第二届GECAM研讨会

SPECIAL SUPERNOVA SIGNATURE FROM BH-NS/BH PROGENITOR SYSTEMS

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Gao et al. 2020, ApJL, 902,37; arXiv: 2008.09846

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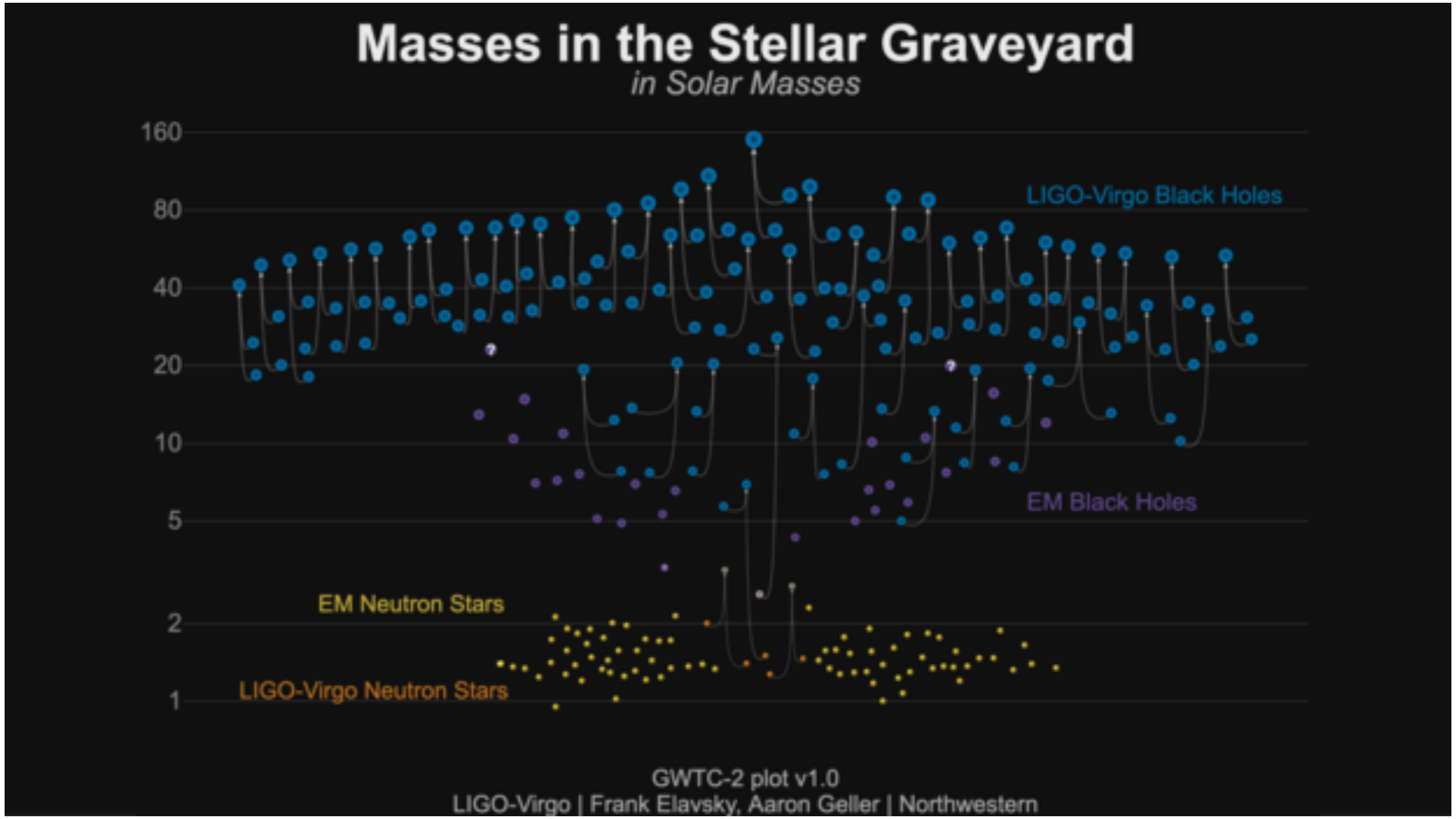
BH-BH and BH-NS Systems Widely Exist



O1 & O2

10 BH-BH systems detected

Event rate density

$$R = 53.2^{+55.8}_{-28.2}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

O3

3 BHNS

(GW190426, GW200105, GW200115)

1 MassGap (GW190814)

36 BBHs

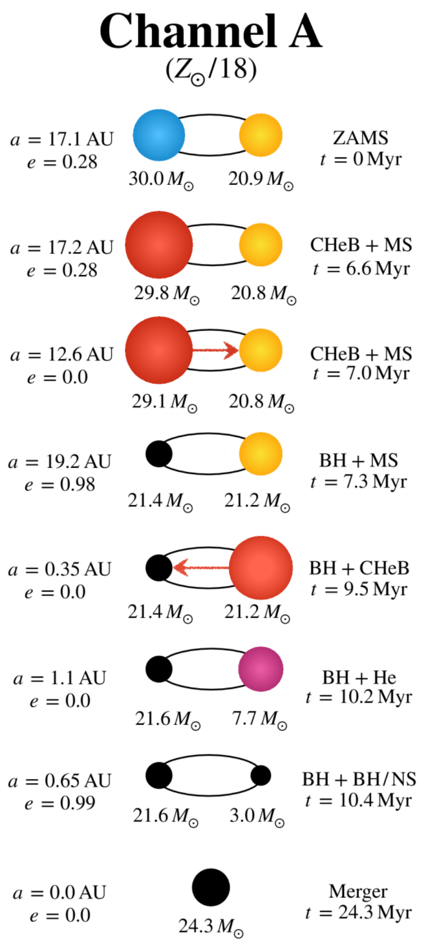
GW190412 (asymmetric),

GW190521(most massive)

