Gravitational Waves and **Neutrinos from** Central Engine of Gamma-Ray Bursts

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Today's talk is based on collaboration with K. Murase, D. Nakauchi, K. Kashiyama, & T. Nakamura

Long GRBs



- ★ Multi-messenger of GRBs: from radio to gamma-ray
- ★ The central engine is less constrained due to difficulty of the observation by photons
- **\star** The required energy for jet: **E~10⁵¹⁻⁵² erg**

Collapsar model



See also Bromberg's talk

- ★ One of the most promising scenarios
- ★ Central compact
 objects generate
 relativistic jets
- ★ Jets propagating inside the star
- ★ Jets are surrounded by nonrela. cocoon
- ★ There are some supporting evidences

GRBs and SNe

GRB 🗇 SN association

GRB 980425 / SN 1998bw (z=0.0085) GRB 030329 / SN 2003dh (0.1687) GRB 031203 / SN 2003lw (0.1055) XRF 060218 / SN 2006aj (0.0335) GRB 100316D/ SN 2010bh (0.0591) GRB 130427A / SN 2013cq (0.3399) ...



Observations of GRB suggest that some GRBs are connected with some kind of SNe.

SNe which associate with GRB are "Hypernovae" (HNe) with explosion energy, E_{exp}~10⁵² ergs.

The central engine of GRBs is required to supply such an enormous explosion energy of GRBs/HNe.

Ultra-long GRBs and counterparts





Ultra-long GRBs and counterparts



Central engine



Iron core of Massive star BH/NS + disk system
 Relativistic jet formation by some kind of "mechanism" © GRB
 Candidates of "mechanism":
 magnetic field and neutrino annihilation

Magnet-driven jet

Blandford-Znajek process





rotation energy of a BH Poynting flux **production**

$$\begin{split} P_{\mathsf{BZ}} &\sim 10^{51} \tilde{a}^2 \left(\frac{M_{\mathsf{BH}}}{3M_{\odot}}\right)^2 \left(\frac{B}{10^{15} \mathsf{G}}\right)^2 \mathsf{ergs s}^{-1} \quad \mathsf{Lee} + 00 \\ E_{\mathsf{rot}} &= 5.4 \times 10^{54} f(\tilde{a}) \left(\frac{M}{3M_{\odot}}\right) \mathsf{ergs} \quad f(\tilde{a}) = 1 - \sqrt{\frac{1}{2} [1 + \sqrt{1 - 1}]} \end{split}$$



binding energy of an accretion disk
Poynting flux **production**



Neutrino-driven jet

McFadyen & Woosley 99



Neutrino pairs are generated in the hot disk Impact each other Energy deposition at rotational axis **jet production**

How to probe the center?

★ In multi-messenger era, the other signals than photons would be usable

★ What are they?

How to probe the center?

- ★ In multi-messenger era, the other signals than photons would be usable
- ★ What are they?
- ★ Gravitational waves and (thermal) neutrinos!

Listening to the beginn DECIGOU Gravitational waves

Neutrino emission

$$\frac{dL_{\nu}}{d\Omega'} = \frac{L_{\nu}}{2\pi} |\cos\theta|$$

GW amplitude ($\xi = \pi/2$)

$$\begin{split} h_{+}(t) &= \frac{2G}{c^{4}R} \int_{-\infty}^{t-R/c} dt' \int_{0}^{\pi} d\theta' \Phi(\theta') \frac{dL_{\nu}}{d\Omega'}(\theta',t') \\ &= \frac{2G}{c^{4}R} \int_{-\infty}^{t-R/c} dt' L_{\nu}(t') \times \int_{0}^{\pi} d\theta' (-1+2\cos\theta') \sin\theta' |\cos\theta'| \\ &= \frac{2G}{c^{4}R} \left(\frac{1}{3}\right) \int_{-\infty}^{t-R/c} L_{\nu}(t') dt'. \end{split}$$

 $10 \mathrm{Mpc}$

copious amount of Final converged value neutrinos are emitted $h_0 \sim 1.8 imes 10^{-21}$

oun

asymmetrically

CGT

witatio al Waves from 200 Mp, Away

These asymmetric neutrinos generate gravitational waves!

In neutrino scenario,



R: distance E_{ν} : total neutrino energy $\Leftrightarrow E_v = 3x10^{53}$ ergs for ordinary SNe

 10^{54} ergs

Gravitational waves

100 10 YS & Murase 2009 PRD ergs Mpc $E_v = 10^{54}$ ergs, R=10 kpc, T= 10 sec 10⁻¹⁶ $E_v = 10^{54}$ ergs, R=10 Mpc, T= 10 sec E_v=10⁵⁴ ergs, R=10 Mpc, T=200 sec 10⁻¹⁸ 10 $E_{y}=10^{53}$ ergs, R=10 Mpc, T=10 sec Ev / R [10⁵⁴ LISA $h_{c}(f), h_{n}(f)$ 10⁻²⁰ advanced LIGO SNR = 1 $d(\ln f)$ 10⁻²² 0.1 800 900 1000 700 T [sec] 10⁻²⁴ ultimate-DECIGO 10⁻²⁶ 0.001 1000 SNR>10⇔ 0.01 0.1 10 100 f [Hz] < 1 Mpc for ad.-LIGO/ad.-Virgo/ **KAGRA** There are other GW emitting mechanisms from collapsar at ~kHz: < 1 Mpc for LISA e.g., van Putten 2001, Kobayashi & Meszaros 2003, < 100 Mpc for DECIGO Piro & Pfahl 2007, Romero+ 2010, Ott+ 2011, Kotake+ 2012...

LCGT

Neutrinos

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★ Simultaneous detection of neutrinos is also expected

★ Thermal (~MeV) neutrinos tells us what is the central engine of GRB



Neutrino acceleration

Generally, neutrino spectrum is assumed as purely thermal

★ There is a possibility for acceleration of neutrinos from the central engine inside the accretion flow

Since $\mathbf{G}_{\mathbf{v}} \propto \mathbf{E}_{\mathbf{v}}^2$, non-thermal tail amplify the detection rate \Rightarrow

expanded detection horizon by a factor of ~10, i.e. for HK we can observe ≤ 100 Mpc



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Multi-messenger time domain astronomy





- ★ The most unknown part in collapsar scenario is how relativistic jets are generated?
- ★ Possible smoking gun: simultaneous detection of gravitational waves and thermal neutrinos
- ★ They will also tell us the *exact* time of jet production, i.e. birth of GRB engine