Electromagnetic Counterparts of Gravitational Waves

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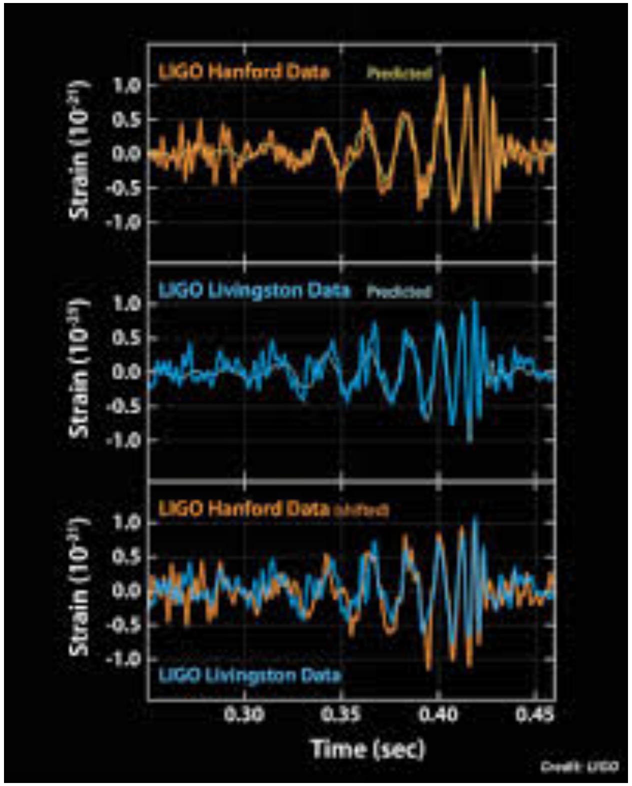
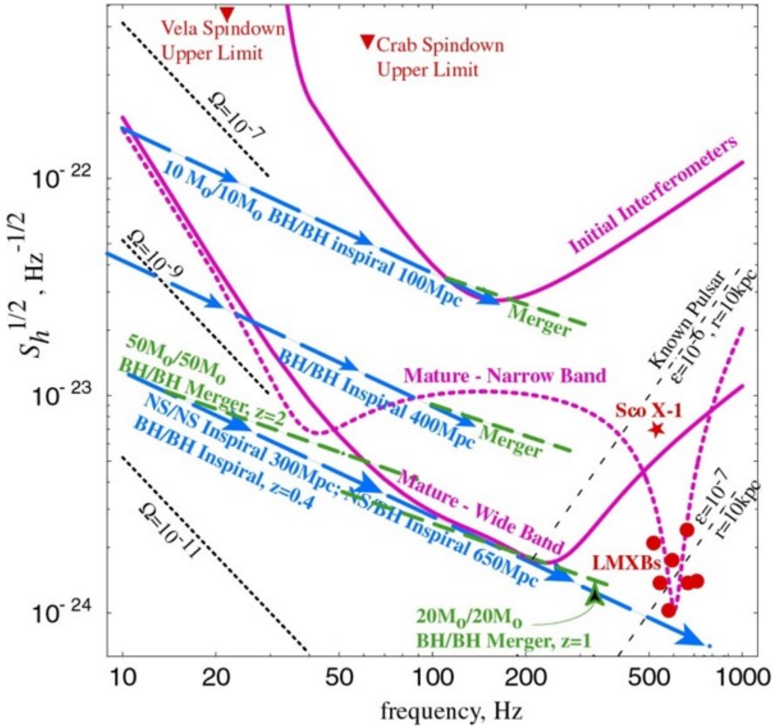
University of Nevada, Las Vegas / Peking University

Apr. 25, 2017

Second SVOM Workshop
Qiannan, Guizhou, China (Apr. 24-28)

Gravitational waves detected!





GW 150914, GW 151226, LVT 151012

BH-BH mergers (Abbott et al. 2016a,b)

NS-NS, NS-BH mergers?

T. Li's talk

Gravitational waves

- Quadrupole rather than dipole (acceleration of acceleration)

$$-\dot{E} = \frac{G}{5c^3}\left\langle \dddot{I}_{ij}\dddot{I}^{ij}\right\rangle$$

Quadrupole moment tensor:

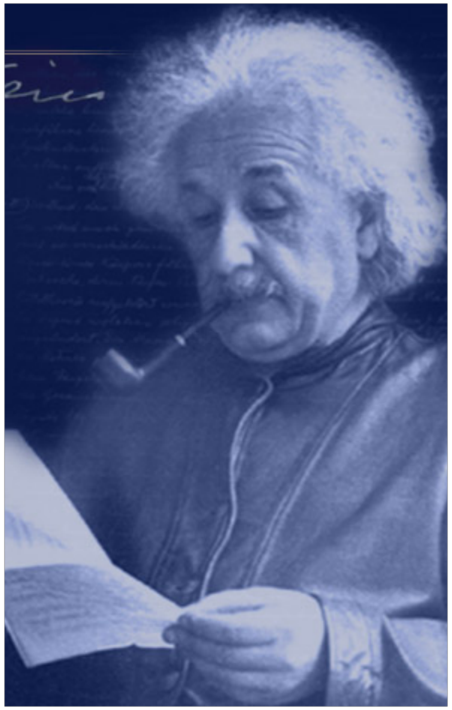
$$I_{ij} = \int \rho(x_i x_j - r^2\delta_{ij}/3)d^3x$$

- Astrophysical binaries are natural sources
- Luminosity (equal masses)

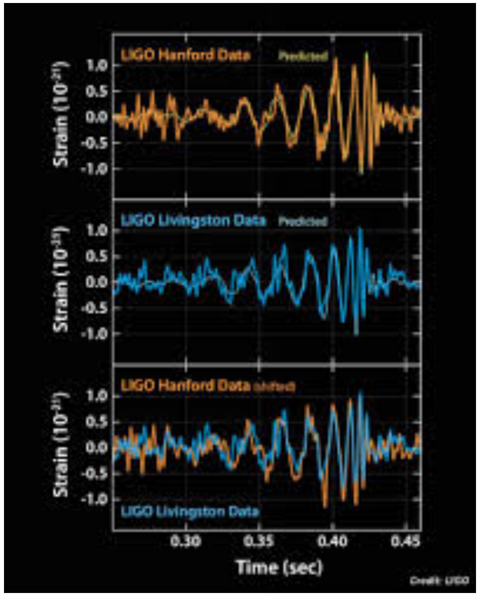
$$L_{\rm GW} = \frac{2}{5}\frac{c^5}{G}\left(\frac{r_s}{a}\right)^5 f(e), \qquad \frac{c^5}{G} \simeq 3.6\times 10^{59}\ {\rm erg\ s^{-1}}$$