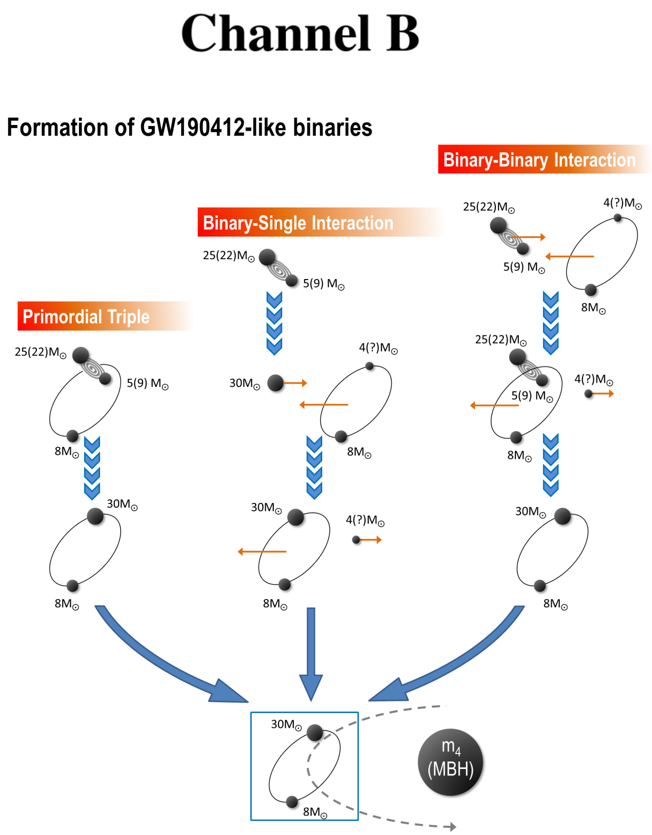
…

$$\mathcal{R}_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Formation Channel of BH-NS/BH Systems ?



Zevin et al. (2020)



Liu & Lai (2020)

Two main types of scenarios have been invoked for the formation of BH-NS/BH systems:

- **Channel A: isolated binary evolution in galactic fields**

  Tutukov & Yungelson 1973; Lipunov et al. 1997; Belczynski et al. 2016; …

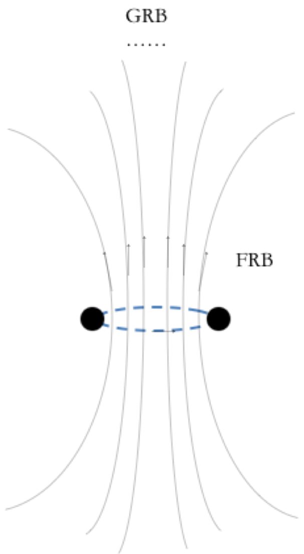
- **Channel B: dynamical interactions in dense environments**

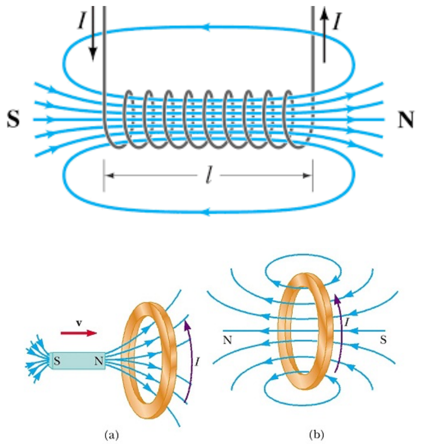
  Sigurdsson & Hernquist 1993; Portegies Zwart & McMil- lan 2000; Rodriguez et al. 2015; …

Can EM Observations Help to Distinguish the Formation Channel of BH-NS/BH Systems ?

EM Counterparts of GW detection?

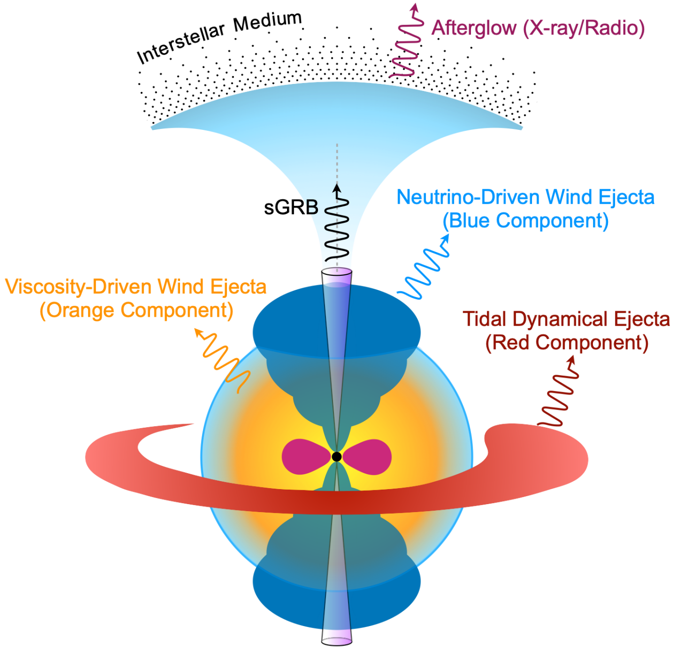
BH-BH





Zhang 2016

BH-NS



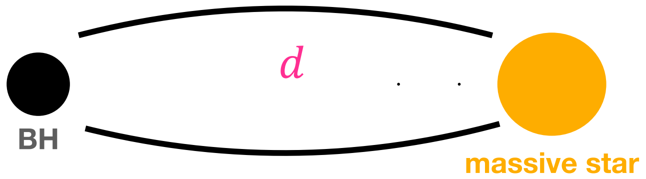
Zhu, et al. 2020

Delay time between compact binary formation and coalescence is too long

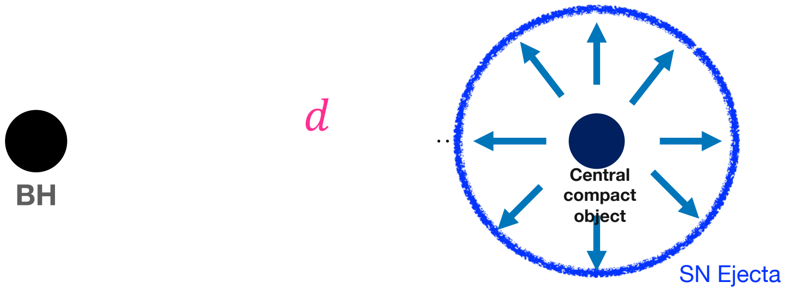
$$\tau_{\rm GW} \approx 4.8 \times 10^{10}\ {\rm yr} \left(\frac{P_{\rm b}}{\rm d}\right)^{8/3} \left(\frac{\mu}{M_\odot}\right)^{-1} \left(\frac{M_{\rm c}+M_{\rm p}}{M_\odot}\right)^{-2/3} (1-e^2)^{7/2}$$

Can EM Observations Help to Distinguish the Formation Channel of BH-NS/BH Systems ?

