Koutarou Kyutoku, JGRG 22(2012)111405

“Electromagnetic counterparts to binary neutron star mergers”

RESCEU SYMPOSIUM ON

GENERAL RELATIVITY AND GRAVITATION

JGRG 22

November 12-16 2012

Koshiba Hall, The University of Tokyo, Hongo, Tokyo, Japan

Electromagnetic counterparts to binary neutron star mergers

Koutarou Kyutoku (KEK)

Collaborators:

Kunihito Ioka (KEK), Masaru Shibata (YITP)

Summary

Electromagnetic counterparts to gravitational waves from binary neutron star mergers will be important, and we still have no “perfect” counterpart model

We propose a possibility of ultra-relativistic outflows and associated X-ray-to-radio bands, second-to-day timescale emission from the shock breakout at the binary merger, ejecta-ISM shock, and synchrotron

This model is bright enough and has tight association with GWs, but it will be challenging to observe

Binary neutron star mergers

The most promising sources of gravitational waves

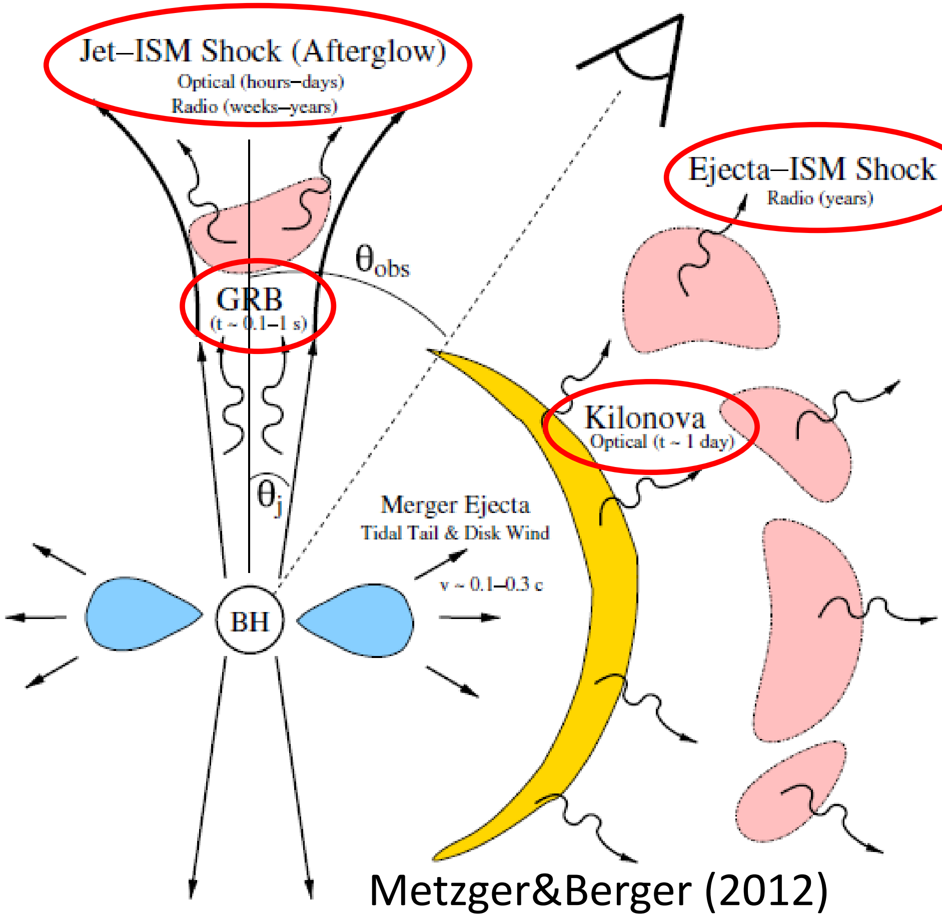
- neutron star masses, spins (if any), and radii
- supranuclear-density matter equations of state
- a way to (purely) gravitational-wave cosmology

Many electromagnetic signals are also expected

- short-hard gamma-ray bursts and afterglows
- radioactive decays of rapid-process elements
- interaction with surrounding interstellar media

Electromagnetic counterparts

The neutron star merger must be highly energetic



Metzger&Berger (2012)

EM emission with GWs are naturally expected

- detectable strength
- frequent association
- unique feature
- accurate localization

and so on are desired

Short-hard gamma-ray burst

The most energetic explosion

“Binary merger hypothesis”