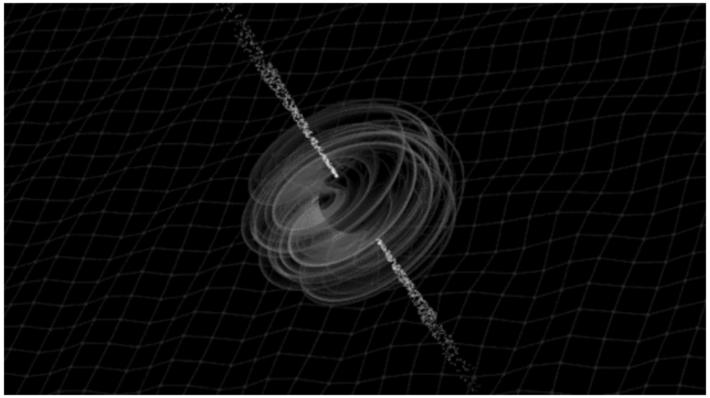
- Top candidates: NS-NS, BH-NS, BH-BH mergers
- Amplitude (measured directly) r^{-1}
- Speed of light
- Final frequency

$$\Omega \sim \frac{c^3}{GM} \simeq 2.0\times 10^5\ {\rm Hz}\ \left(\frac{M}{M_\odot}\right)^{-1}$$



EM signals associated with GWs: Not firmly detected yet





- Confirm the astrophysical origin of the GW signals
- Study the astrophysical physical origin of the GW sources (e.g. host galaxy, environment, etc)
- Study the detailed physics involved in GW events (e.g. equation of state of nuclear matter, black hole electrodynamics)

- General power sources for astrophysical EM radiation
  - Gravitational
  - nuclear
  - rotational (spindown)
  - magnetic

Summary

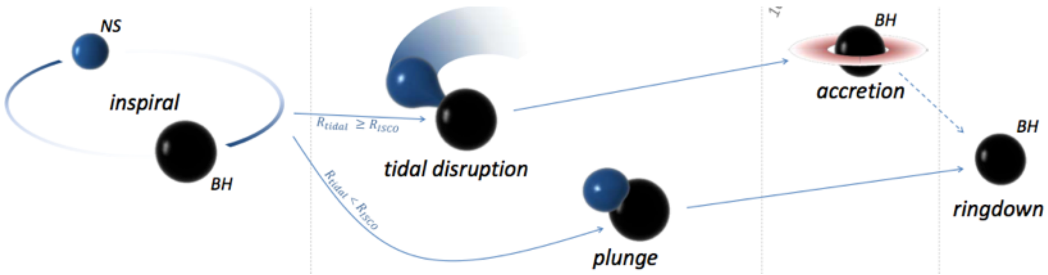
Three types of merger systems:

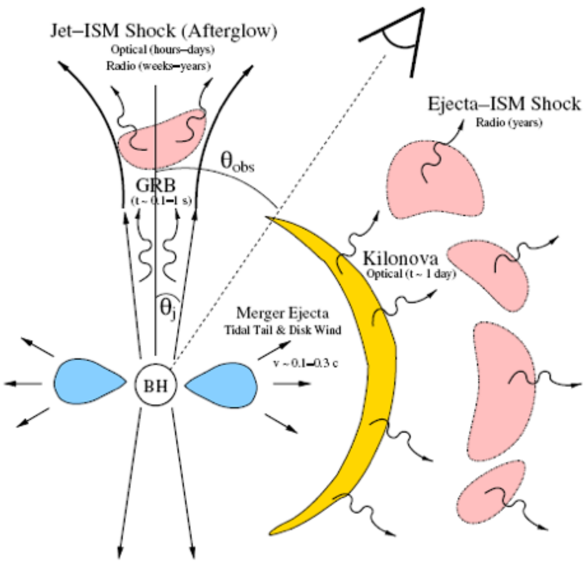
- BH - NS mergers
- NS - NS mergers
  - BH remnant
  - millisecond magnetar remnant
- BH - BH mergers

Four (six) possible EM counterparts:

- short GRBs and afterglows
- kilonova / macronova / mergernova and afterglows
- sGRB-less (large viewing angle) X-ray emission from magnetar
- Fast radio bursts?

BH-NS mergers

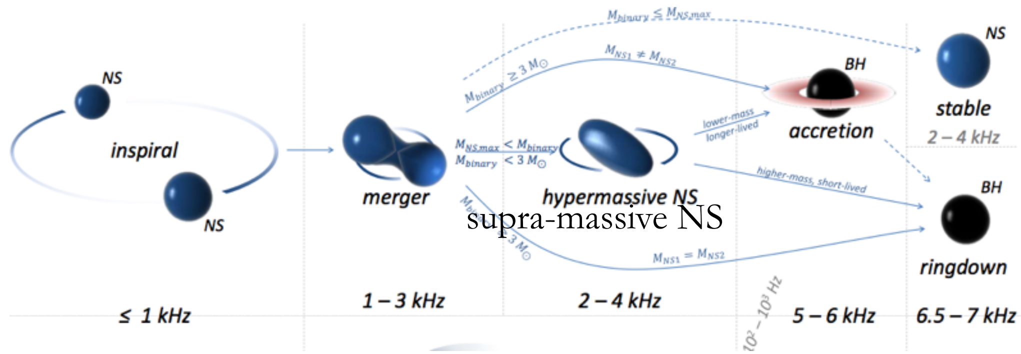




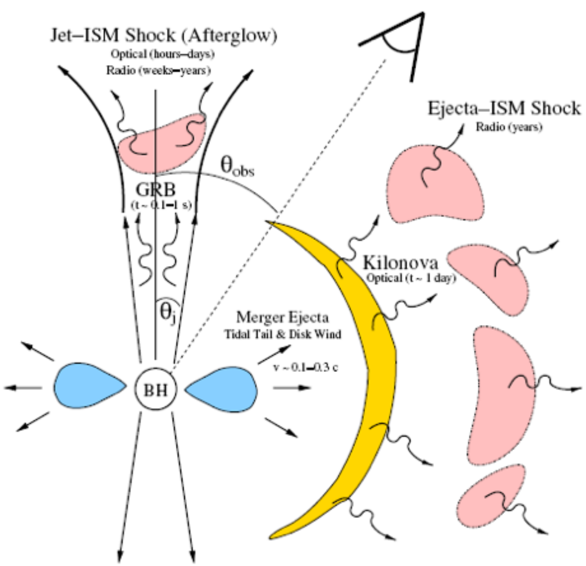
Metzger & Berger (2012)

- Jetted component (likely, but low probability):
  - Short GRB (sGRB)
  - sGRB afterglow (X-ray, UV/optical/IR, radio)
- Quasi-Isotropic component (likely, but faint):
  - Macronova/kilonova/mergernova (optical/IR) - detected with sGRBs
  - kilonova afterglow (radio flare)