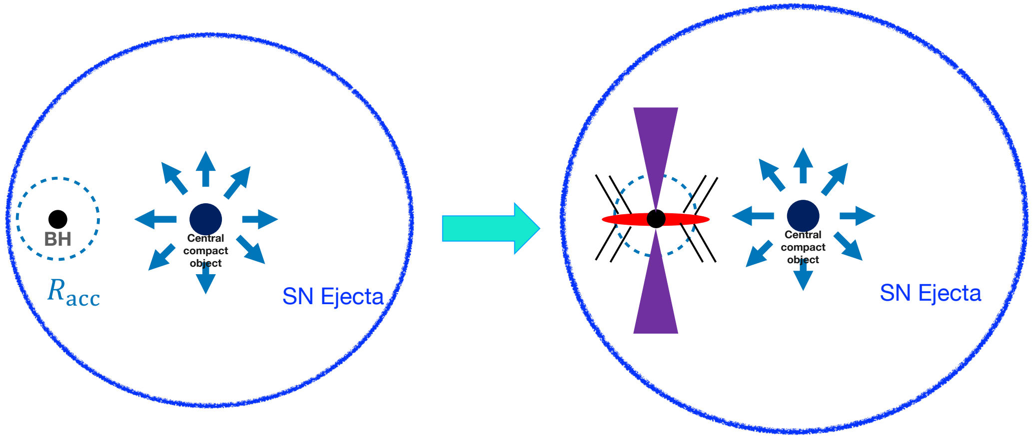
EM signatures at the formation time?



If the BH-NS/BH systems are formed from Channel A (isolated binary evolution):

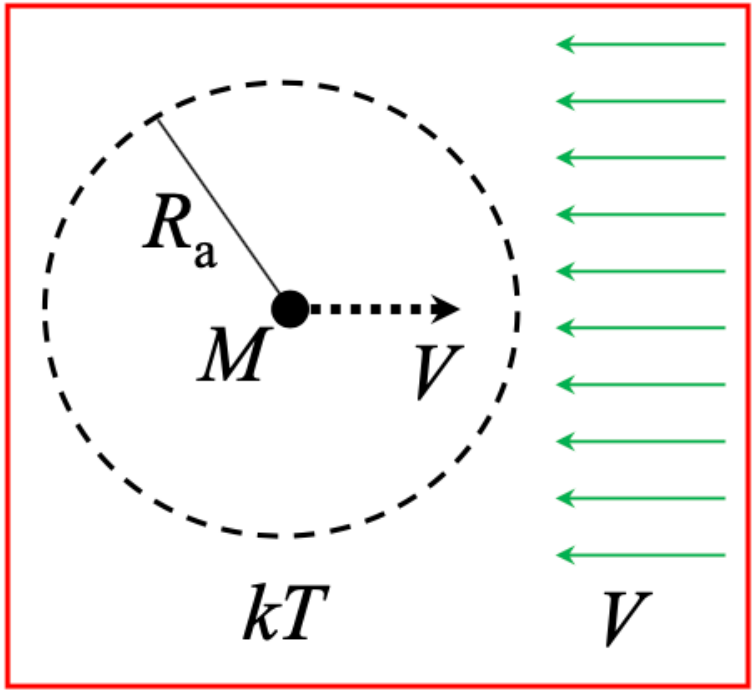


The second core collapse SN would show some identifiable features, due to the accretion feedback from the companion BH.



Comparing the event rate density of these special supernova signals with the event rate density of LIGO-Virgo detected BH-NS/BH systems could help to distinguish the BH-NS/BH formation channel.

Model Details



The accretion radius of the BH

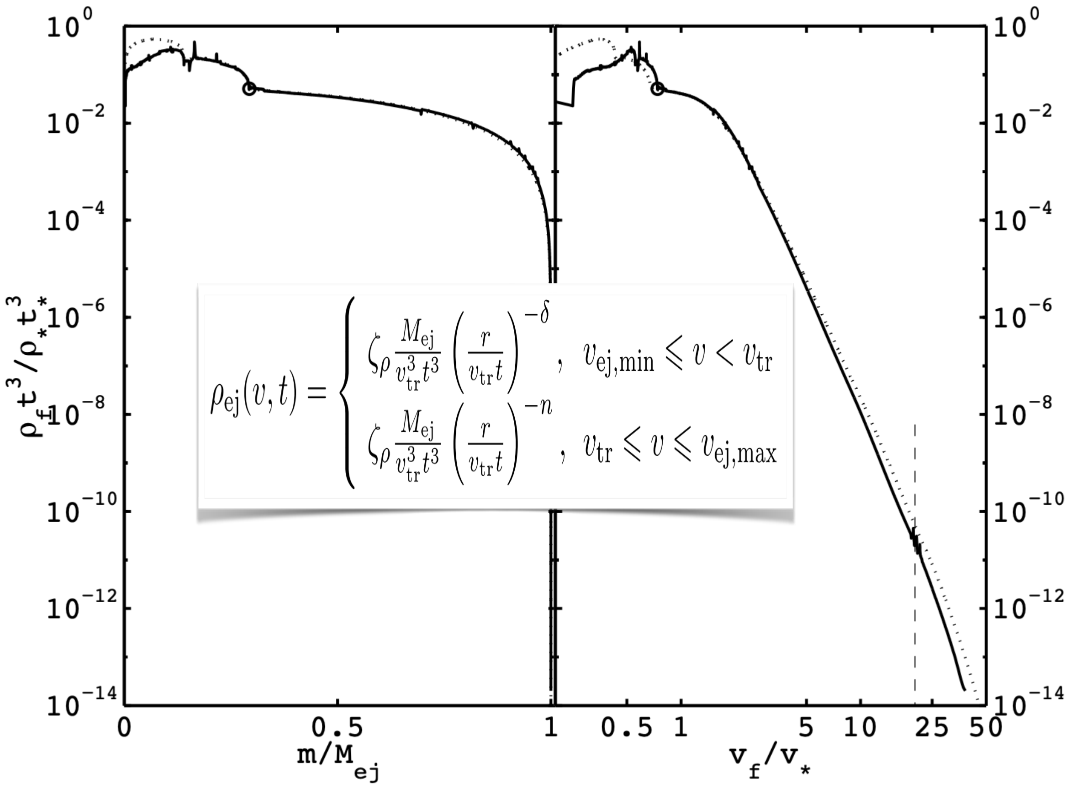
$$R_{\rm acc} = \frac{2GM_{\rm BH}}{v^2} \simeq 5.3\times10^9 {\rm cm} \left(\frac{M_{\rm BH}}{20 M_\odot}\right) \left(\frac{v}{10^4 {\rm km\ s^{-1}}}\right)^{-2}$$