should be tested by

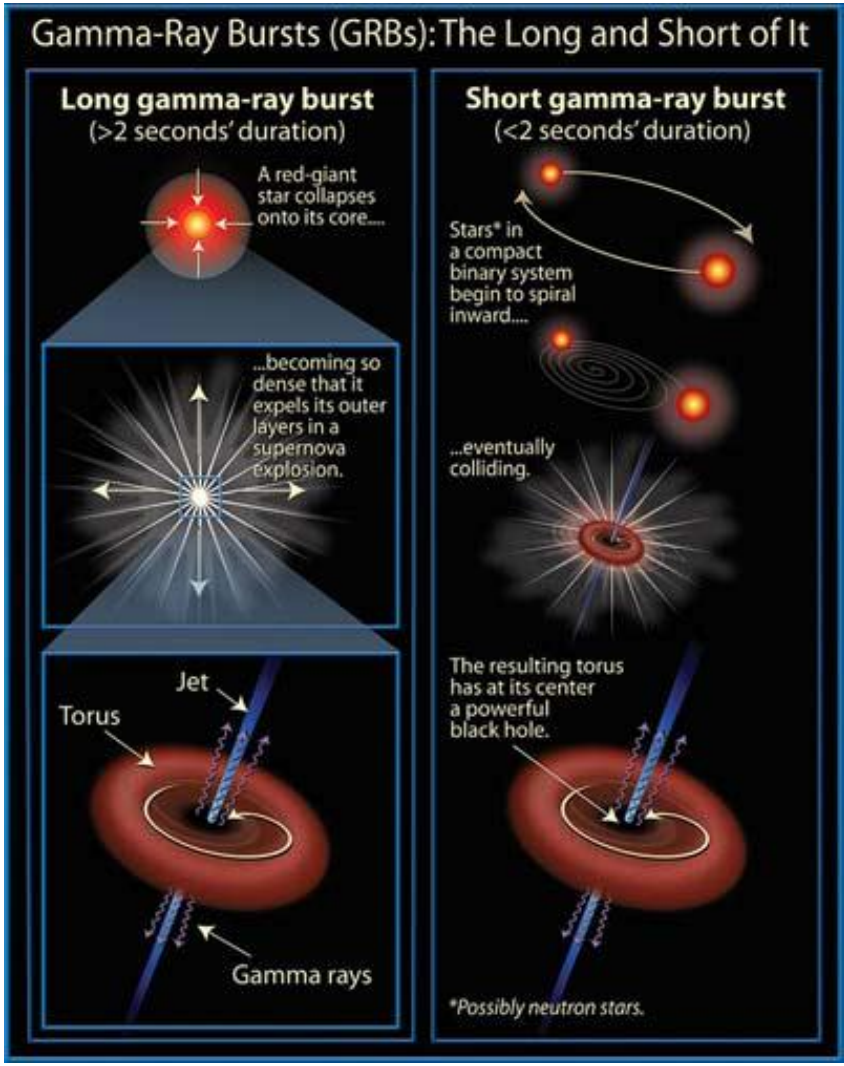
simultaneous detection

(or its absence) of GWs and

short-hard gamma-ray bursts

Afterglows will localize events

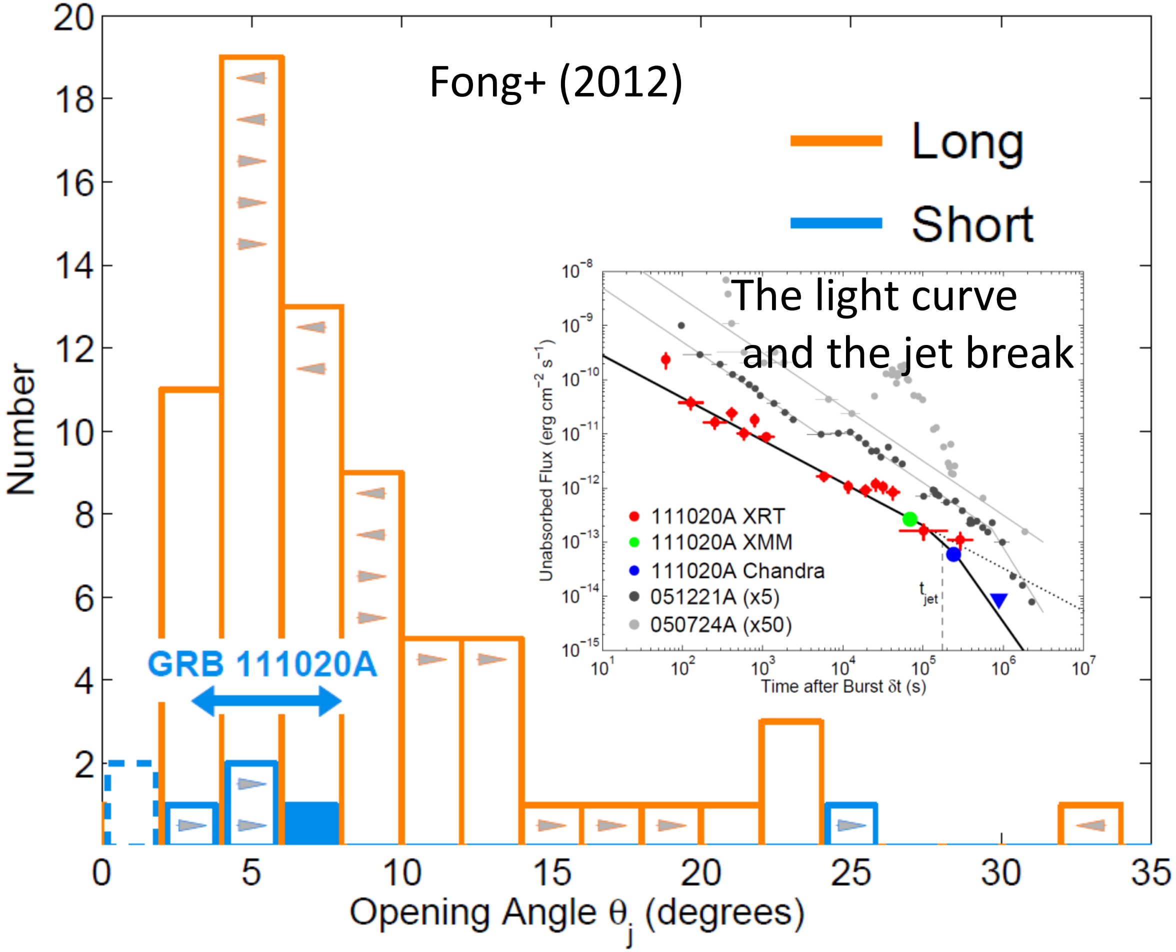
with sufficient accuracy



From encyclopedia of science

Problem: jet opening angle

Not necessarily accompany GWs due to the beaming


Fong+ (2012)

The light curve and the jet break

Two events suggest jet angle < 10 deg.

A few % of mergers accompany GRBs even if all mergers leads to the bursts

Mass ejection from the merger

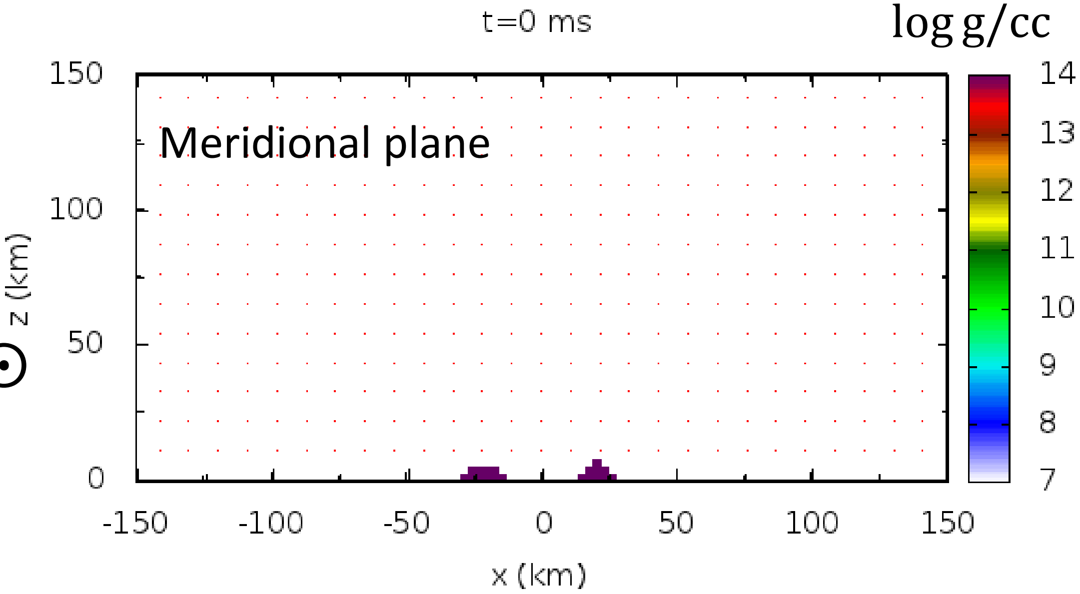
- tidal torques by the rapidly (differentially) rotating, non-axisymmetric hypermassive neutron star
- heating by shocks generated at/after the merger

Nearly spherical:
"4π-counterpart"

mass: $10^{-2} - 10^{-3} M_{\odot}$

velocity: $0.15 - 0.25c$

kinetic E: $\sim 10^{50}$ erg



Hotokezaka, KK+ (submitted)
Movies made by Kenta Hotokezaka

Emission mechanisms

1. ejecta-ISM shock radio flare (Nakar&Piran 2011)
   synchrotron radiation like GRB afterglow and SNR
   O(year) to the peak: loose association with GWs

2. kilonova/macronova (Li&Paczynski 1992, Metger+ 2010)
   radioactive decay of r-process elements
   O(day) optical transients: many contaminations

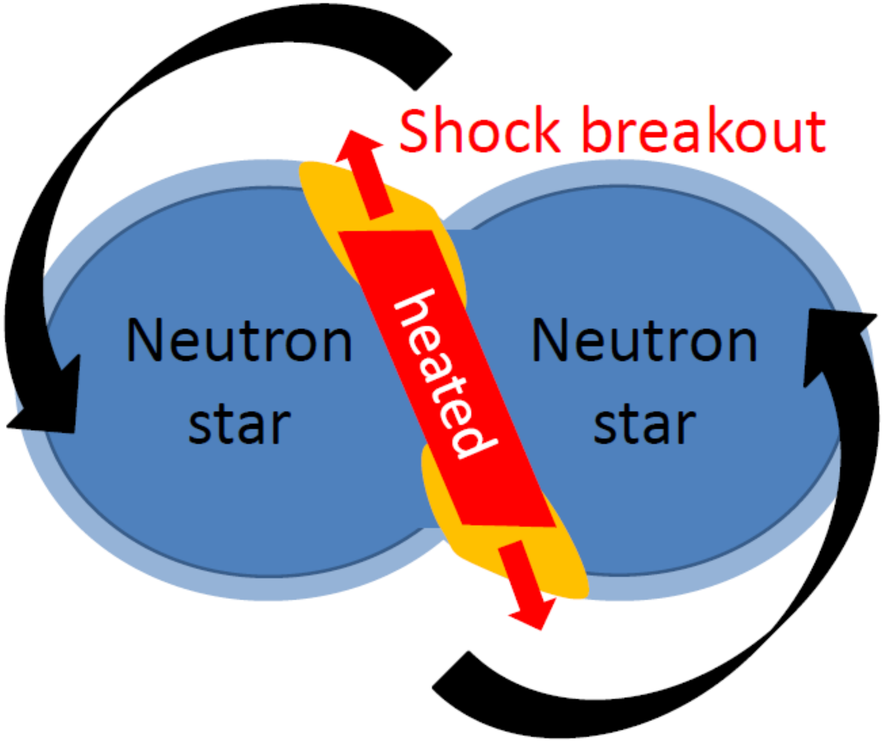
No emission mechanism is perfect as counterparts