NS-NS mergers



NS-NS mergers forming a BH: same as BH-NS mergers



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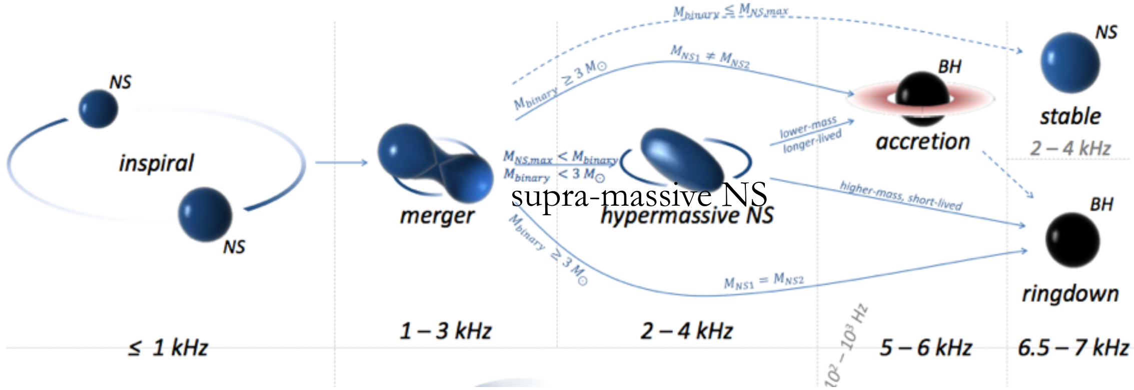
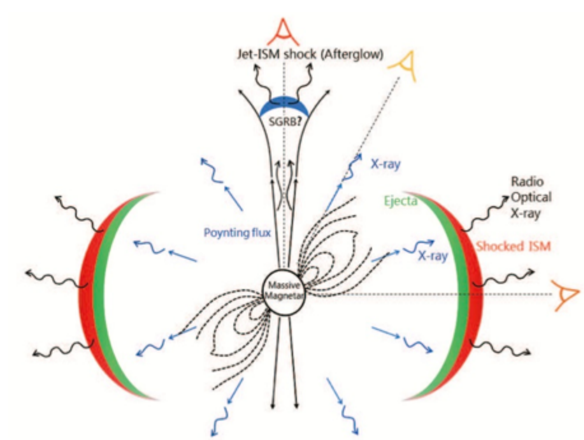
  - kilonova afterglow (radio flare)

NS-NS mergers

(forming a stable or supra-massive NS)





Gao et al. (2013)

- Jetted component (likely, still low probability):
  - Short GRB (sGRB)
  - sGRB afterglow (X-ray, UV/optical/IR, radio)
- Quasi-Isotropic component:
  - Macronova/kilonova/mergernova (optical/IR): enhanced
  - mergernova afterglow: enhanced
  - sGRB-less X-ray transients (plausible)
  - Fast radio bursts (speculative)

The Gehrels' Question:

Are short GRBs produced by NS-NS mergers or NS-BH mergers?

The Swift breakthrough

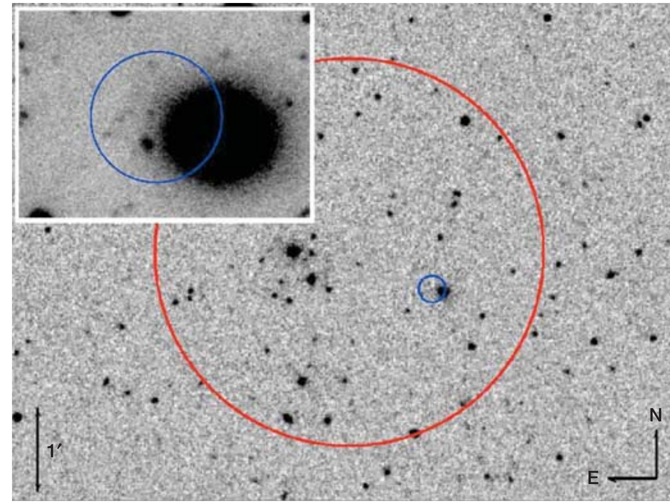
Vol 437|6 October 2005|doi:10.1038/nature04142 nature

LETTERS

A short γ-ray burst apparently associated with an elliptical galaxy at redshift $z = 0.225$

N. Gehrels[1], C. L. Sarazin[2], P. T. O'Brien[3], B. Zhang[4], L. Barbier[1], S. D. Barthelmy[1], A. Blustin[5], D. N. Burrows[6], J. Cannizzo[1,7], J. R. Cummings[1,8], M. Goad[3], S. T. Holland[1,9], C. P. Hurkett[3], J. A. Kennea[6], A. Levan[3], C. B. Markwardt[1,10], K. O. Mason[5], P. Meszaros[6], M. Page[5], D. M. Palmer[11], E. Rol[3], T. Sakamoto[1,8], R. Willingale[3], L. Angelini[1,7], A. Beardmore[3], P. T. Boyd[1,7], A. Breeveld[5], S. Campana[12], M. M. Chester[6], G. Chincarini[12,13], L. R. Cominsky[14], G. Cusumano[15], M. de Pasquale[5], E. E. Fenimore[11], P. Giommi[16], C. Gronwall[6], D. Grupe[6], J. E. Hill[6], D. Hinshaw[1,17], J. Hjorth[18], D. Hullinger[1,10], K. C. Hurley[19], S. Klose[20], S. Kobayashi[6], C. Kouveliotou[21], H. A. Krimm[1,9], V. Mangano[12], F. E. Marshall[1], K. McGowan[5], A. Moretti[12], R. F. Mushotzky[1], K. Nakazawa[22], J. P. Norris[1], J. A. Nousek[6], J. P. Osborne[3], K. Page[3], A. M. Parsons[1], S. Patel[23], M. Perri[16], T. Poole[5], P. Romano[12], P. W. A. Roming[6], S. Rosen[5], G. Sato[22], P. Schady[5], A. P. Smale[24], J. Sollerman[25], R. Starling[26], M. Still[1,9], M. Suzuki[27], G. Tagliaferri[12], T. Takahashi[22], M. Tashiro[27], J. Tueller[1], A. A. Wells[3], N. E. White[1] & R. A. M. J. Wijers[26]

