity

→ brief (~ 2 day) **blue optical transient**

Kasen et al. 2015, Perego et al. 2014, Wanajo et al. 2010

Most Elements above the iron peak are believed to be produced through neutron capture

The two extremes are

- **s-process:** neutron capture timescale is longer (slower) than the decay timescale
- **r-process** neutron capture timescale is faster (more rapid) than the decay timescale

basic reactions:

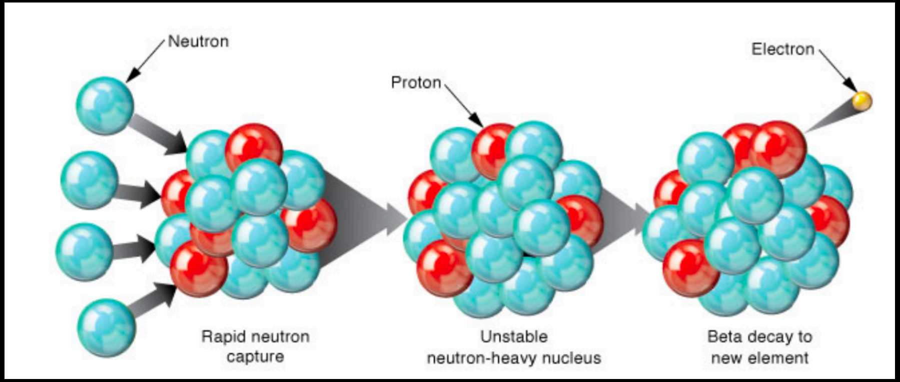
a) n-capture: $n + (Z,A) \Rightarrow (Z,A+1)$

b) β-decay: $(Z,A) \Rightarrow (Z+1,A) + e + \bar{\nu}_e$

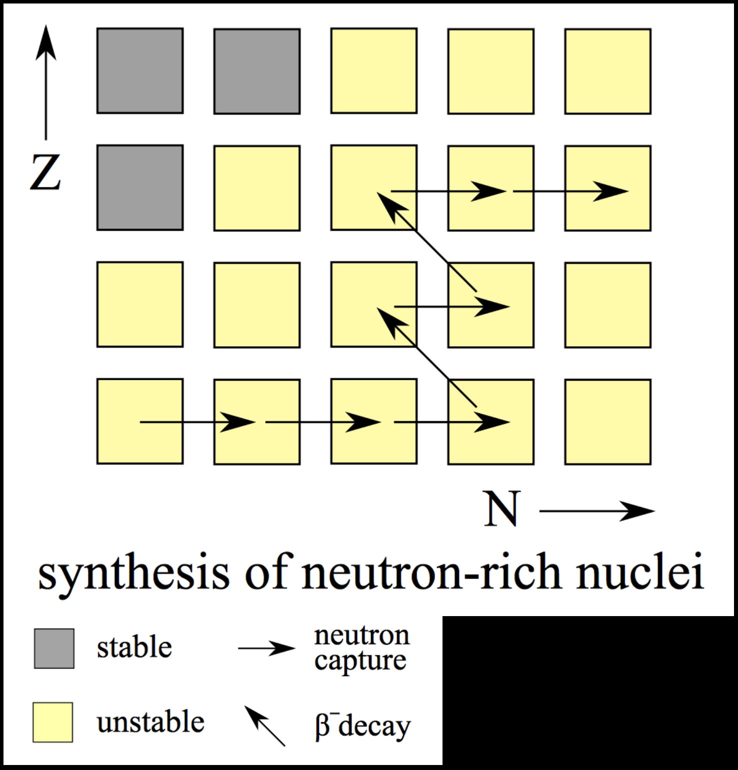
Z=proton number

N=neutron number

A=mass number=Z+N

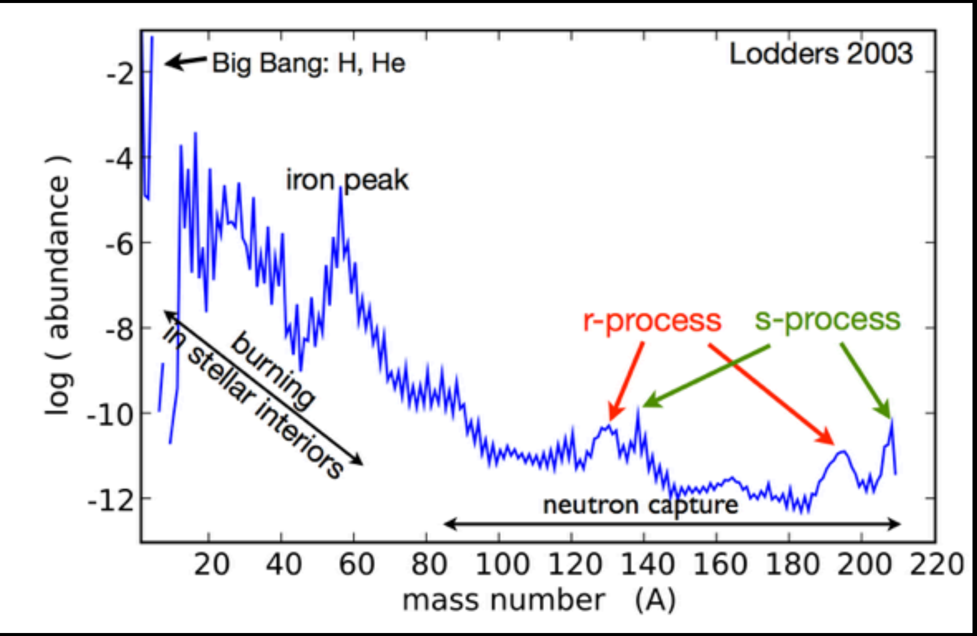


r-process



BNS and NS-BH mergers as factories of heavy elements in the Universe

Solar system abundances



Examples of r-process elements

Iridium
Z= 77, A= 192

Platinum
Z= 78, A= 195

Gold
Z= 79, A= 197

Lead
Z= 82, A= 207

R-PROCESS: ELECTRON FRACTION Y_E PLAYS DECISIVE ROLE!

$$\text{“electron fraction”} \quad Y_e = \frac{\#\ \text{protons}}{\#\ \text{nucleons}} = \frac{\#\ \text{electrons}}{\#\ \text{nucleons}}$$

- High temperature (as ~ 10 MeV) → copious e^-e^+ pairs that activate the WEAK INTERACTIONS