The time for the falling process is set as

$$t_{\rm start} = \frac{d - R_{\rm acc} - R_{\rm max,0}}{v_{\rm ej,max}} \sim 10^4 \ {\rm s} \left(\frac{d}{10^{13} {\rm cm}}\right) \left(\frac{v_{\rm ej,max}}{10^4 {\rm km\ s^{-1}}}\right)^{-1}.$$

Model Details

Density Profile of SNe ejecta



$$\rho_{ej}(v,t) = \begin{cases} \zeta_\rho \frac{M_{ej}}{v_{tr}^3 t^3}\left(\frac{r}{v_{tr} t}\right)^{-\delta}, & v_{ej,min} \leqslant v < v_{tr} \\ \zeta_\rho \frac{M_{ej}}{v_{tr}^3 t^3}\left(\frac{r}{v_{tr} t}\right)^{-n}, & v_{tr} \leqslant v \leqslant v_{ej,max} \end{cases}$$

(Matzner & McKee 1999)

The material falling rate is

$$\begin{aligned} \dot{M} &\simeq \pi R_{acc}^2 v \rho_{ej}, \\ &= \frac{4\pi G^2 M_{BH}^2}{d^3} \zeta_\rho \frac{M_{ej}}{v_{tr}^3}\left(\frac{d}{v_{tr} t}\right)^{-n}, \quad t_{start} \leqslant t < t_{tr}, \end{aligned}$$

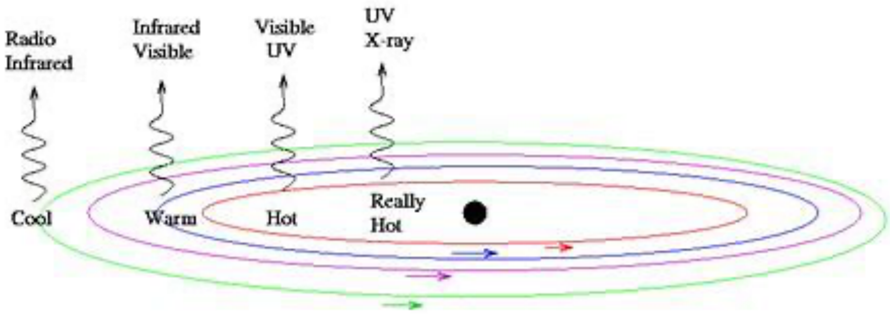
At the characteristic time $t_{tr} \sim d/v_{tr}$ when the falling region reaches down to the inner part ejecta

$$\dot{M}_{tr} \simeq 4.1 \times 10^{-9} M_\odot\ s^{-1} \left(\frac{M_{ej}}{10 M_\odot}\right)^{5/2} \left(\frac{M_{BH}}{20 M_\odot}\right)^2 \times \left(\frac{d}{10^{13} cm}\right)^{-3} \left(\frac{E_{sn}}{10^{51} erg}\right)^{-3/2}.$$

Model Details

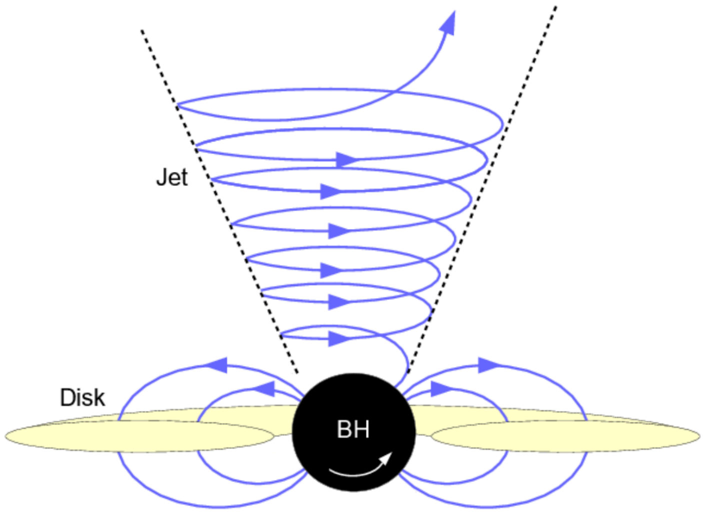
Accretion feedback power

Disk Radiation

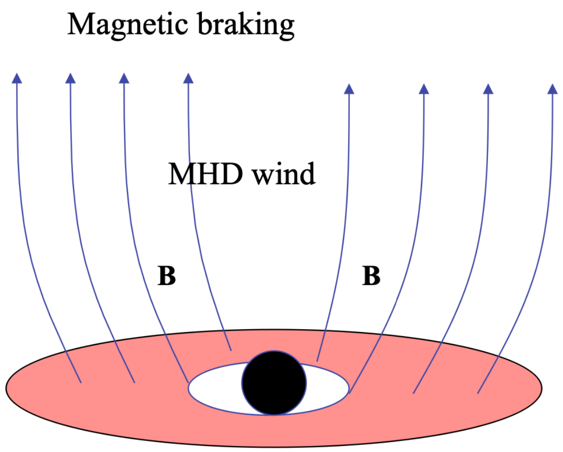


$$L_{\rm disk} = 2\int_{R_{\rm ms}}^{R_{\rm out}} 2\pi R\sigma T_{\rm eff}^4 dR.$$