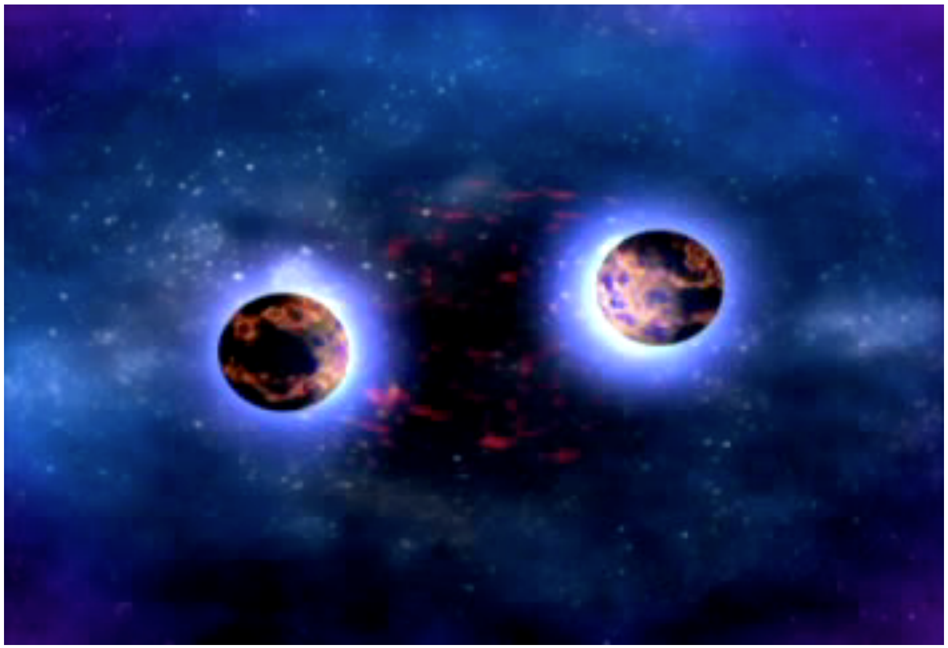
Gamma-ray bursts (GRBs) come in two classes[1]: long (>2 s), soft-spectrum bursts and short, hard events. Most progress has been made on understanding the long GRBs, which are typically observed at high redshift ($z \approx 1$) and found in subluminous star-forming host galaxies. They are likely to be produced in core-collapse explosions of massive stars[2]. In contrast, no short GRB had been accurately (<10″) and rapidly (minutes) located. Here we report the detection of the X-ray afterglow from—and the localization of—the short burst GRB 050509B. Its position on the sky is near a luminous, non-star-forming elliptical galaxy at a redshift of 0.225, which is the location one would expect[3,4] if the origin of this GRB is through the merger of neutron-star or black-hole binaries. The X-ray afterglow was weak and faded below the detection limit within a few hours; no optical afterglow was detected to stringent limits, explaining the past difficulty in localizing short GRBs.



Clues for the merger origin of short GRBs:

- Early afterglow detections. None has a SN signature.
- In different types of host galaxies, including a few in elliptical/early-type galaxies, and most in star-forming galaxies
- Do not follow bright sights of hosts
- In regions of low star formation in star-forming galaxies
- Redshift distribution (a good fraction of low-z).
- Theoretical expectation should be "short"

Two possibilities



NS - NS merger

NS - BH merger

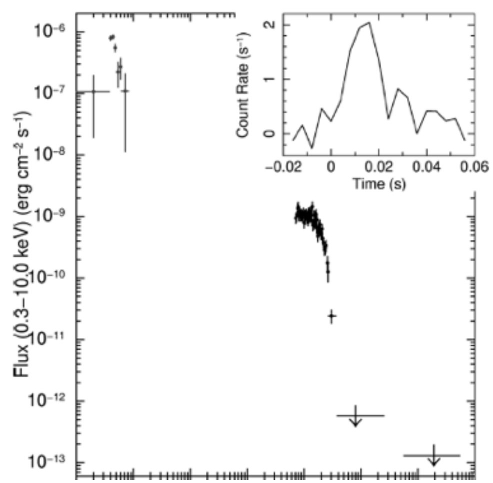
Bing's last dialog with Neil

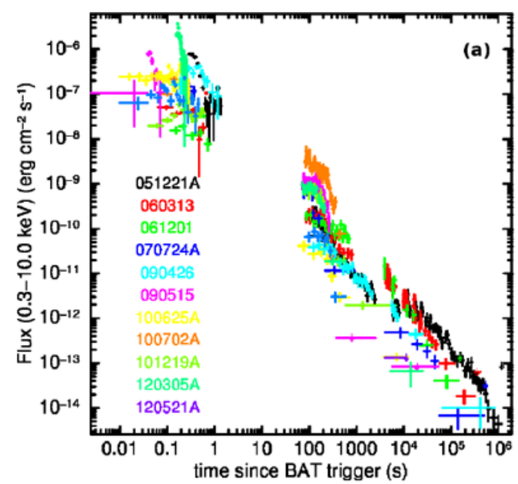
Nov. 11, 2016, Annapolis, Maryland

Neil (as session chair, to everyone):
Which do you guys think could be the progenitor of short GRBs, NS-NS mergers or NS-BH mergers?

Bing (raised hand and spoke):
At least some should be NS-NS mergers, since we see the magnetar signature in the internal X-ray plateau of some SGRBs.

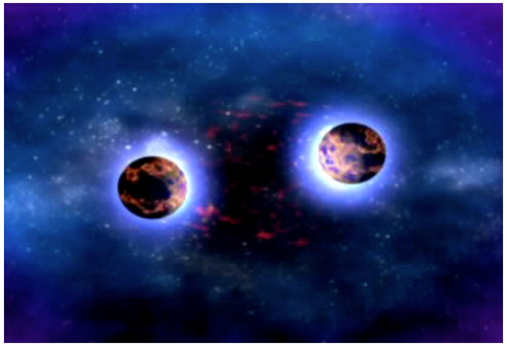
Neil (not very convinced):
Yes, from that perspective.

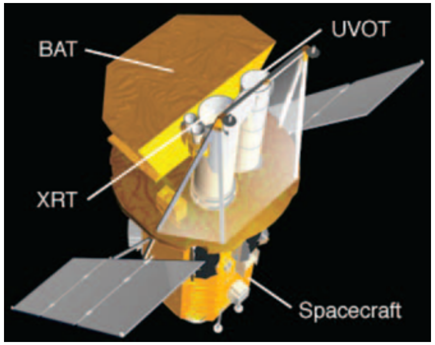


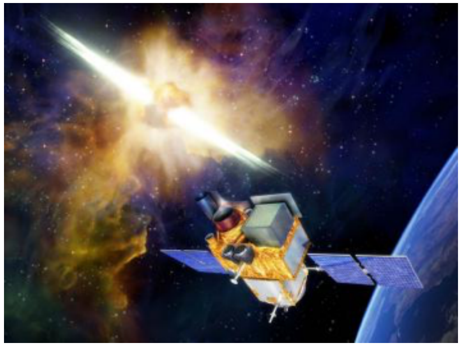


Neil wanted to see the final observational proof from the direct joint GW-EM observations. Unfortunately he could not see this happen.