$$e^+ + n \longrightarrow p + \bar{\nu}_e$$

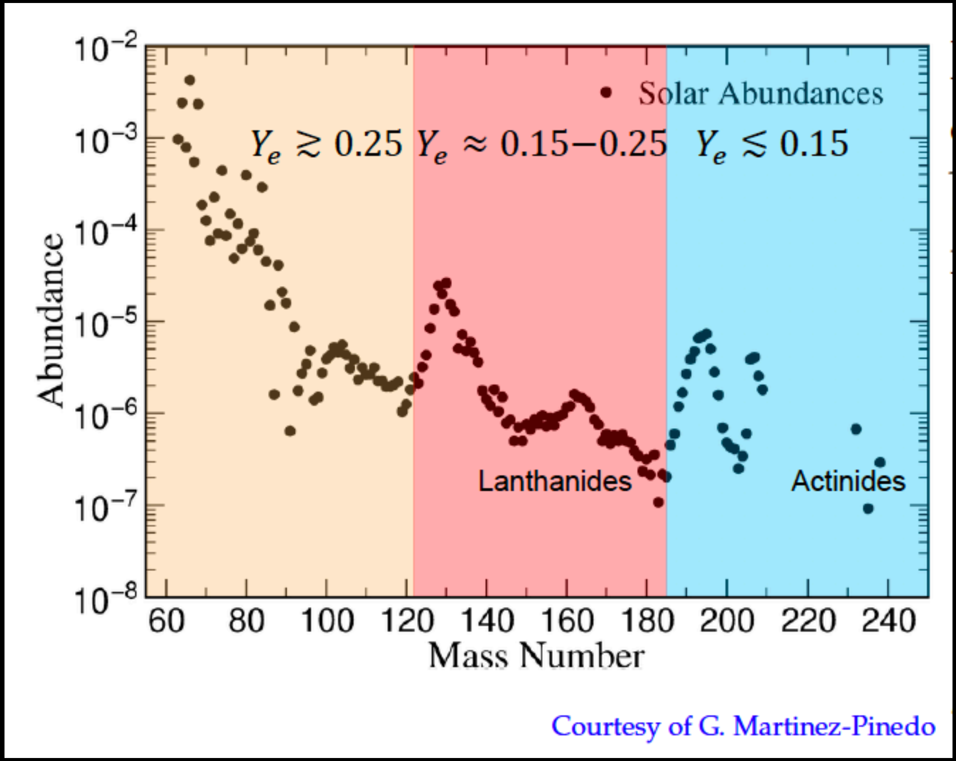
$$p + e^- \longleftarrow \nu_e + n$$

The e+ and ν_e captures convert some part of neutrons to protons → Ye increase

- High neutrino flux, neutrino-matter interactions→ Ye increase

$$\nu_e + n \longrightarrow p + e^-$$ Neutrino-absorption

- $Y_e > 0.5$: no r-process
- $0.25 \lesssim Y_e < 0.5$: weak r-process
- $Y_e \lesssim 0.25$: strong r-process



Production of lathanides dramatically changes photon opacity

- no lanthanides: low opacity ($\kappa_\gamma \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$)
- presence of lanthanides: increased opacity ($\kappa_\gamma \gtrsim 10\,\mathrm{cm}^2/\mathrm{g}$)

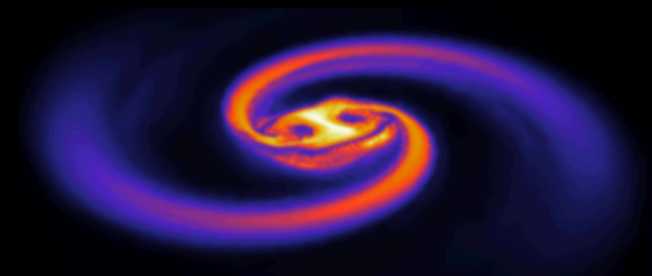
EJECTA TYPE

i) dynamic

a) tidal:

- equatorial
- cold
- low Ye~ 0.1
- ~1% Mo

~1 ms



From Rosswog et al. 2017

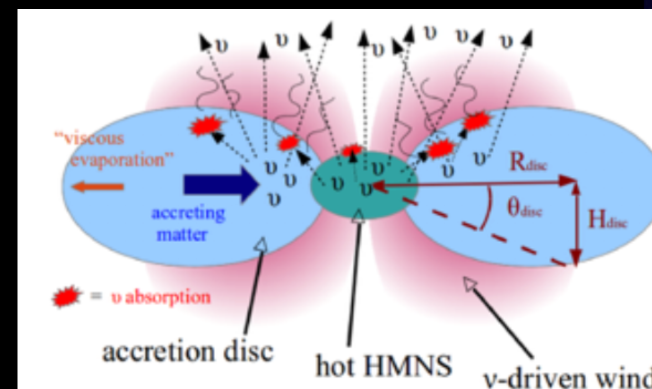
b) shock-heated:

- polar
- hot
- higher Ye> 0.1
- ~1% Mo

~10-100 ms

ii) neutrino-driven winds

- polar
- higher Ye> 0.1
- ~1% Mo

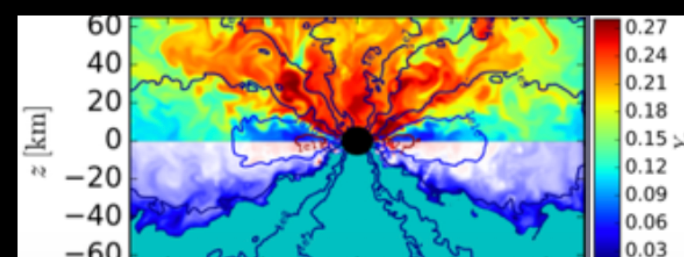


From Perego et al. 2014

iii) Secular

- isotropic
- broad range of Ye
- ~30% initial disk mass

~1s



From Siegel & Metzger et al. 2014

Kilonova: Main Ingredients

k ← Opacity

m_{ej} ← Mass of the Ejecta

v_{ej} ← Velocity of the Ejecta

(Grossman et al. 2014)

$$t_{peak} \simeq 4.9\,days\left(\frac{k}{10\,cm^2/g}\frac{m_{ej}}{0.01\,M_\odot}\frac{0.1\,c}{v_{ej}}\right)^{1/2}$$

$$L_{peak} \simeq 2.5\times 10^{40}\,\frac{erg}{s}\left(\frac{v_{ej}}{0.1\,c}\frac{10\,cm^2/g}{k}\right)^{0.65}\left(\frac{m_{ej}}{0.01\,M_\odot}\right)^{0.35}$$

EM emissiom key ingredients:

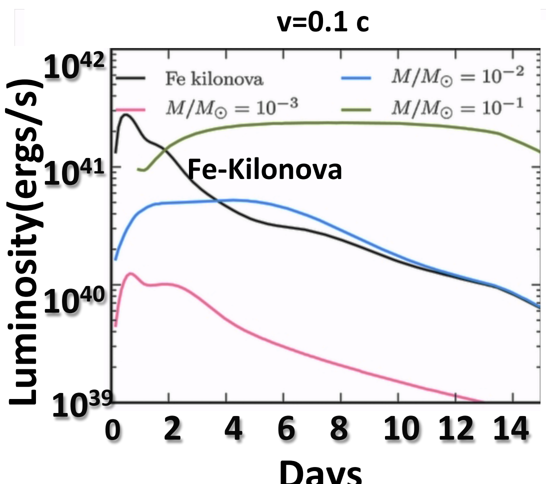
- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics

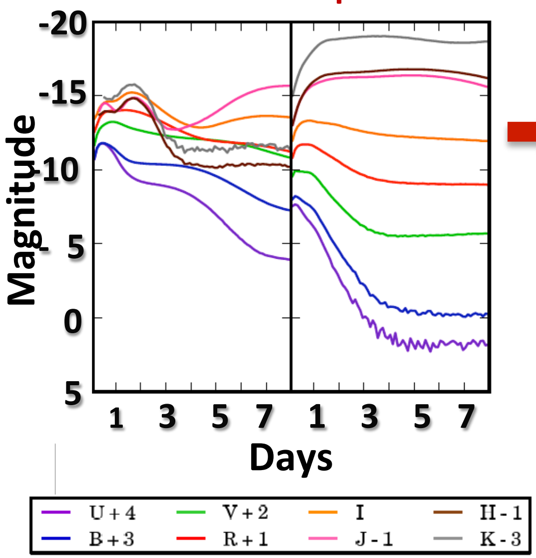
OPACITY of Fe and “heavy r-process elements”

Barnes & Kasen 2013, ApJ, 775



Opacities:

Fe **r-process**

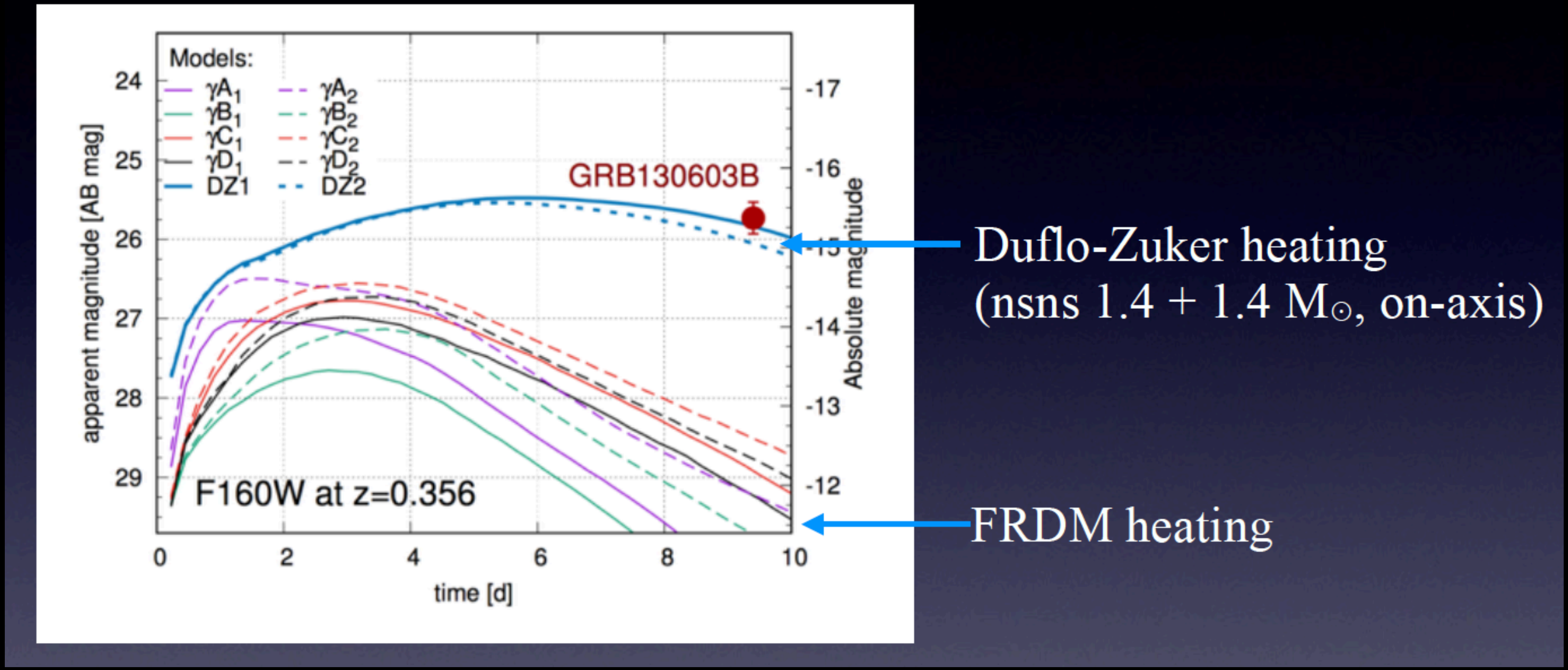


r-process opacity

- broader light curve
- suppression of UV/O emission and shift to IR

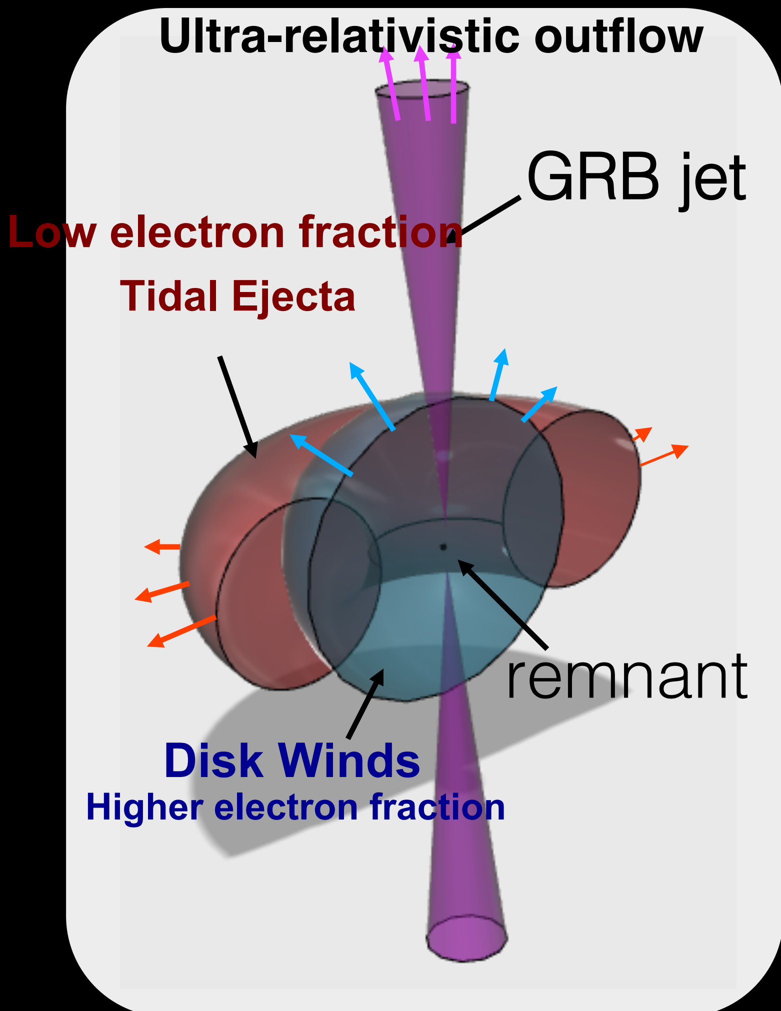
EM emissiom key ingredients:

- ejecta mass and velocity ⇒ astrophysics
- opacity κ ⇒ atomic physics
- radioactive heating rate ⇒ nuclear physics



Credit:
Rosswog@GWPAW2017

Geometry of the Ejecta



Courtesy of S. Ascenzi

Tidal Ejecta → **Red Macronova**

unbound by hydrodynamic interaction and gravitational torques

Peaks at days - 1 week after the merger

Secular – isotropic

accretion disk matter unbound by viscous and nuclear heating

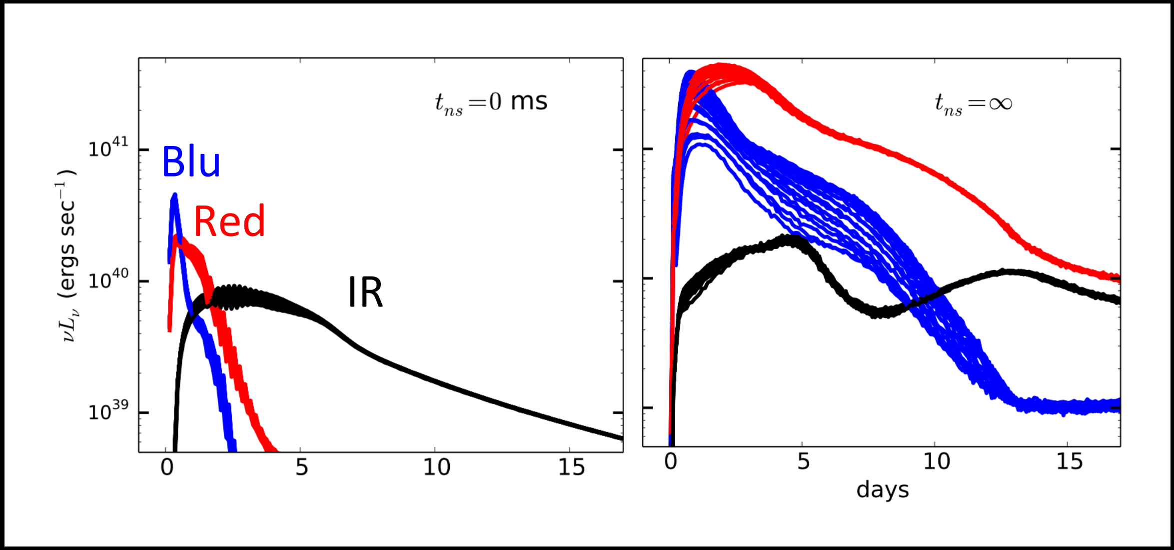
Shock-heated → **Blue Macronova**

squeezed matss at NS contact interface ejected by remnant pulsations

Peaks at 1-2 day after the merger

Disk Winds

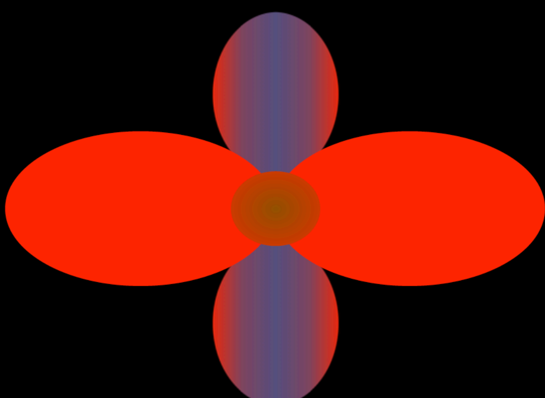
neutrino absorption or magnetically launched winds longer-lived NS → stronger neutrino irradiation