Blandford-Znajek



Blandford-Payne



Blandford & Payne (1982)

For super-Eddington accretion

$L_{\rm disk} \sim 0.2L_{\rm Edd} \sim 5\times10^{38}{\rm erg\ s^{-1}}(M_{\rm BH}/20M_\odot)$

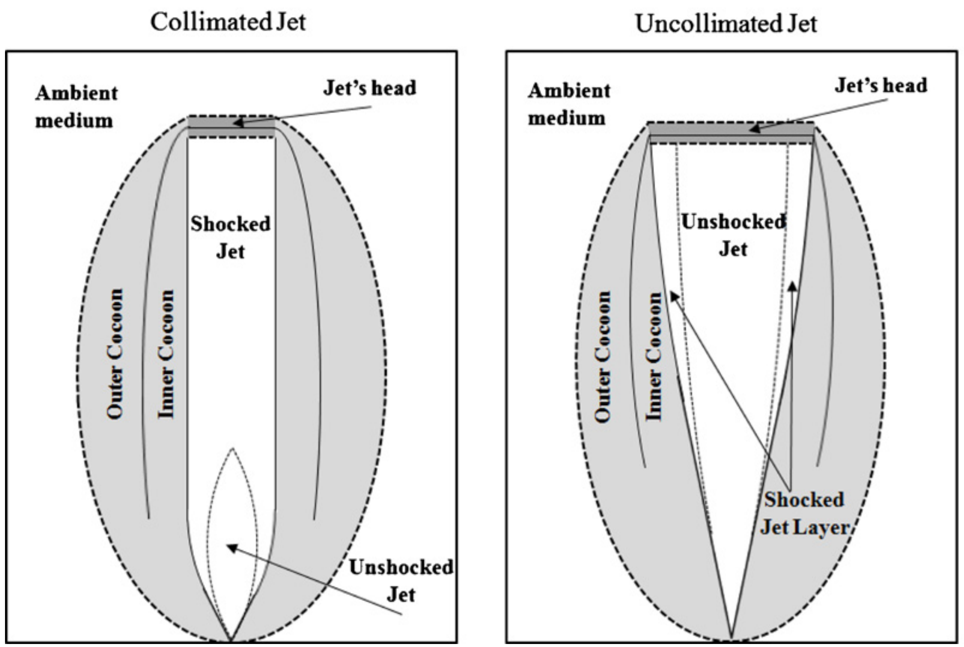
$$L_{\rm BZ} = 1.7\times10^{50}a^2\left(\frac{M_{\rm BH}}{M_\odot}\right)^2 B_{\rm H,15}^2 F(a)\ {\rm erg\ s^{-1}},$$

$$L_{\rm BP} = \frac{(B_{\rm ms}^P)^2 r_{\rm ms}^4 \Omega_{\rm ms}^2}{32c},$$

Model Details

When the SN expands to a radius of R_{SN}, it will roughly take t_B for the BZ jet to breakout the SN material

$$t_B \sim 3000 \ s \times L_{\mathrm{BZ},45}^{-1/3} \theta_{10^o}^{4/3} R_{13}^{2/3} M_{10\odot}^{1/3}$$



Bromberg et al. 2011

Since the breakout timescale is smaller than the termination timescale of the accretion process, the BZ jet very likely penetrates through the SN envelope.

- **The feedback effect from BZ power could be neglected**
- **Non-thermal emissions from the BZ jet is expected**

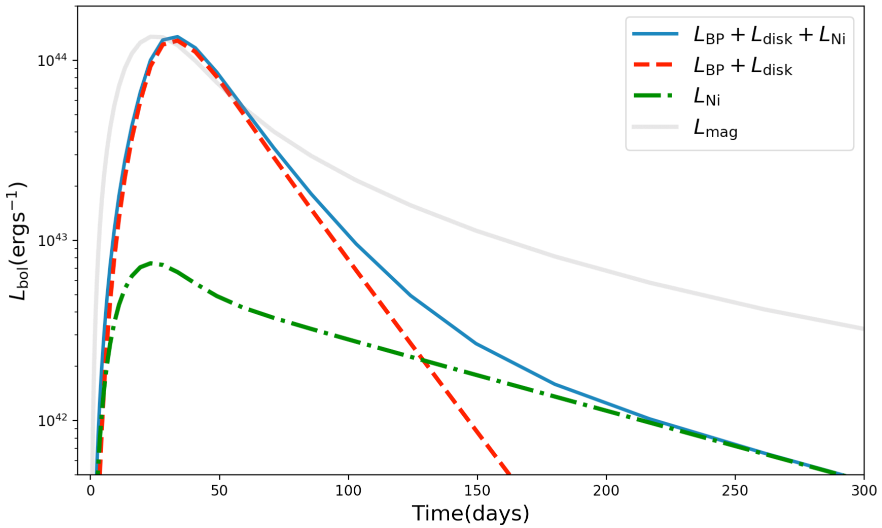
Model Results

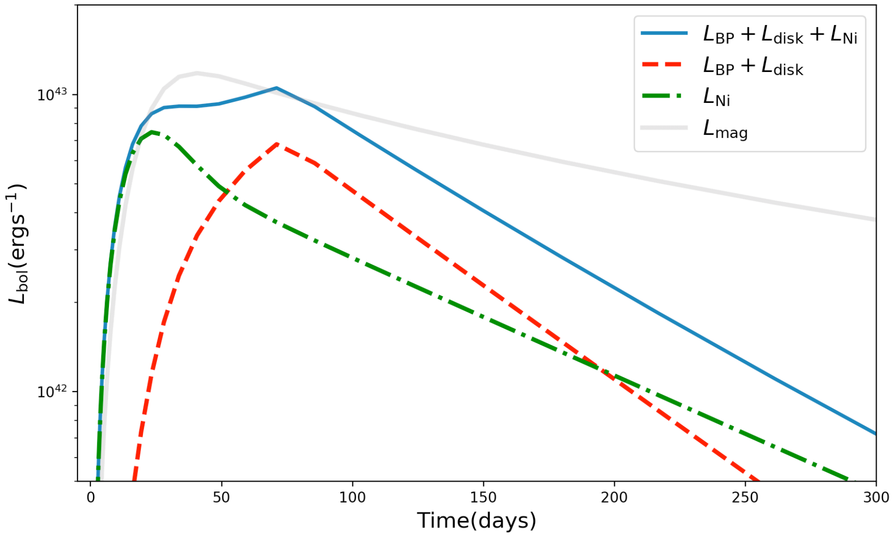
In this scenario, the SN bolometric luminosity can be expressed by (Arnett 1982)