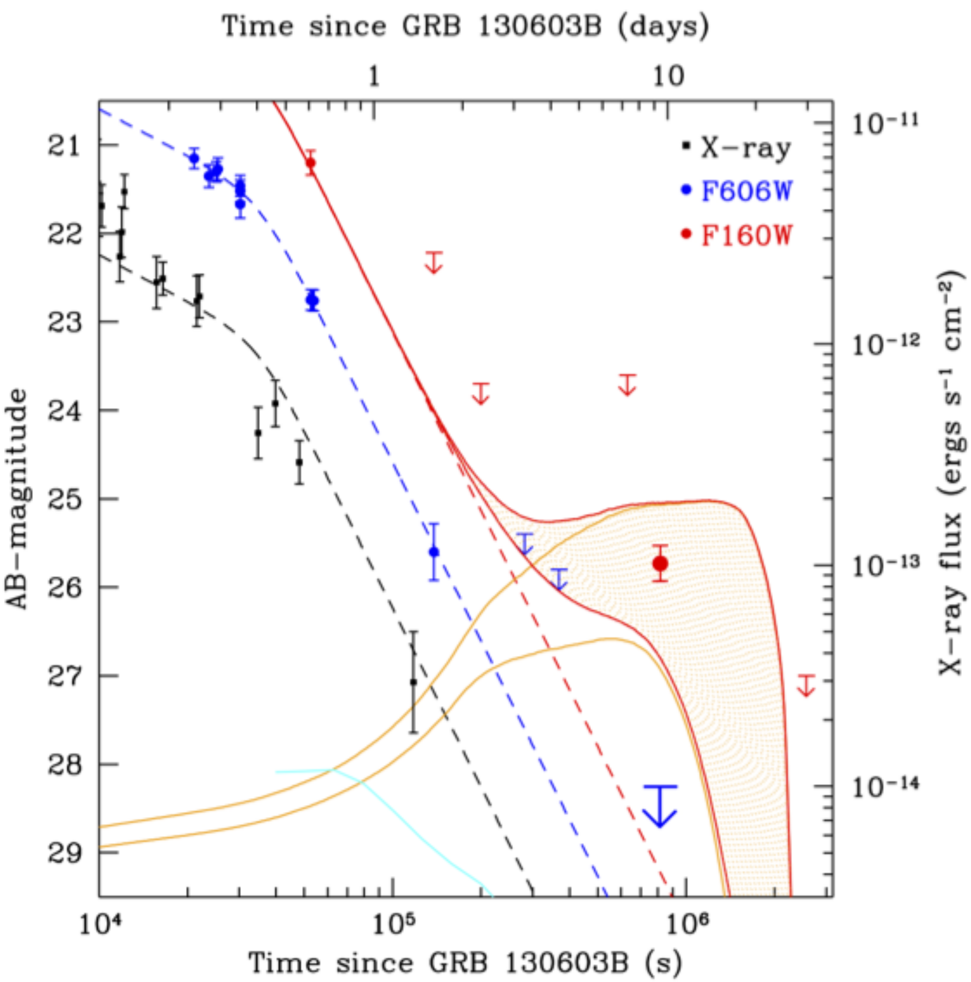
We will find out sometime soon!







Kilonova, macronova, mergernova



Tanvir et al. (2013, Nature), Berger et al. (2013, ApJL)

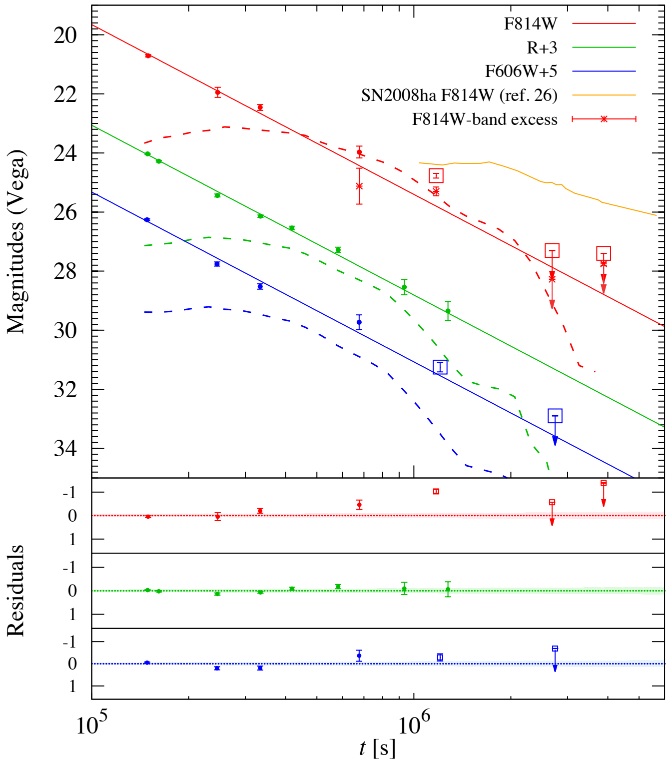
N. Tavir's talk

1974 • Lattimer & Schramm: *r*-process from BH-NS mergers
1975 • Hulse & Taylor: discovery of binary pulsar system PSR 1913+16
1989 • Eichler et al.: GRBs, *r*-process from NS-NS mergers
1998 • Li & Paczynski: first kilonova model, with parametrized heating
1999 • Freiburghaus et al.: NS-NS dynamical ejecta ⇒ r-process abundances
2005 • Kulkarni: kilonova powered by free neutron-decay ("macronova")
2009 • Perley et al.: optical kilonova candidate following GRB 080503 (Fig. 10)
2010 • Metzger et al., Roberts et al.: kilonova powered by *r*-process heating
2013 • Barnes & Kasen, Tanaka & Hotokezaka: La/Ac opacities ⇒ NIR spectral peak
2013 • Tanvir et al., Berger et al.: NIR kilonova candidate following GRB 130603B
2013 • Yu, Zhang, Gao: magnetar-boosted kilonova ("merger-nova")
2014 • Metzger & Fernandez, Kasen et al.: blue kilonova from the disk winds

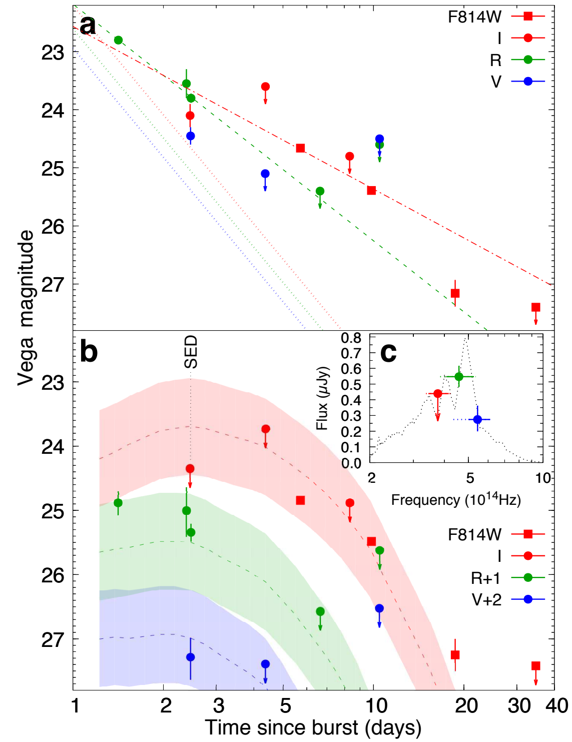
Figure 1: Timeline of major developments in kilonova research