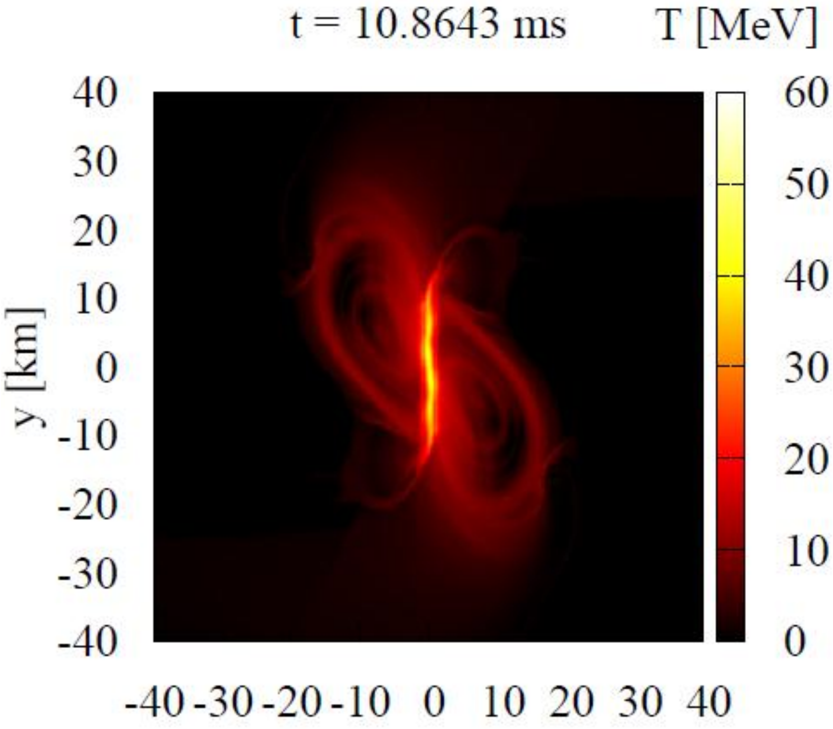
We need yet another electromagnetic counterpart!

Shock breakouts just at the merger

A contact surface is heated up to ~50MeV, so that hot material escape into the cold, low-density crust

The shock breakout should result unavoidably





Shock and post-shock acceleration

A smaller mass is accelerated to a higher velocity

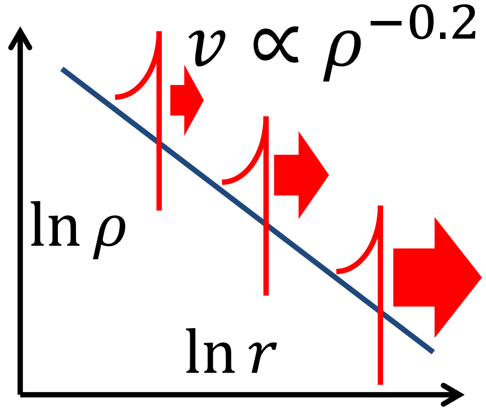
(Whitham 1958, Sakurai 1960, Johnson&Mckee 1971)

Shock acceleration

the acceleration of shock waves as they descend the density gradient = the neutron star crust

Post-shock acceleration

the acceleration of ejected material by converting thermal E. to kinetic. E and by the pressure gradient inside them

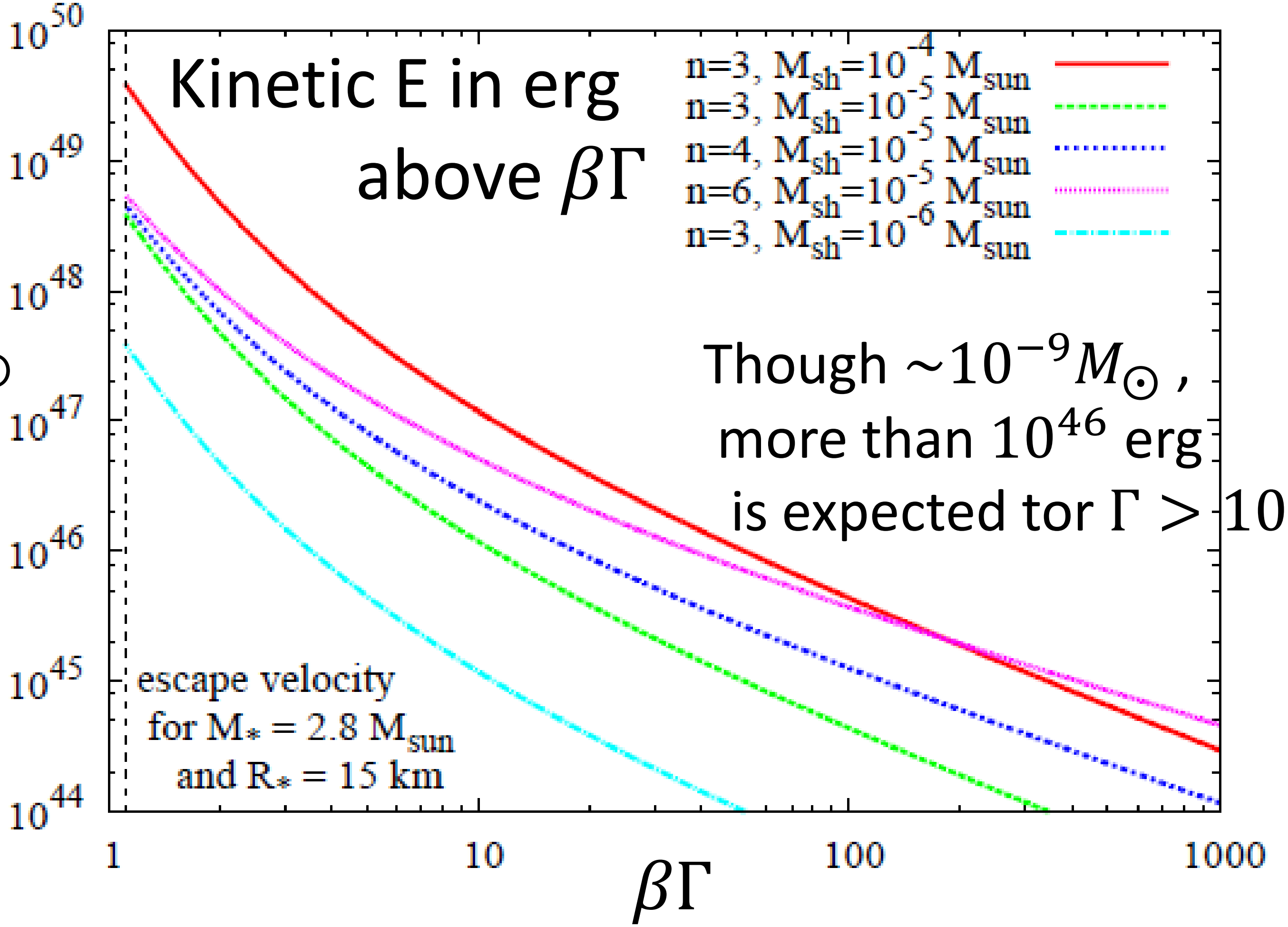


$v \propto \rho^{-0.2}$

Ultra-relativistic outflows

Based on a spherical SNe model (Tan, Matzner, Mckee 2001)