$$L_{\rm SN}(t) = e^{-\left(\frac{t^2}{\tau_m^2}\right)} \int_0^t 2\frac{t}{\tau_m^2} L_{\rm heat}(t') e^{\left(\frac{t'^2}{\tau_m^2}\right)} dt'$$

$$L_{\rm heat}(t) = L_{\rm disk}(t) + L_{\rm BP}(t) + L_{\rm Ni}(t),$$

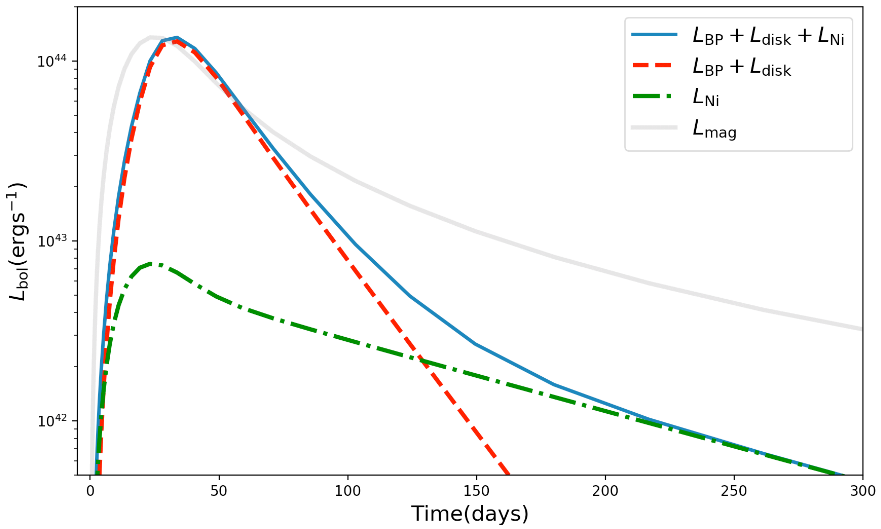
- **When the feedback power is much greater than the radioactive decay power, the SN lightcurve could show a sharp peak as luminous as the SLSNe**
- **When the feedback power is comparable to the radioactive decay power, the SN lightcurve could contain a plateau (re-brightening) feature**





Distinguishing Features

Different from magnetar model

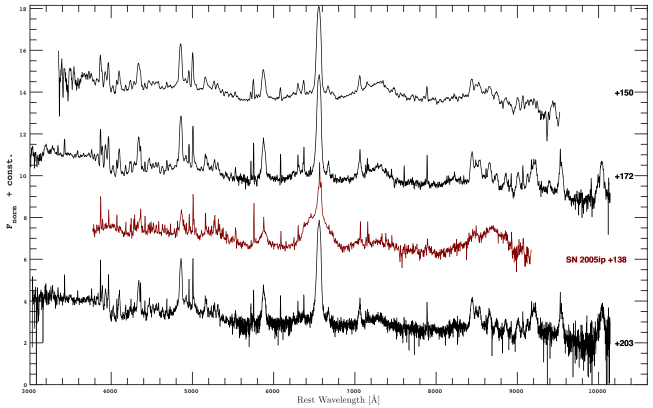


- For our model, SN lightcurve would undergo a rapid decay after the peak
- But for the magnetar model, the energy injection always continues, so that the SN lightcurve would undergo a relatively slow decay after the peak.

Different from fall-back accretion model

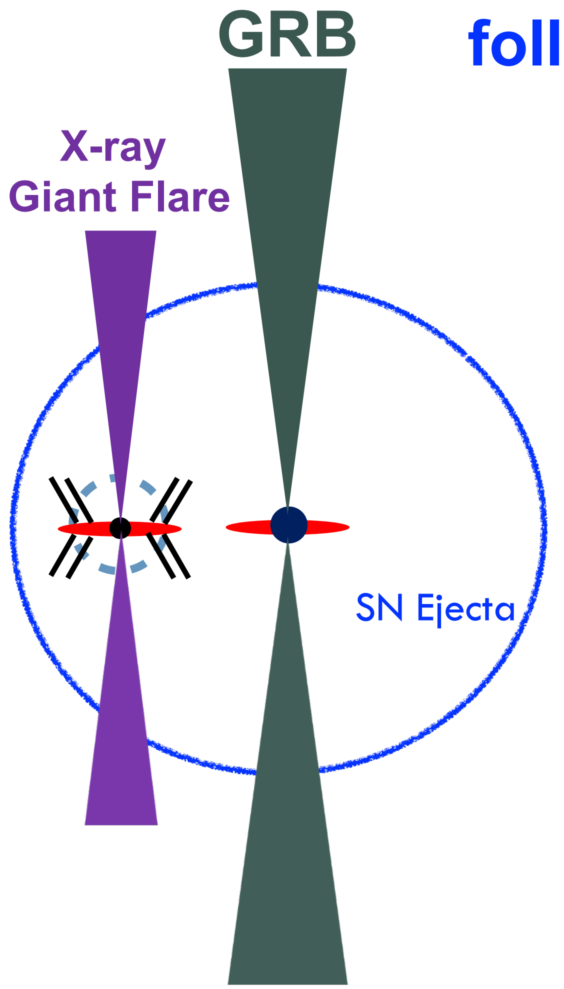
The main difference is that for the single star case, the weaker the initial SN explosion, the stronger the fallback feedback, which is opposite for the scenario discussed here.