B. Metzger (2016)

Kilonova, macronova, mergernova



GRB 060614
Yang et al. (2015)



GRB 050709
Jin et al. (2016)

Enhanced (Magnetar powered) Merger Novae

Yu, Zhang & Gao, 2013, ApJ, 763, L22

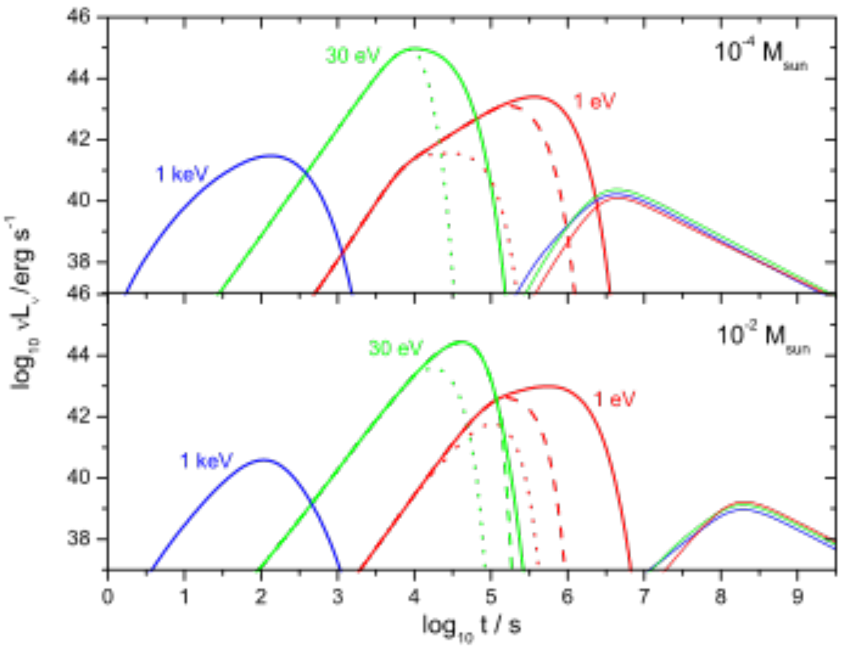


Figure 2. Light curves of the merger-nova (thick) and afterglow (thin) emissions at different observational frequencies as labeled. The dashed and dotted lines are obtained for an optionally taken magnetar collapsing time as $t_{col} = 2t_{md}$ and $t_{col} = 10^4$ s, respectively. The ambient density is taken as $0.1\ cm^{-3}$, and other model parameters are the same as Figure 1.

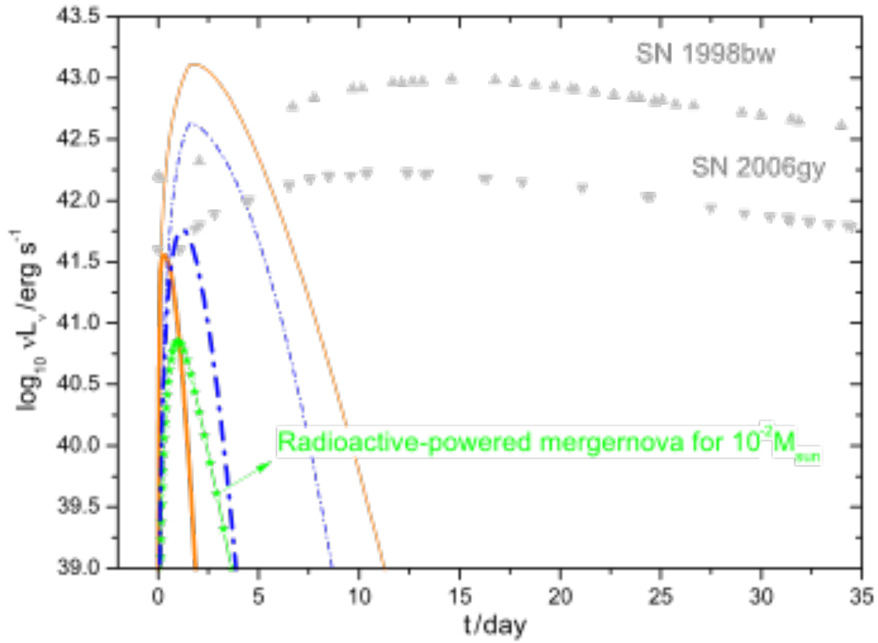
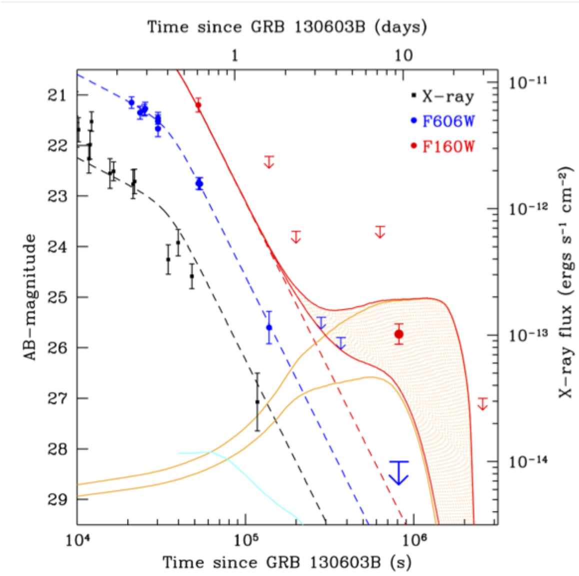
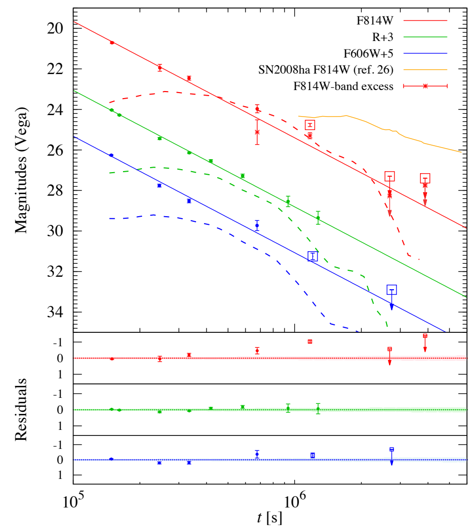


Figure 3. Optical (~1 eV) light curves of the millisecond-magnetar-powered merger-nova, in comparison with the light curves of two supernovae (bolometric) and one radioactive-powered merger-nova (as labeled). The dash-dotted (blue) and solid (orange) lines represent $M_{ej} = 10^{-2}\ M_\odot$ and $10^{-4}\ M_\odot$, respectively. The thick and thin lines correspond to a magnetar collapsing time as $t_{col} = 10^4\ s \ll t_{md}$ and $t_{col} = 2t_{md}$, respectively. The zero-times of the supernovae are set at the first available data.