Ejecta mass is $\sim 10^{-4} - 10^{-5} M_{\odot}$



Kinetic E in erg above $\beta\Gamma$

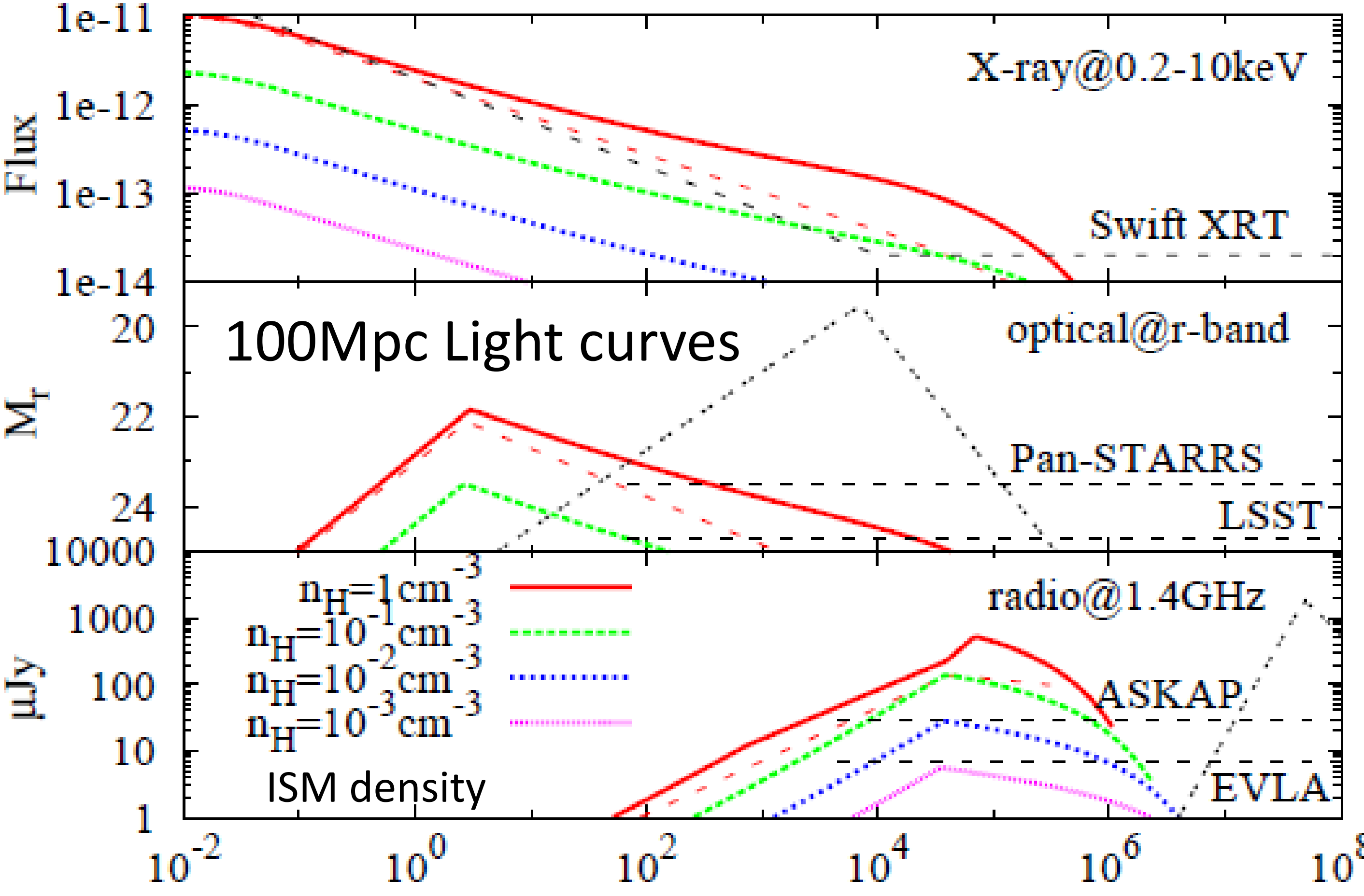
Though $\sim 10^{-9} M_{\odot}$, more than 10^{46} erg is expected tor $\Gamma > 10$

Blast waves and synchrotron emission

Ultra-relativistic -> fast and high-energy emission

How to observe in practice?

- GW alert
- galaxy monitor



100Mpc Light curves

ISM density

time after the merger in seconds

Summary

Electromagnetic counterparts to gravitational waves from binary neutron star mergers will be important, and we still have no “perfect” counterpart model

We propose a possibility of ultra-relativistic outflows and associated X-ray-to-radio bands, second-to-day timescale emission from the shock breakout at the binary merger, ejecta-ISM shock, and synchrotron

This model is bright enough and has tight association with GWs, but it will be challenging to observe

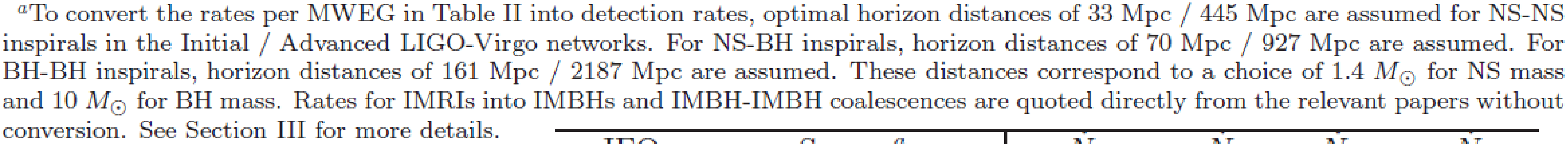
appendix

Horizon distance/detection rate

The signal-to-noise ratio threshold is taken to be ~8

For a best-oriented binaries (face-on to the detector),

445/927/2187Mpc for NSNS/BHNS/BHBH binaries

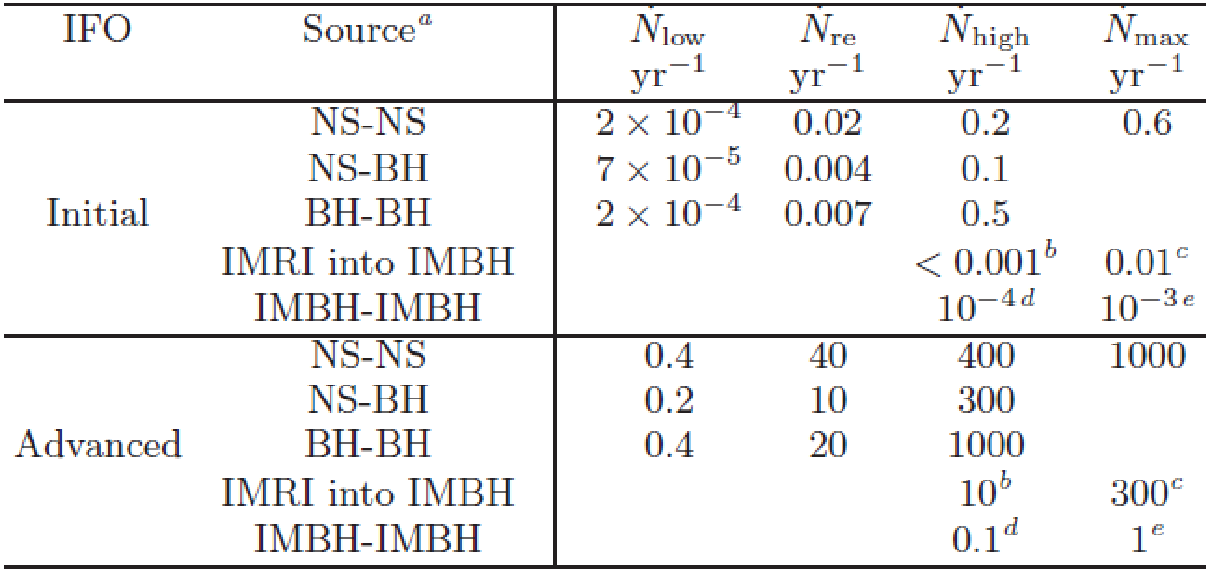


[a]To convert the rates per MWEG in Table II into detection rates, optimal horizon distances of 33 Mpc / 445 Mpc are assumed for NS-NS inspirals in the Initial / Advanced LIGO-Virgo networks. For NS-BH inspirals, horizon distances of 70 Mpc / 927 Mpc are assumed. For BH-BH inspirals, horizon distances of 161 Mpc / 2187 Mpc are assumed. These distances correspond to a choice of 1.4 $M_\odot$ for NS mass and 10 $M_\odot$ for BH mass. Rates for IMRIs into IMBHs and IMBH-IMBH coalescences are quoted directly from the relevant papers without conversion. See Section III for more details.