Kasen et al. 2015, MNRAS, 450

Cartoon picture

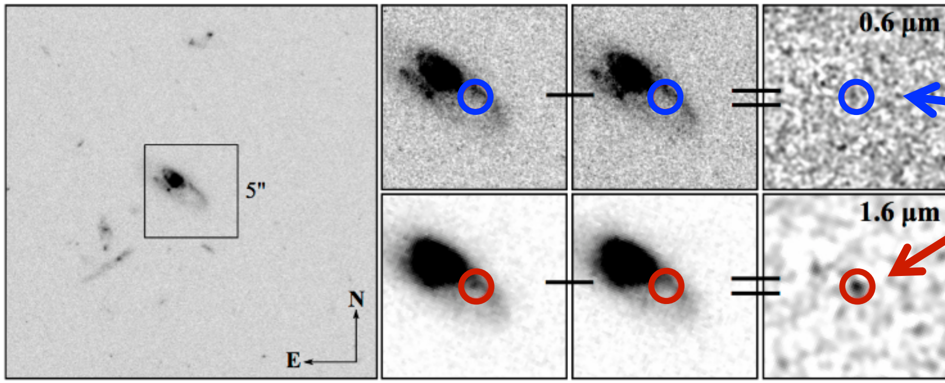
- "Winds", Ye ~ 0.3
- "weak r-process" (A <130)
- lanthanide/actinide-free
- moderately opaque ⇒ blue
- τpeak ~ 1 day



- **Dynamic Tidal ejecta**, Ye ~ 0.1
- "strong r-process"
- lanthanide/actinide
- very opaque ⇒ Red/IR
- τpeak ~ 1 week/10 days

Credit:
Rosswog@GWPAW2017

Possible HST kilonova detection for short GRB130603B after 9.4 days (Tanvir et al. 2013, Nature ,500)

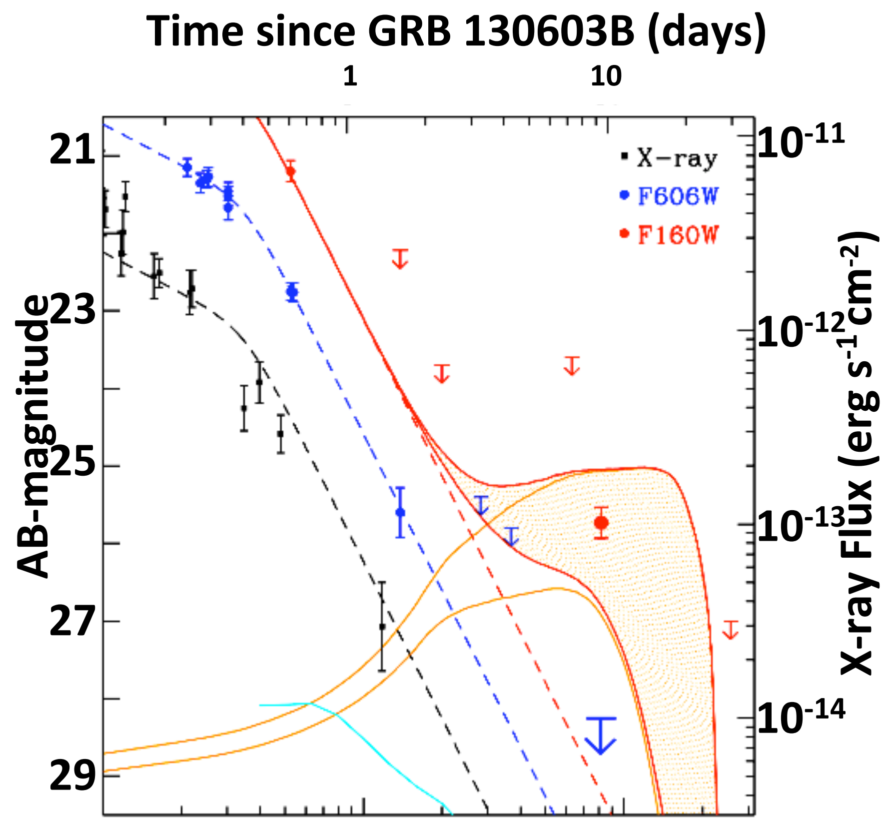


HST two epochs (9d, 30d) observations

F606W/optical

NIR/F160W

Afterglow and host galaxy z=0.356

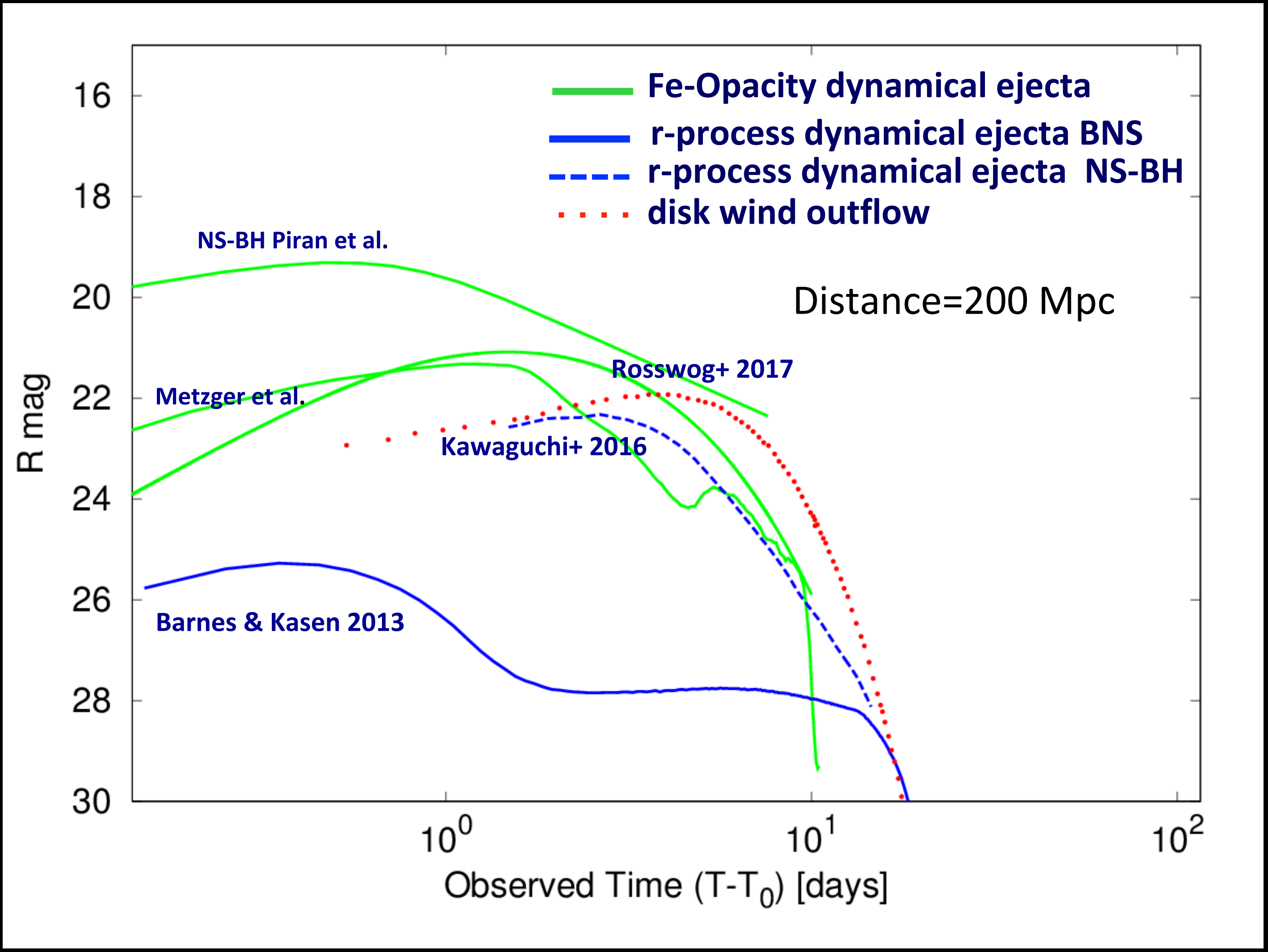


Orange curves → kilonova NIR model
ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