Different from interaction model

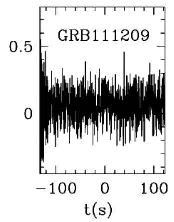


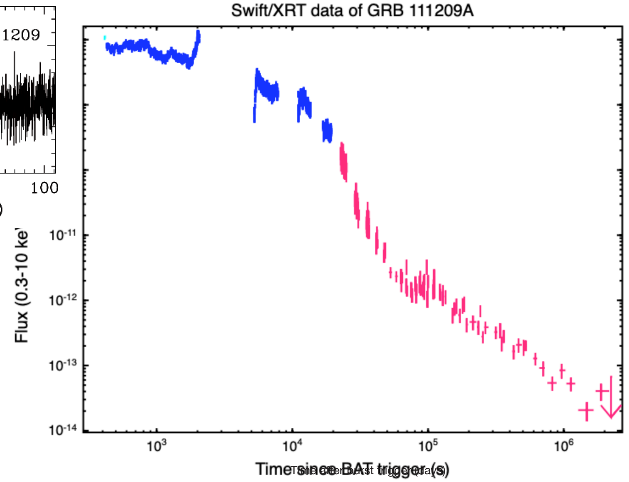
Spectra never show signs of narrow emission lines that would indicate CSM interaction

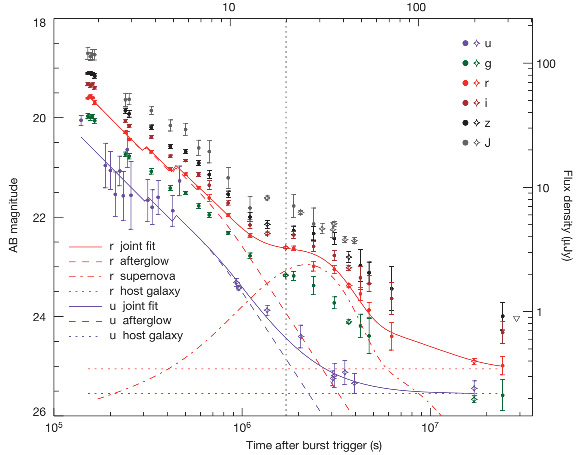
Related with GRBs



The second core collapse could generate a GRB, which will be followed by a giant X-ray flare and a bright SN with a rapidly decay.







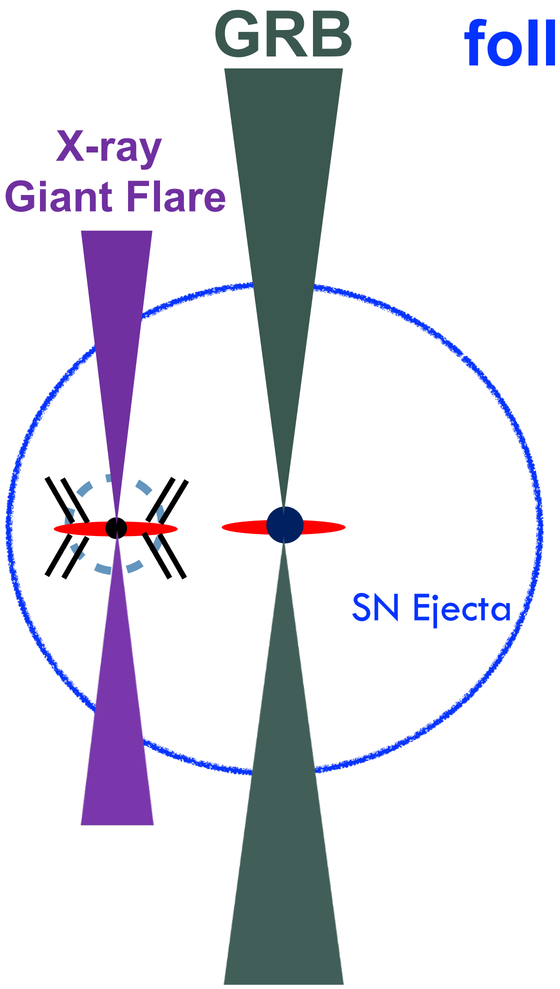
GRB111209A

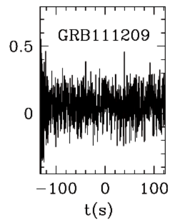
Greiner et al. 2015 Nature

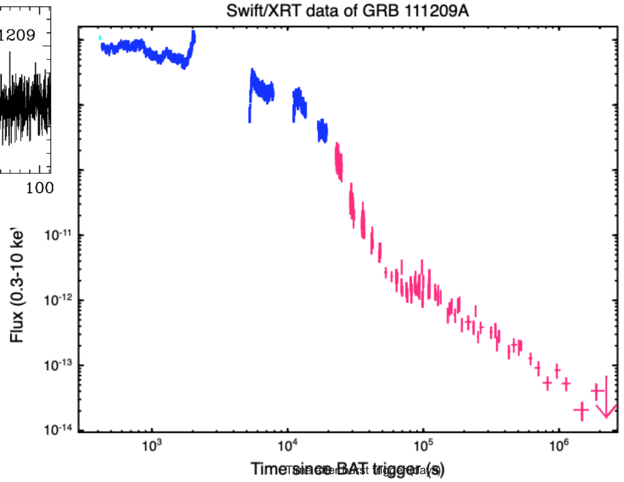
A new class of ultra-long-duration (more than 10,000 seconds) γ-ray bursts has recently been suggested[1–3]. They may originate in the explosion of stars with much larger radii than those producing normal long-duration γ-ray bursts[3,4] or in the tidal disruption of a star[3]. No clear supernova has yet been associated with an ultra-long-duration γ-ray burst. Here we report that a supernova (SN 2011kl) was associated with the ultra-long-duration γ-ray burst GRB 111209A, at a redshift z of 0.677. This supernova is more than three times more luminous than type Ic supernovae associated with long-duration γ-ray bursts[5–7], and its spectrum is distinctly different. The slope of the continuum resembles those of super-luminous supernovae[8,9], but extends further down into the rest-frame ultraviolet implying a low metal content. The light curve evolves much more rapidly than those of super-luminous supernovae. This combination of high luminosity and low metal-line opacity cannot be reconciled with typical type Ic supernovae, but can be reproduced by a model where extra energy is injected by a strongly magnetized neutron star (a magnetar), which has also been proposed as the explanation for super-luminous supernovae[10].