Detection rates

are estimated

with models



IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Abadie+ (2010)

Why we need counterparts?

One/two GW detectors cannot localize GW sources

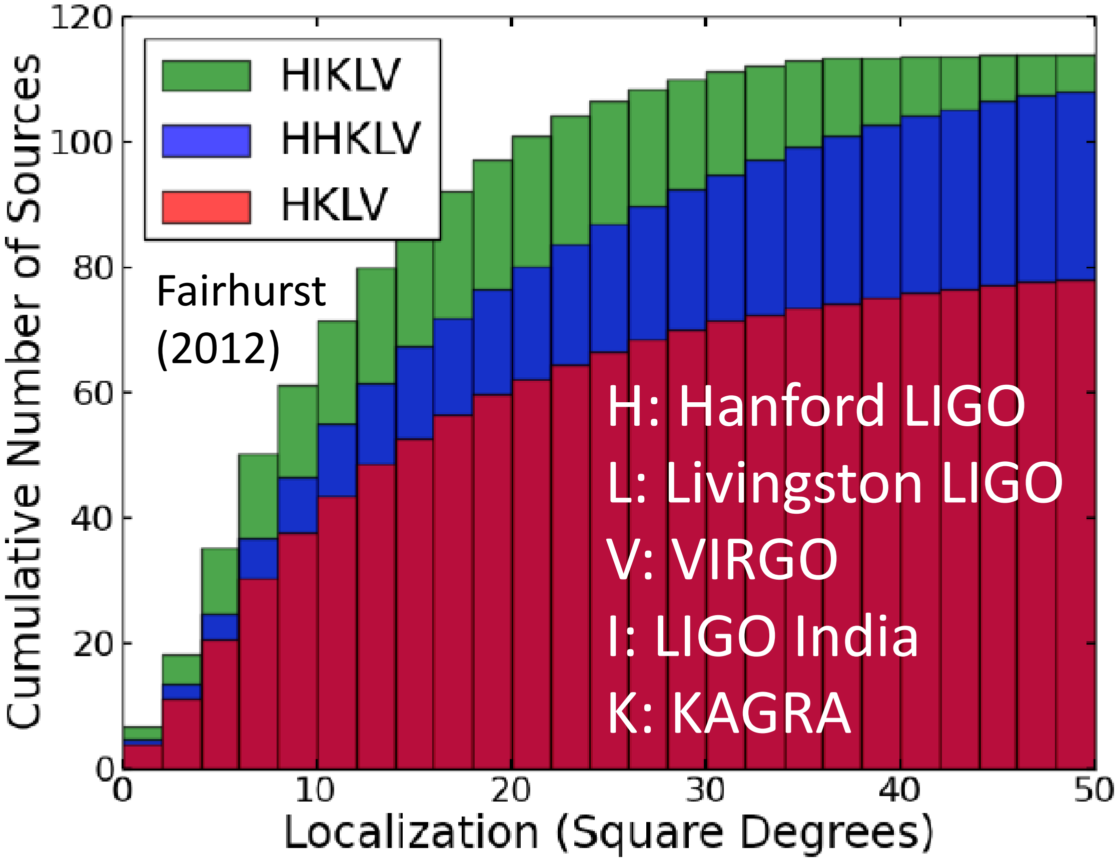
O(10 degrees^2) for future GW detector networks

EM detection helps

- param. estimation
- host galaxy search

+ EM mechanisms

+ (psychologically) add GW evidences



Fairhurst (2012)

H: Hanford LIGO
L: Livingston LIGO
V: VIRGO
I: LIGO India
K: KAGRA

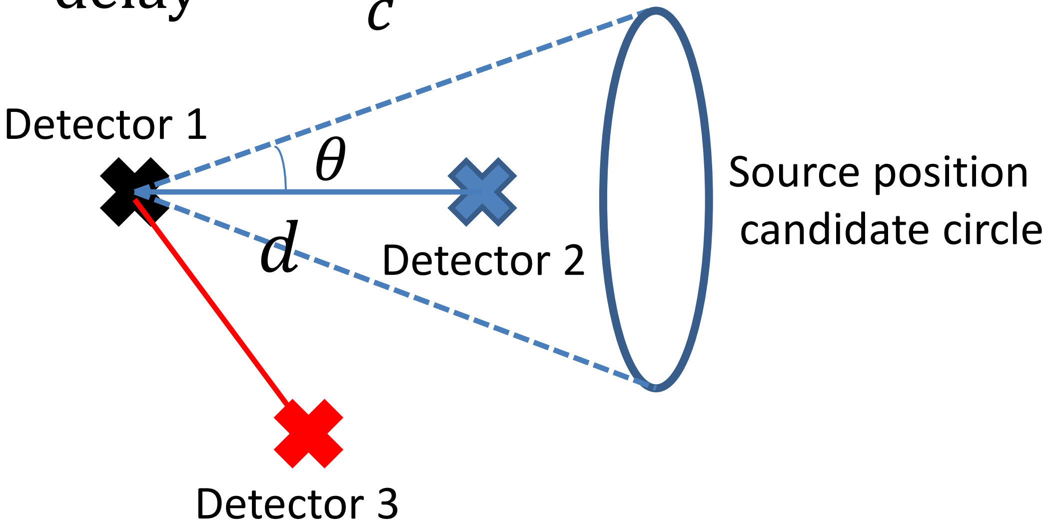
How to localize by GWs?

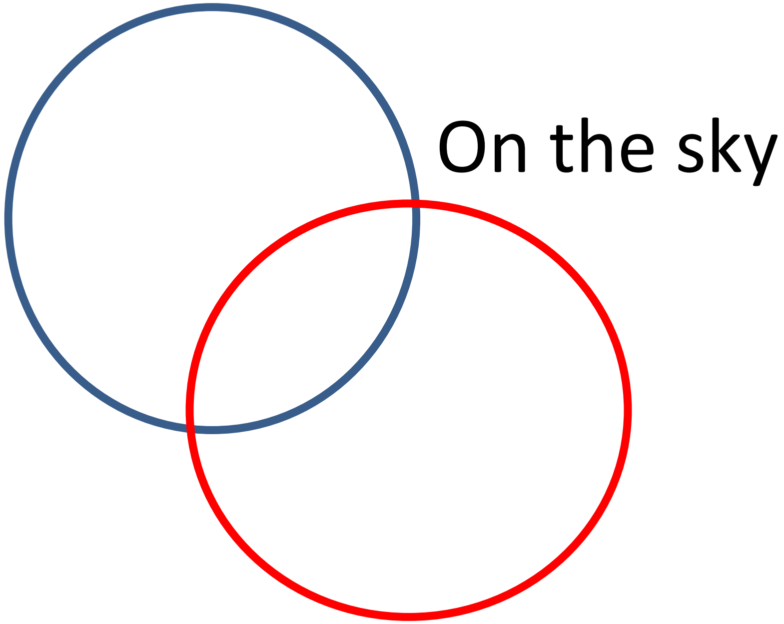
Triangulation by time delays between GW detectors