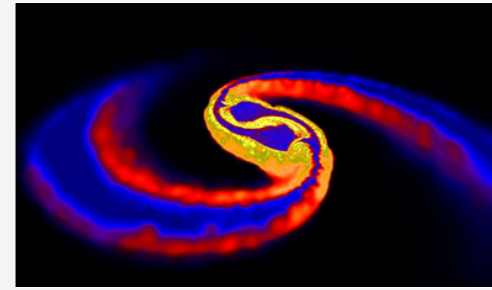
Cyan curve → kilonova optical model

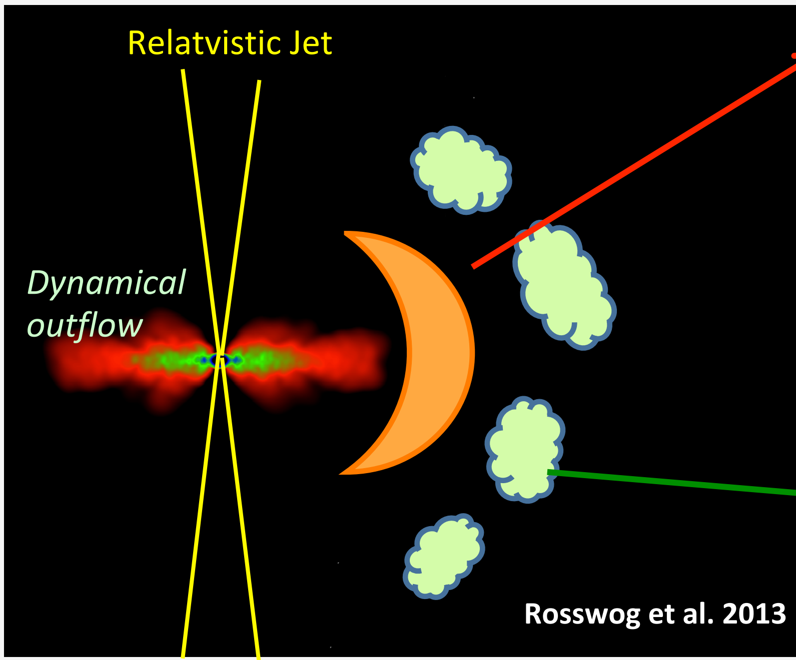
Examples of Optical kilonova ligth curves



Kilonova-Radio remnant

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected**
during **NS-NS NS-BH mergers**
at **sub-relativistic velocity (0.1-0.3 c)**



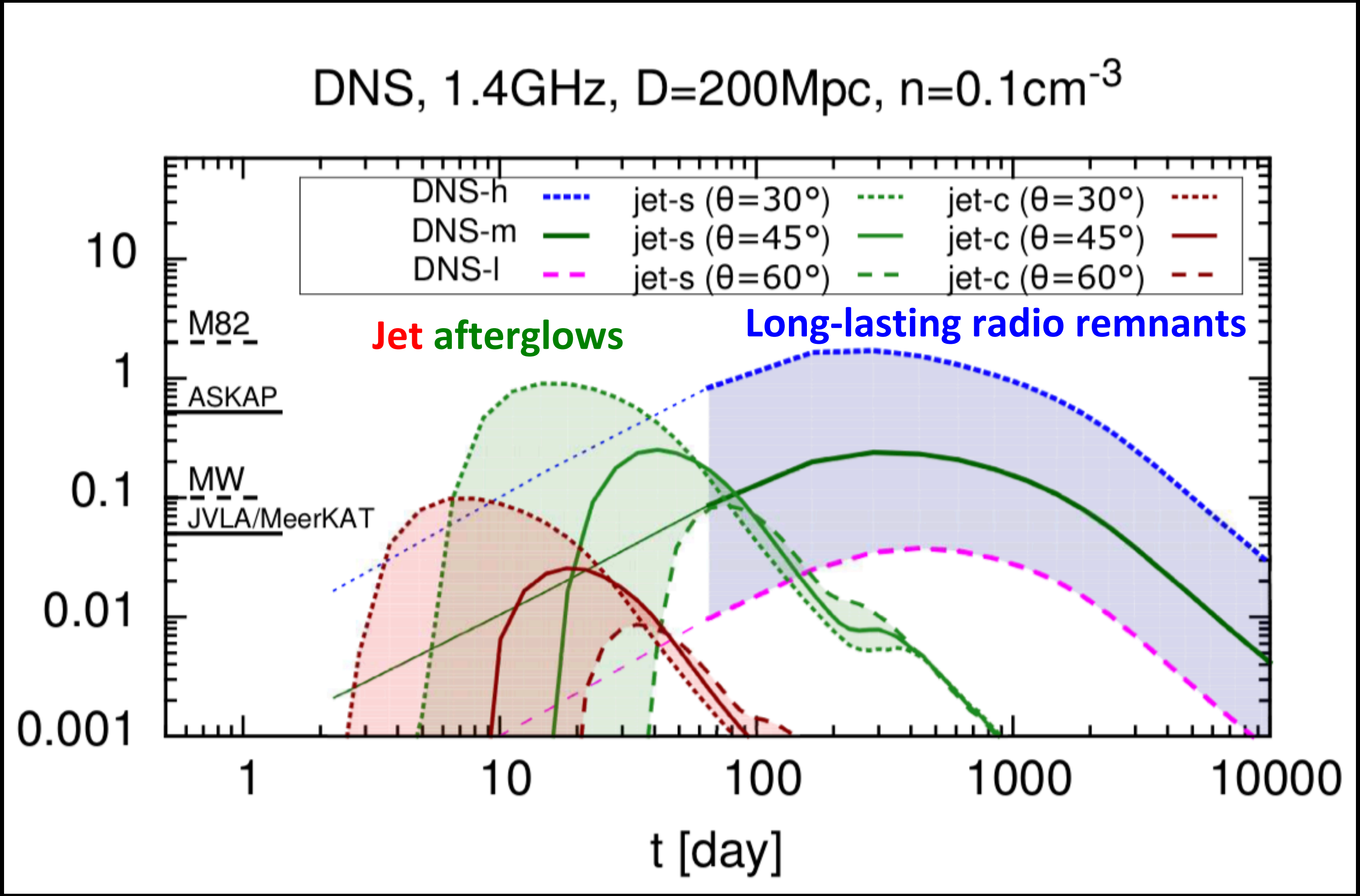


Power KILONOVA
short lived IR-UV signal (days)

RADIO REMNANT
long lasting radio signals (months-years)
produced by interaction of sub-relativistic outflow with surrounding matter