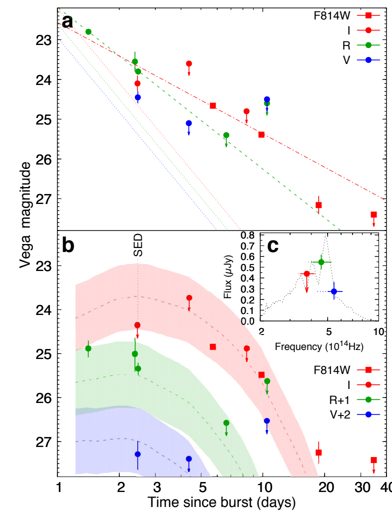
Kilonova, macronova, mergernova



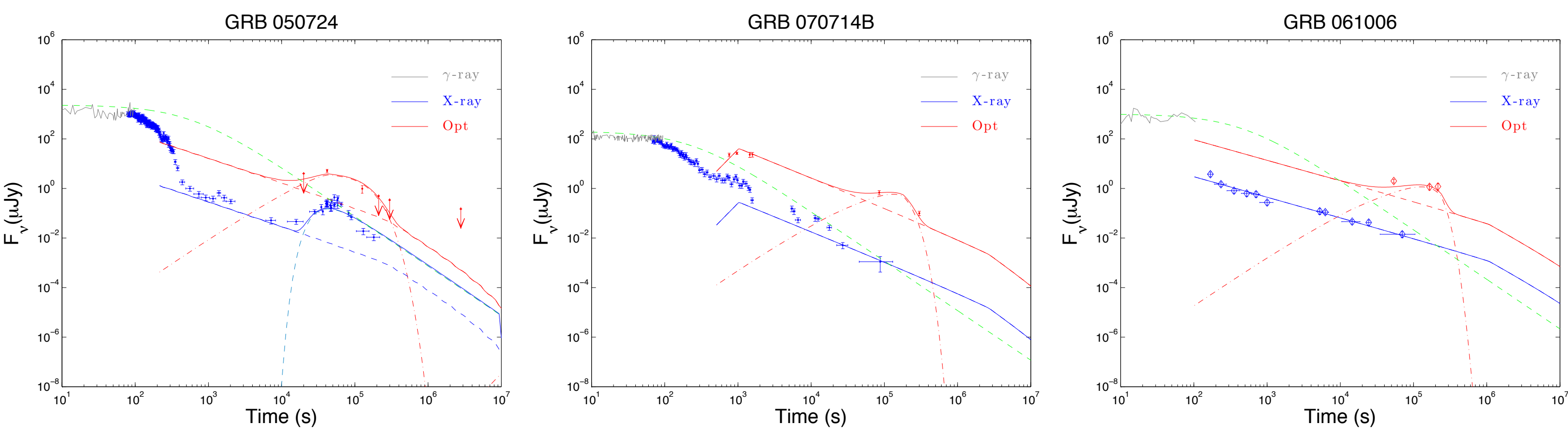
GRB 130603B, Tanvir et al. (2015); Berger et al. (2015)



GRB 060614, Yang et al. (2015)

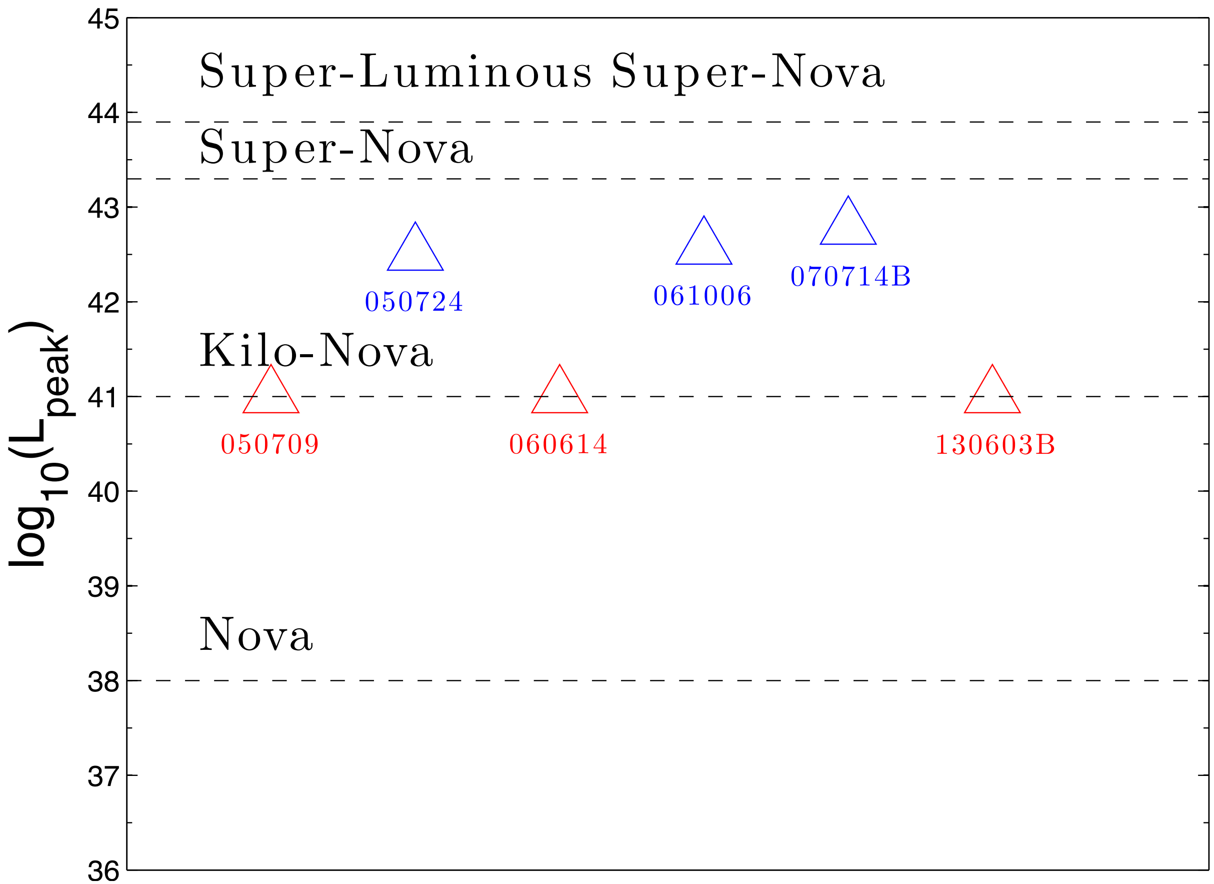


GRB 050709, Jin et al. (2016)