For three detectors, we obtain two crosses of circles

The fourth detector=KAGRA improves the situation

$$t_{\mathrm{delay}} = \frac{d\cos\theta}{c}$$





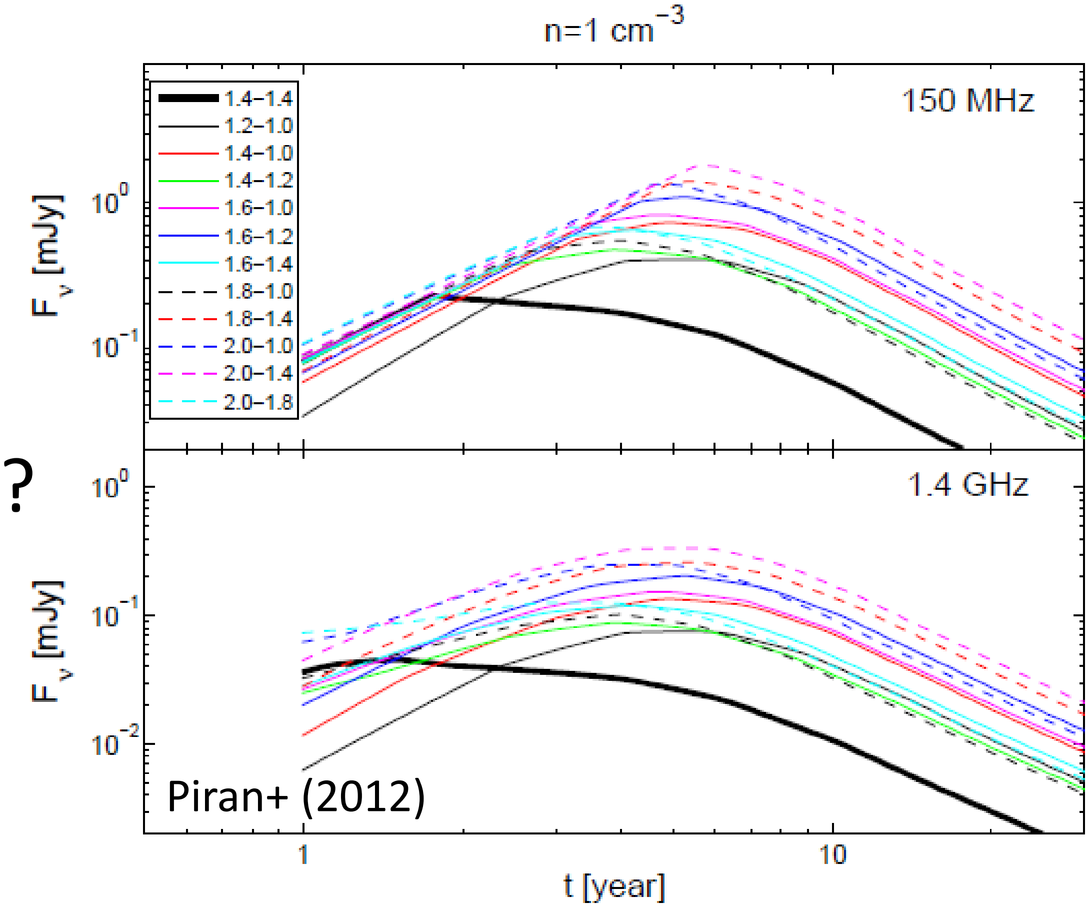
Radio flare

Ejecta forms blast waves colliding the ISM, and magnetic fields amplified & electrons accelerated

Radio synchrotron

O(year) to the peak…

Can we really declare association with GWs?



Piran+ (2012)

macronova/kilonova

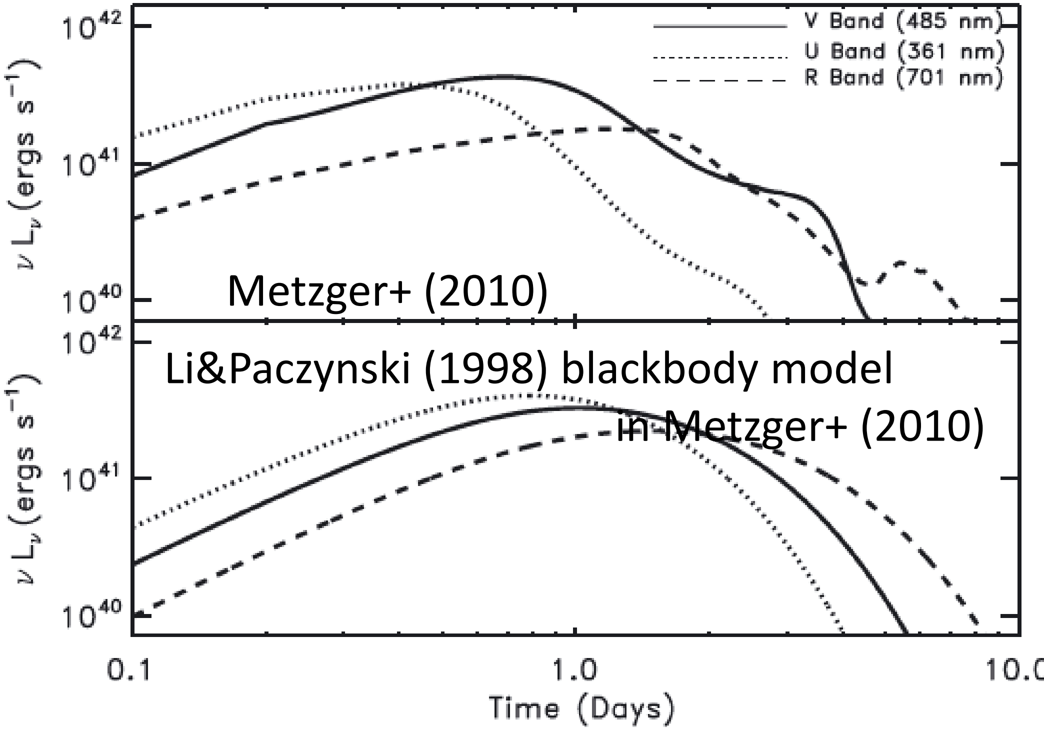
Neutron-rich ejecta may accompany the r-process nucleosynthesis and radioactive nuclei formation

similar to SNe, only 1000 times brighter than novae

Shine in optical/UV

O(<day) to the peak

Uncertainty in r-process reaction, opacity…



Metzger+ (2010)

Li&Paczynski (1998) blackbody model in Metzger+ (2010)