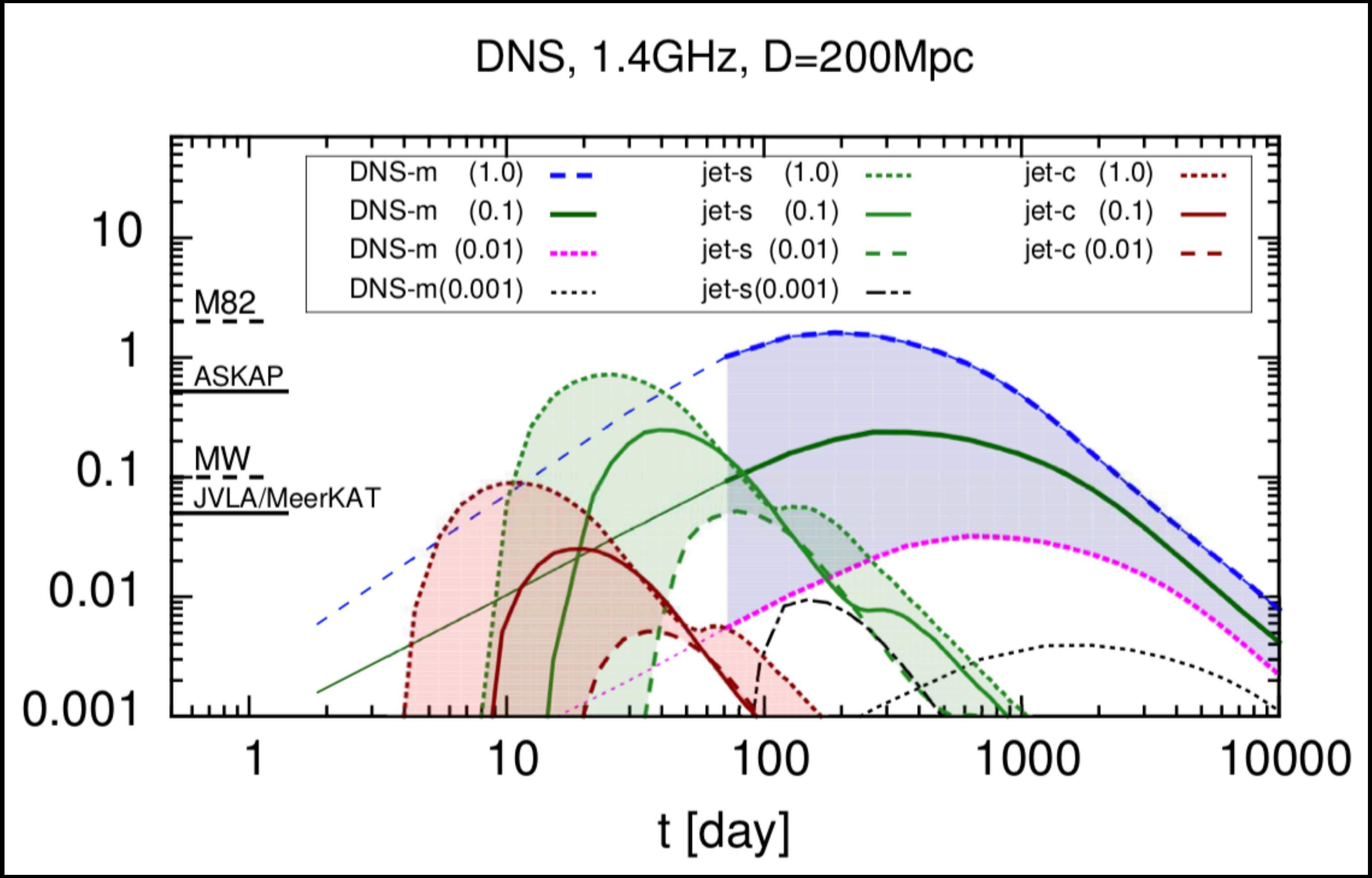
Piran et al. 2013, MNRAS, 430
Hotokezaka 2016, ApJ, 831, 190