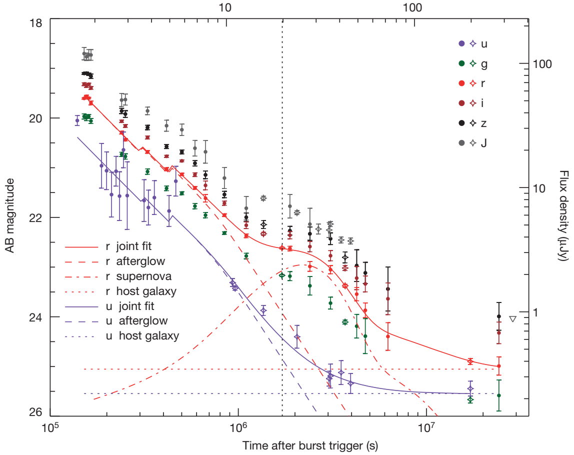
Related with GRBs

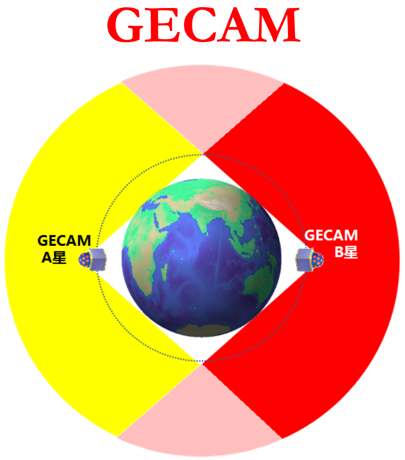
The second core collapse could generate a GRB, which will be followed by a giant X-ray flare and a bright SN with a rapidly decay.

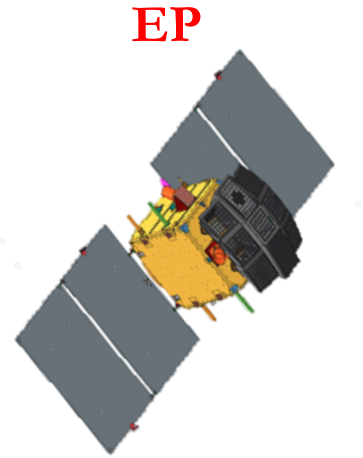












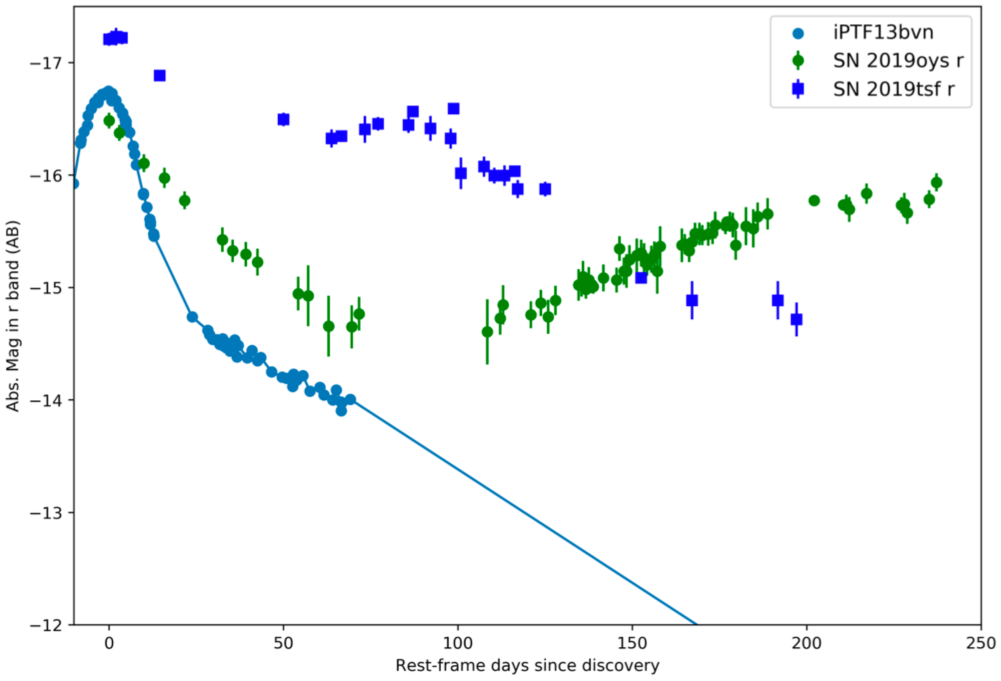
Future Prospective

Table 1. Volumetric event rates, $0 < z < 0.5$

Event type	Rate ($\mathrm{Gpc^{-3}\,yr^{-1}}$)
Superluminous supernovae	40
Long gamma-ray bursts	100
Short gamma-ray bursts	270
Overall millisecond magnetar formation	few $\times$ 10–100
Core-collapse supernovae	2.5×10^5
CCSNe forming magnetars	2.5×10^4
FRB repeater birth	$10^4/\tau$
Cataclysmic FRBs	3.6×10^5

Nicholl+ 2017, arXiv:1704.00022

Many core collapse SNe have been found to have rebrightening signatures, but without narrow emission lines that would indicate CSM interaction



Sollerman et al .2020

The event rate of SLSNe happens to be comparable to the BH-BH merger rate from GW detection

$$\mathcal{R}_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Summary

- BH-BH and BH-NS systems widely exist in the universe
- EM observations could help to distinguish the formation channel of BH-NS/BH systems
- If the BH-NS/BH systems are formed from Channel A (isolated binary evolution):
  - The second SNe could have a sharp peak as luminous as the SLSNe
  - The second SNe could contain a plateau (re-brightening) feature
- Systematically searching for these signals from the SNe archive data to provide their event rate, would be helpful to justify BH–NS/BH systems formation channel.

Thanks for the attention！