Shock acceleration in the envelope

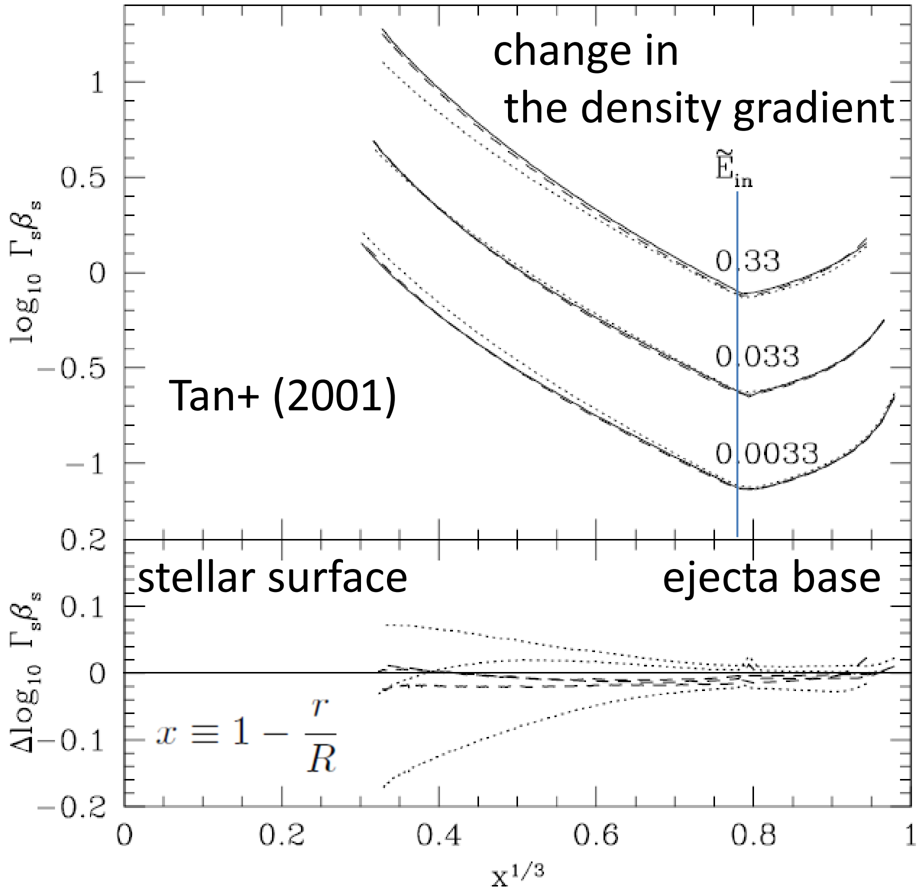
Newtonian

$$\beta_s = A \left(\frac{\tilde{E}_{\rm in}}{\tilde{m}}\right)^{1/2} \left(\frac{\tilde{m} M_{\rm ej}}{\rho r^3}\right)^{\alpha_{\rm nr}}$$

$$\alpha_{\rm nr} \simeq 0.19$$

Semi-analytic

$$\Gamma_s \beta_s = p(1+p^2)^{0.12},$$
$$p \equiv A \left(\frac{\tilde{E}_{\rm in}}{\tilde{m}}\right)^{1/2} \left(\frac{\tilde{m} M_{\rm ej}}{\rho r^3}\right)^{\alpha_{\rm nr}}$$



change in the density gradient

Tan+ (2001)

stellar surface

ejecta base

$x \equiv 1 - \frac{r}{R}$

$$\rho = \rho_h \times \begin{cases} \left(\frac{R}{r_c} - 1\right)^n \left(\frac{r}{r_c}\right)^{-k_\rho}, & r < r_c \\ \left(\frac{R}{r} - 1\right)^n, & r_c < r < R. \end{cases}$$

Post-shock acceleration

Rankine-Hugoniot relation at the strong shock

$\beta_s/\beta_2 = 7/6$ for non-rela, $\Gamma_s/\Gamma_2 = \sqrt{2}$ for ultra-rela

After converting internal energy to thermal energy

$\beta_f/\beta_s = 6\sqrt{2}/7 = 1.21$ for non-rela

$\Gamma_f = 2{\Gamma_s}^2/3$ for ultra-rela (Blandford&Mckee(1976))

But post-shock acceleration is more efficient

$\beta_f/\beta_s = 2.04$ (Sakurai 1960)

$\Gamma_f \simeq \left(\Gamma_s/\sqrt{2}\right)^{1+\sqrt{3}}$ (Johnson&Mckee 1971)

Post-shock acceleration

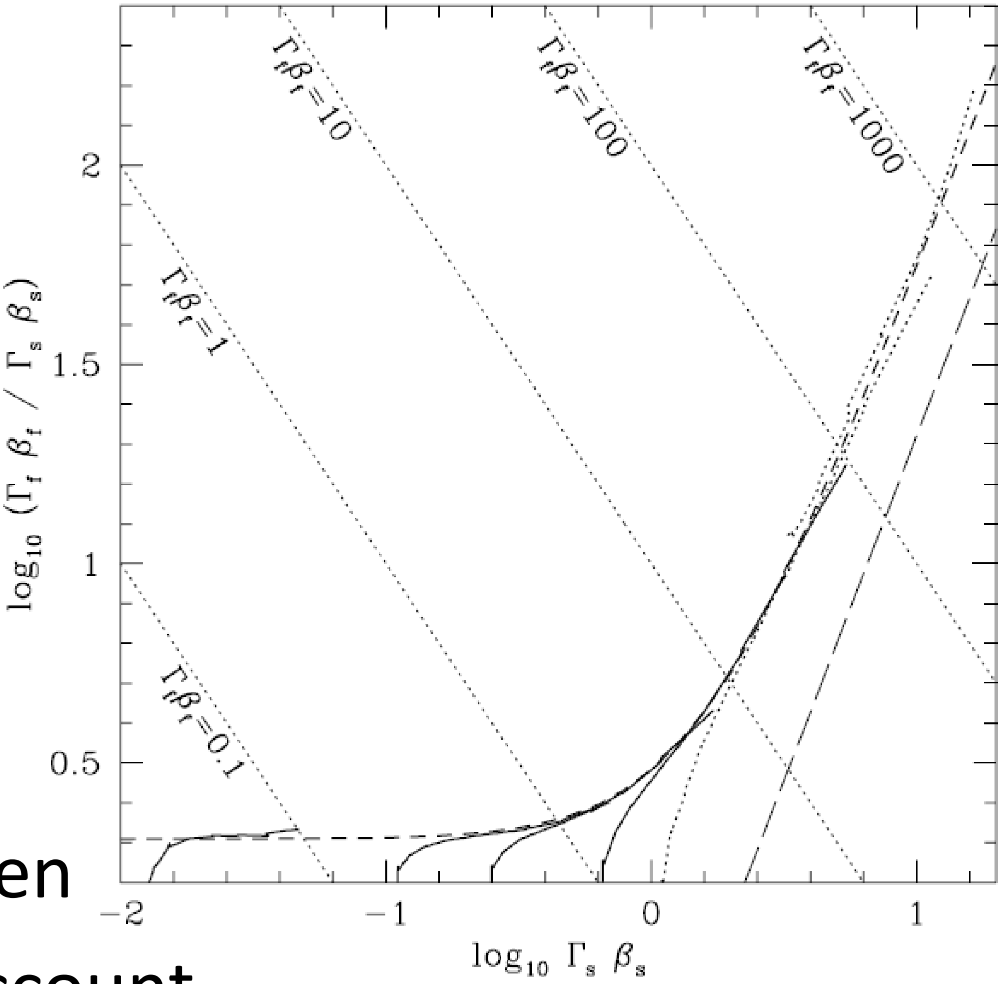
Semi-analytic

$$\frac{\Gamma_f \beta_f}{\Gamma_s \beta_s} \simeq C_{\rm nr} + (\Gamma_s \beta_s)^{\sqrt{3}}$$