Kilonova-Radio remnant + Radio sGRB afterglow



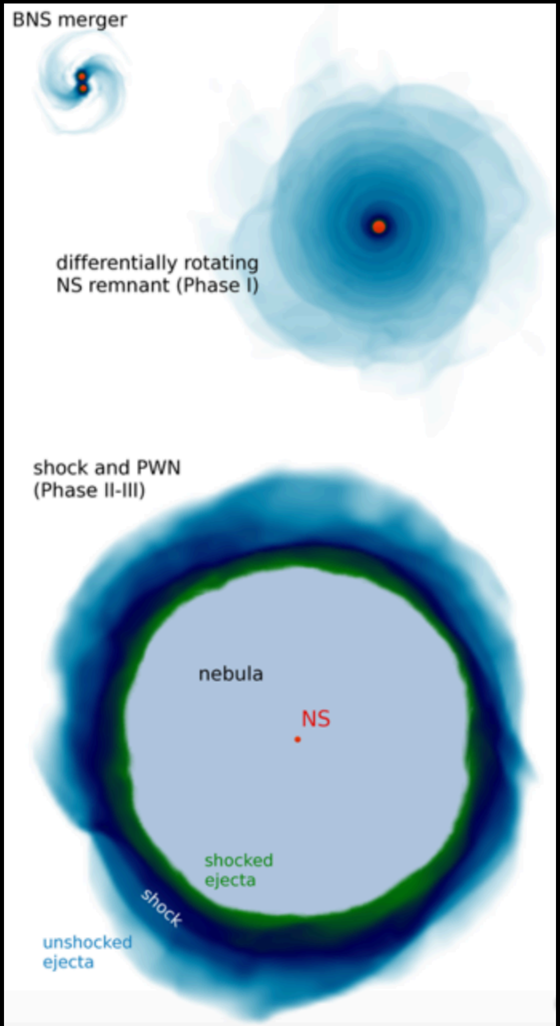
Hotokezaka 2016, ApJ, 831, 190

Key role of the circum-merger densities



Hotokezaka 2016, ApJ, 831, 190

X-ray emission from the long-lived NS remnant

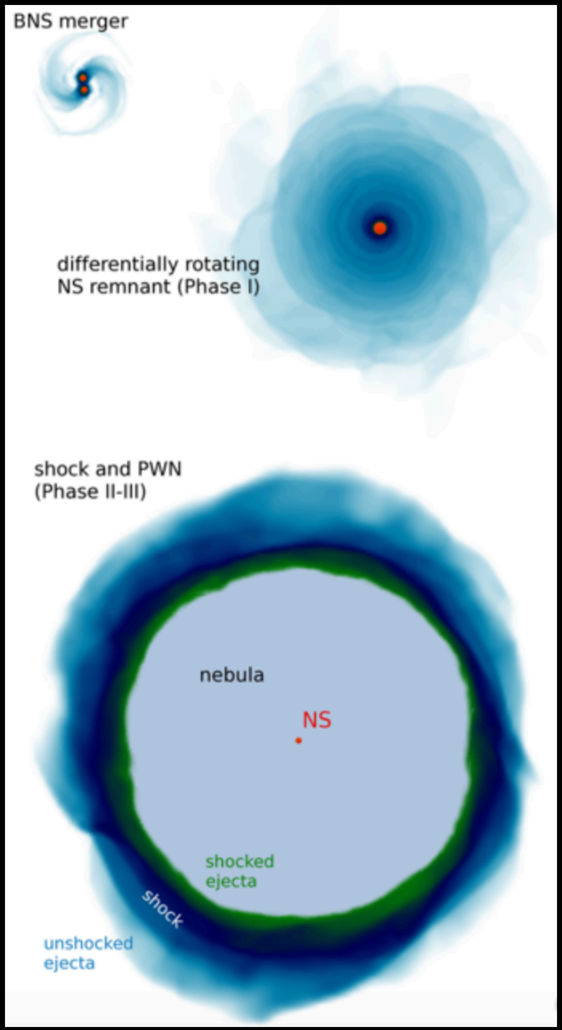


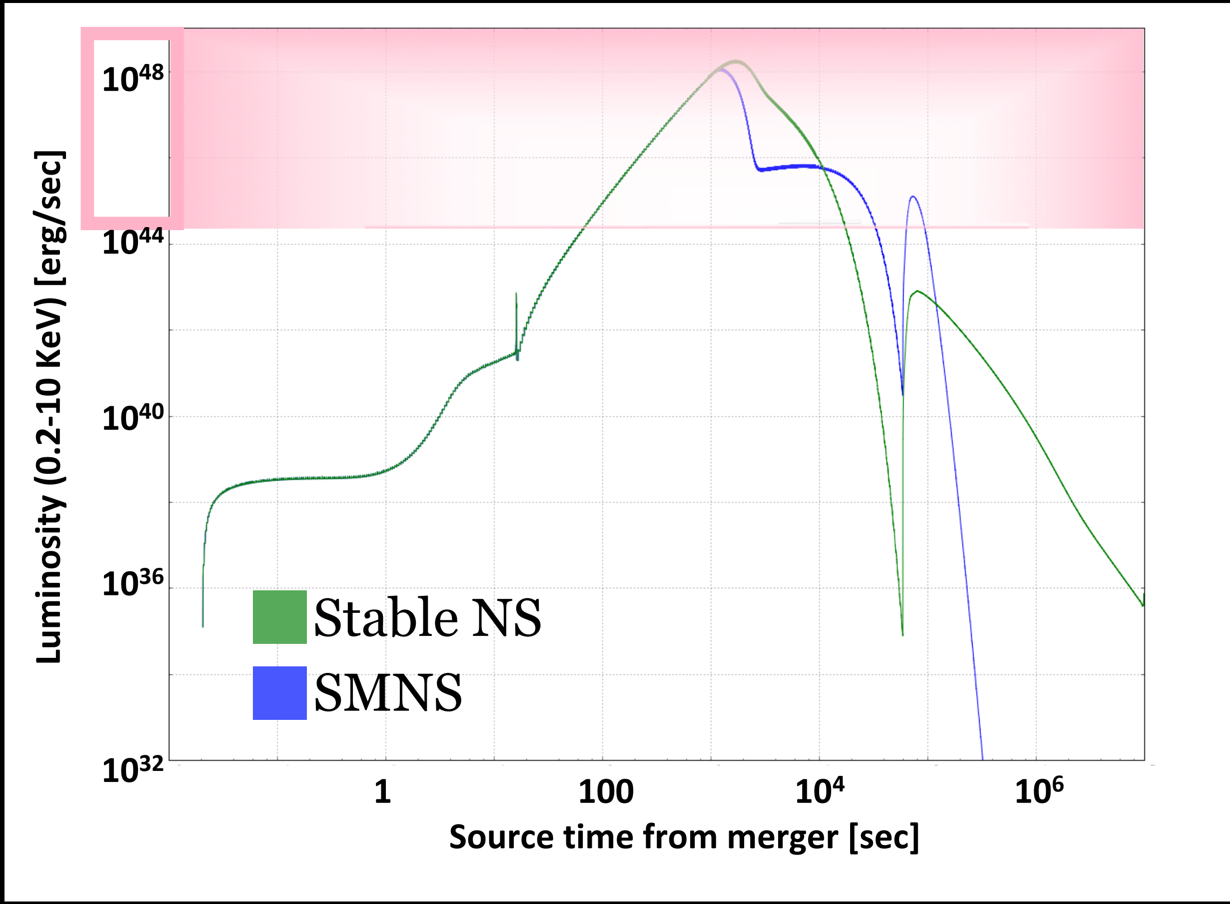
- X-ray afterglow radiation produced by spin-down energy extracted from the NS prior to collapse, slowly diffusing through optically thick environment composed of a pulsar wind nebula (PWN) and outer shell of ejected material
- signal peaks at 10^2-10^4 s after the merger
- luminosities 10^{46}-10^{49} erg/s
- mostly in the soft X-rays (0.2-10 keV)

Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15

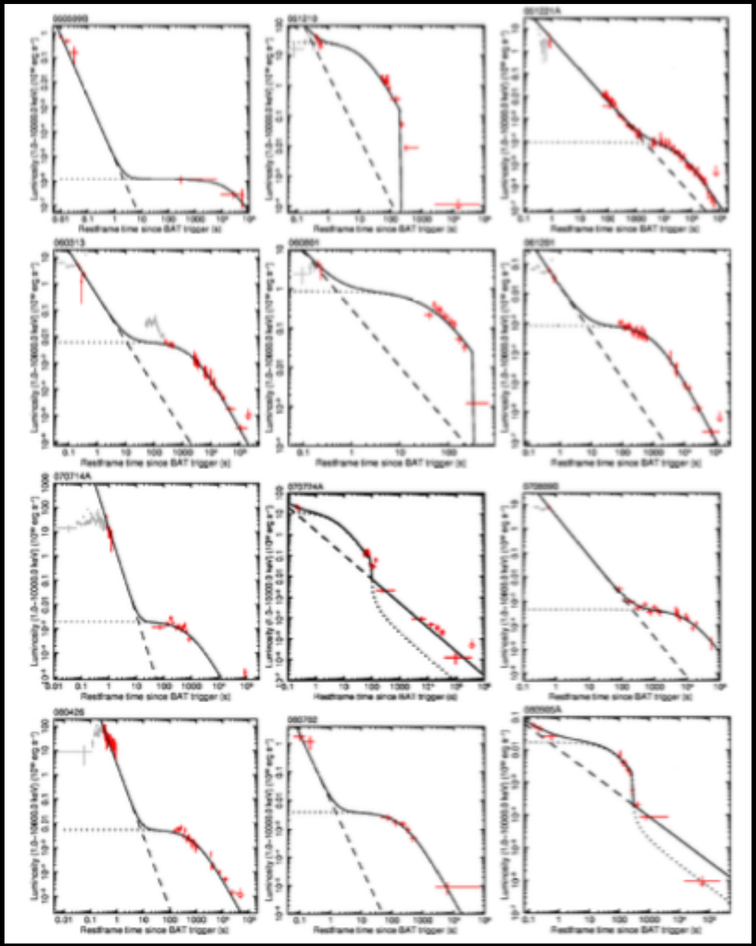
X-ray emission from the long-lived NS remnant

- ISOTROPIC
- BRIGHT
- LONG LASTING





Siegel & Ciolfi 2016, ApJ, 819, 14
Siegel & Ciolfi 2016, ApJ, 819, 15



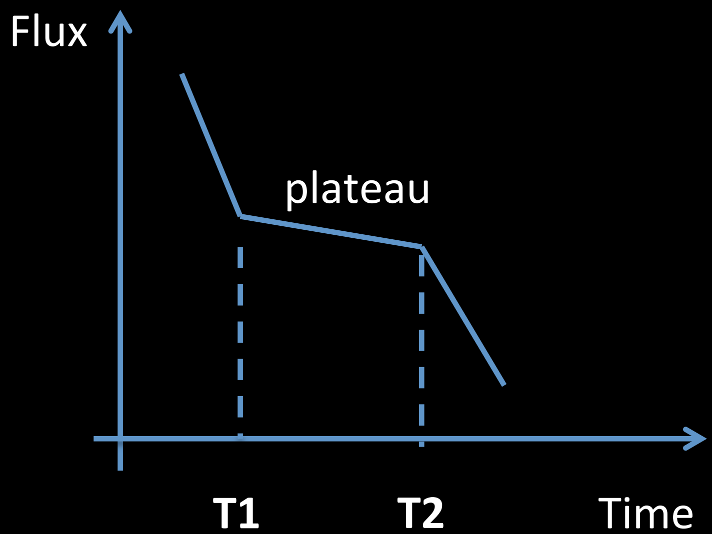
Rowlinson et al. 2013

"X-ray plateaus"