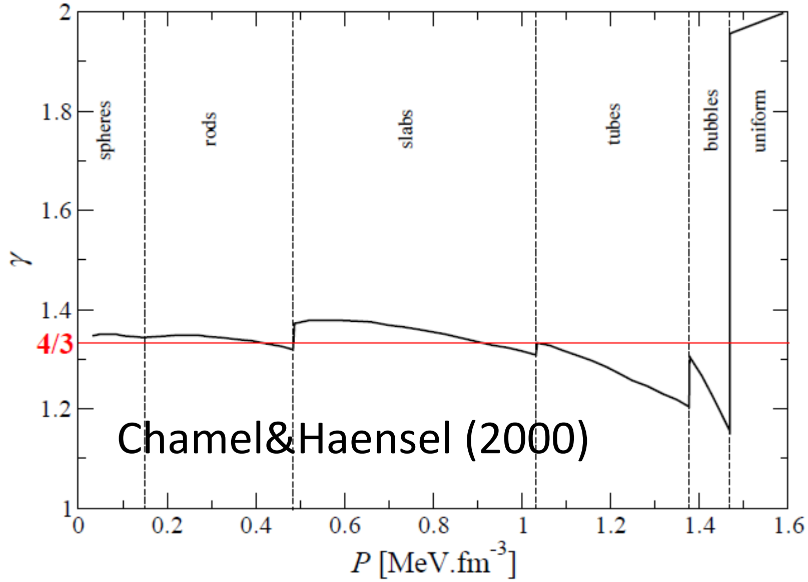
$$C_{\rm nr} = 2.03$$

Reproduce simulations

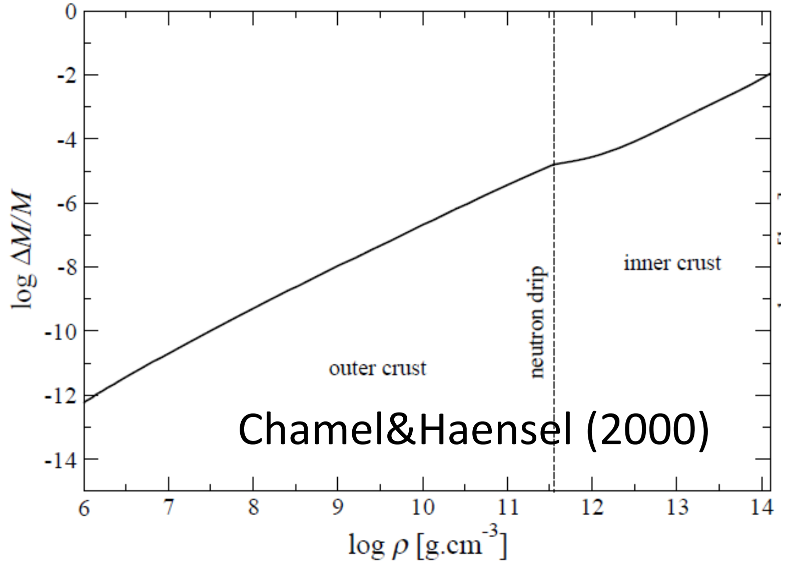
The distribution of velocity-kinetic E. is given taking the mass into account



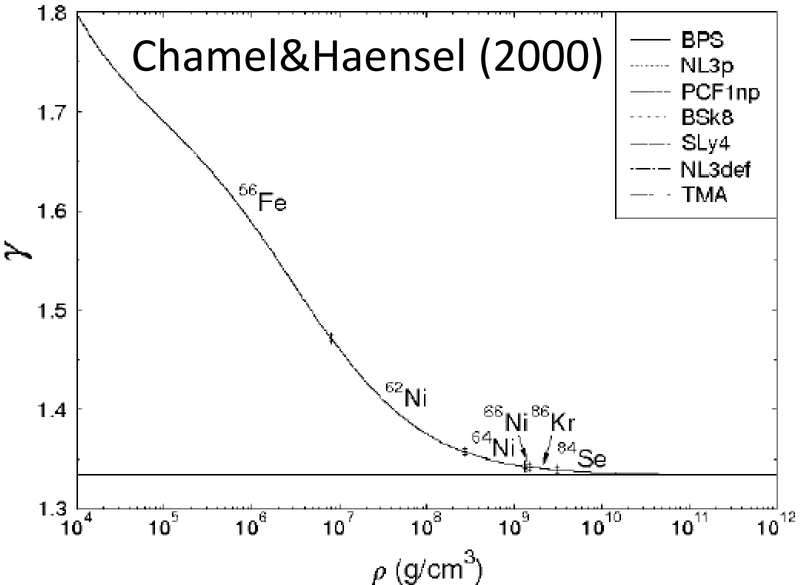
Neutron star crust



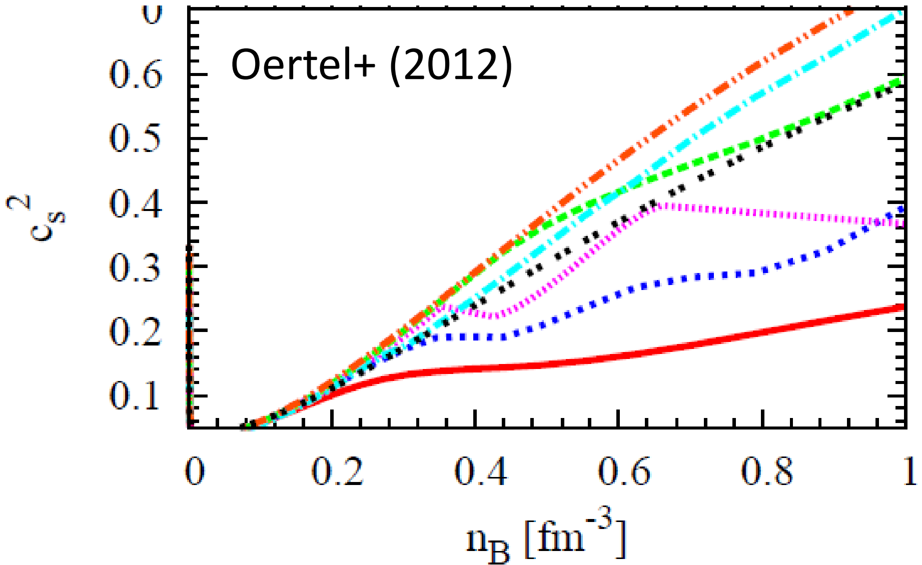
Chamel&Haensel (2000)



Chamel&Haensel (2000)



Chamel&Haensel (2000)



Oertel+ (2012)

Estimation of the ejecta mass

Crust density profile: $\rho \propto (R-r)^n$, here $n \approx 3$

assume a core-crust interface is at some density ρ_0

Shock velocity: $v \propto \rho^{-0.2}$ for polytropic index $n = 3$

assume $v_{\rm ini}$ is the core sound velocity $\sim 0.25c$

$v_{\rm esc} = \sqrt{2GM/R} \sim 0.7c$ for a typical HMNS

Acceleration from initial to escape velocity gives

the ratio between the density $\rho_{\rm esc}/\rho_0$

Integrate this with geometrical reduction gives the ejecta mass to be $10^{-2} \sim 10^{-3} M_{\rm crust} (\sim 0.01 M_\odot)$

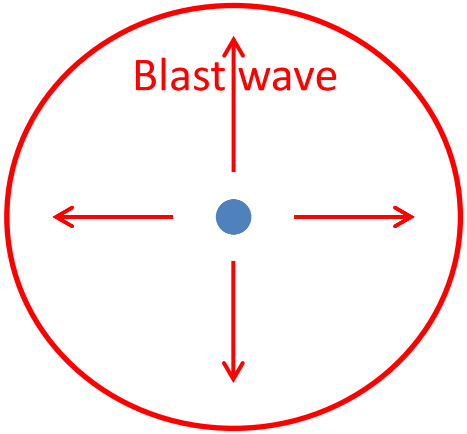
Blast wave evolution

Blandford-Mckee's solution (Blandford&Mckee 1973): the evolution of relativistic self-similar blast waves

An initial shell has energy E and Lorentz factor Γ

BM begins when the shell obtains $\sim E$ from the ISM

$$R(t) \propto t^{1/4}, \Gamma(t) \propto t^{-3/8}$$



InterStellar Medium

For a refreshed shock $E(>\Gamma) \propto \Gamma^{1-s}$

$$R(t) \propto t^{(s+1)/(s+7)}$$

$\Gamma(t) \propto t^{-3/(s+7)}$ (Rees&Meszaros 1998)

Assumption for refreshed shocks

Fully adiabatic evolution (no radiation energy loss)

A radius-Lorentz factor closure relation: $R = 4\Gamma^2 ct$

this exact factor depends on situations

When the slower shell rear-ends, it is decelerated by the material accumulated by all the faster shells

$$E_0 \left(\frac{\Gamma}{\Gamma_0}\right)^{1-s} \sim \Gamma^2 R^3 n_{\mathrm{H}} m_p c$$

These relations determine the time evolution

Synchrotron radiation

Emission by relativistic electrons in a mangetic field

- electron acceleration behind a shock
- magnetic field amplification behind the shock

Fit the GRB afterglow and SNR well

Assume that the same model holds also in our case

- a smaller mass leads earlier deceleration
- more energetic electrons contribute to radiation

Synchrotron radiation

The electron number density in the Lorentz factor is assumed to have a power-law distribution

high frequency: cooling, low frequency: absorption