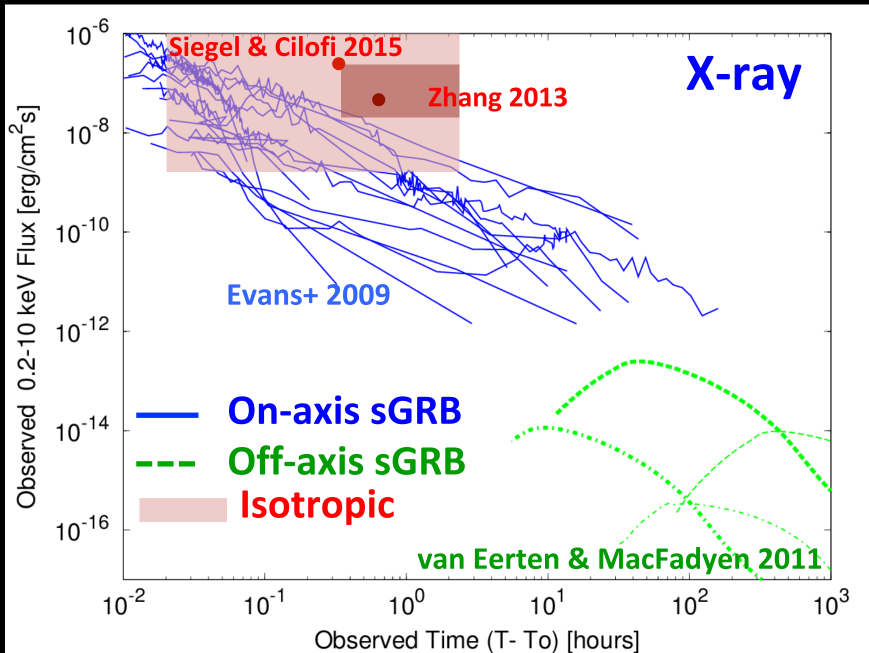
- Plateaus are found in a large fraction of long GRB X-ray light curves
- Possible evidence of ongoing central engine activity

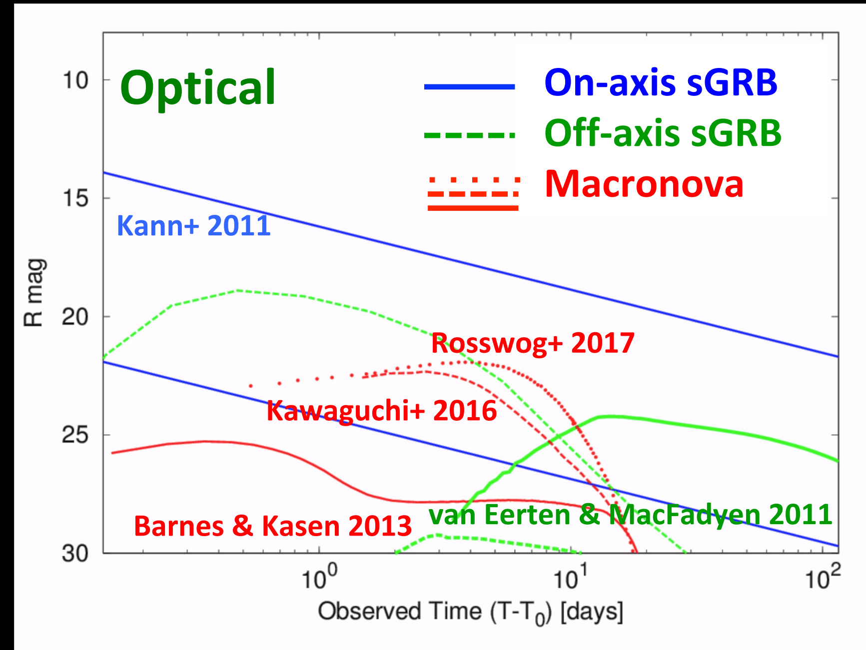
Rowlinson+2013 found that ~50% Short GRB X-ray afterglows show a plateau phase in their light curves

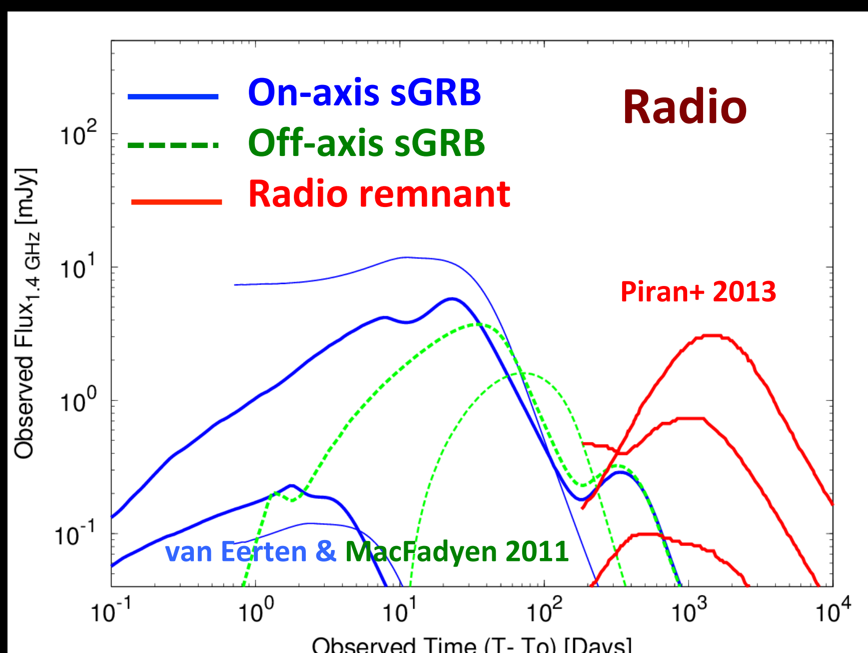
The plateaus can be explained with the spin-down of magnetar or SMNS

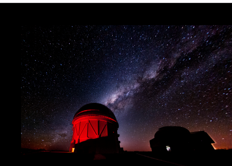


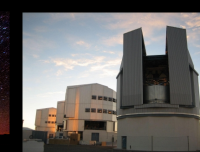
NS-NS merger EM-emissions











Source at 200 Mpc

Different timescale

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)
→ Afterglows X-ray, optical, radio
(minutes, hours, days, months)

Off-axis
afterglo

Macr

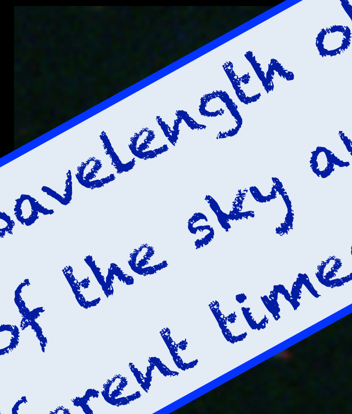
mission

Radio remnants
(months, years)

X-

s)

Core-coll

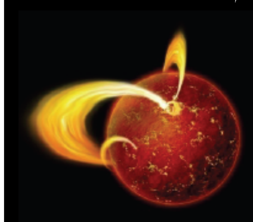


ns)

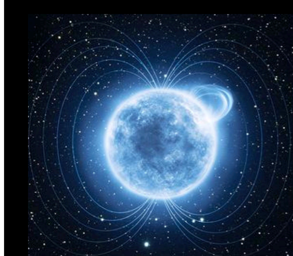
(years)

+ Long GRB

Isolated NS instabilities



Soft Gamma Ray
Repeaters and
Anomalous X-ray Pulsars



Radio/gamma-ray
Pulsar glitches

Request for network of multi-wavelength observatories which cover huge region of the sky and repeat observations over different timescales...

BH-BH mergers → EM emission ?

Stellar-mass BH mergers *are* ***not expected to produce detectable counterparts****, due to the absence of baryonic matter*
(no NS tidal disruption → no accreting material)

Some unlikely scenarios that might produce unusual presence of matter around BBH:

- from the remnants of the stellar progenitors
  (Loeb,2016; Perna et al., 2016; Janiuk et al., 2017)
- the tidal disruption of a star in triple system with two black holes
  (Seto & Muto, 2011; Murase et al., 2016)
- enviroment of binaries residing in active galactic nuclei
  (Bartos et al., 2017; Stone et al., 2017)