Gao et al. (2017, ApJ, 837, 50)

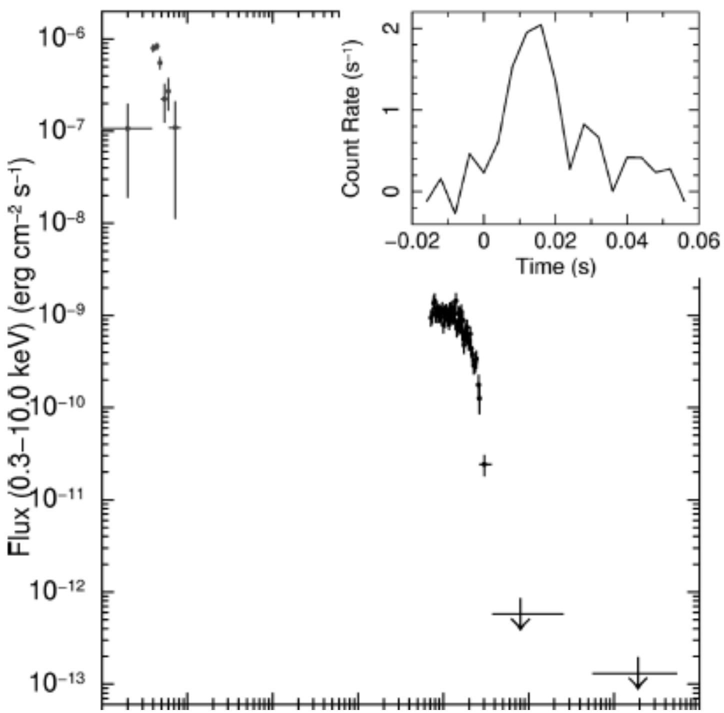
Kilonova, macronova, mergernova



Some could be super-kilo
Some could be hecto

Gao et al. (2017, ApJ, 837, 50)

sGRB-less X-ray counterpart
(orphan internal plateau)



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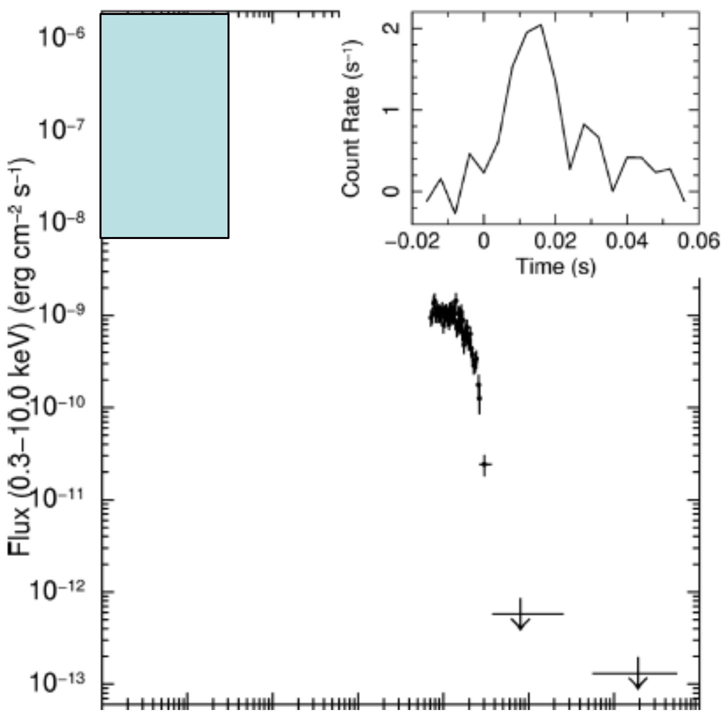
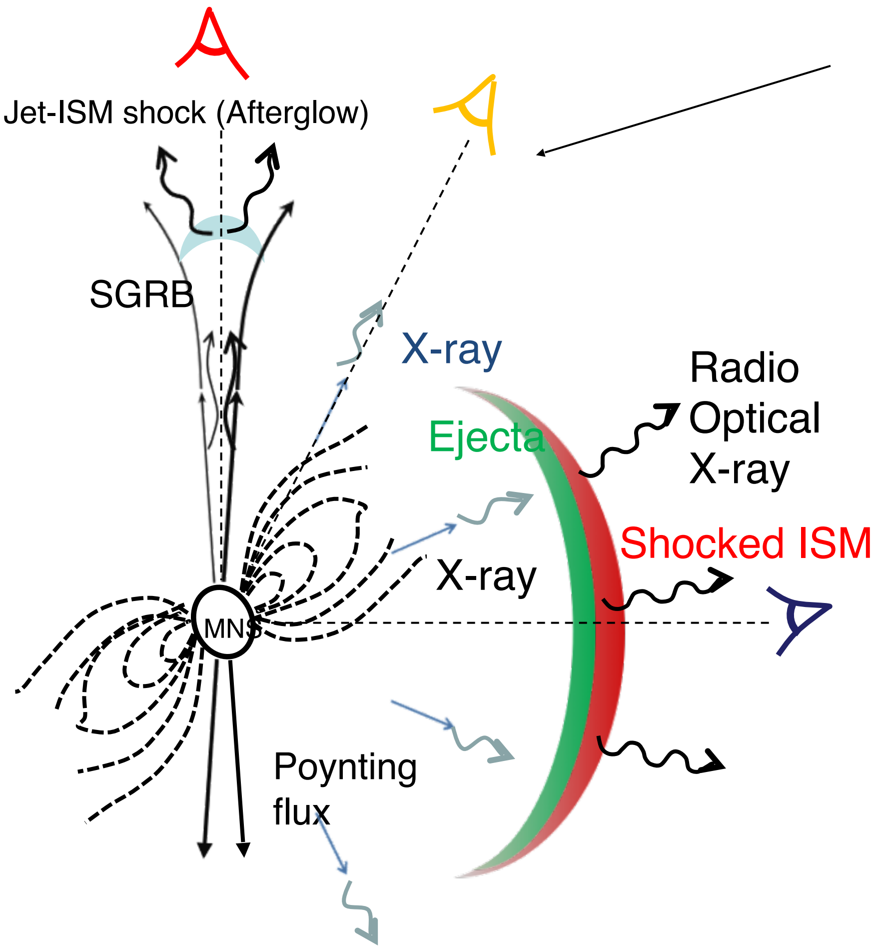
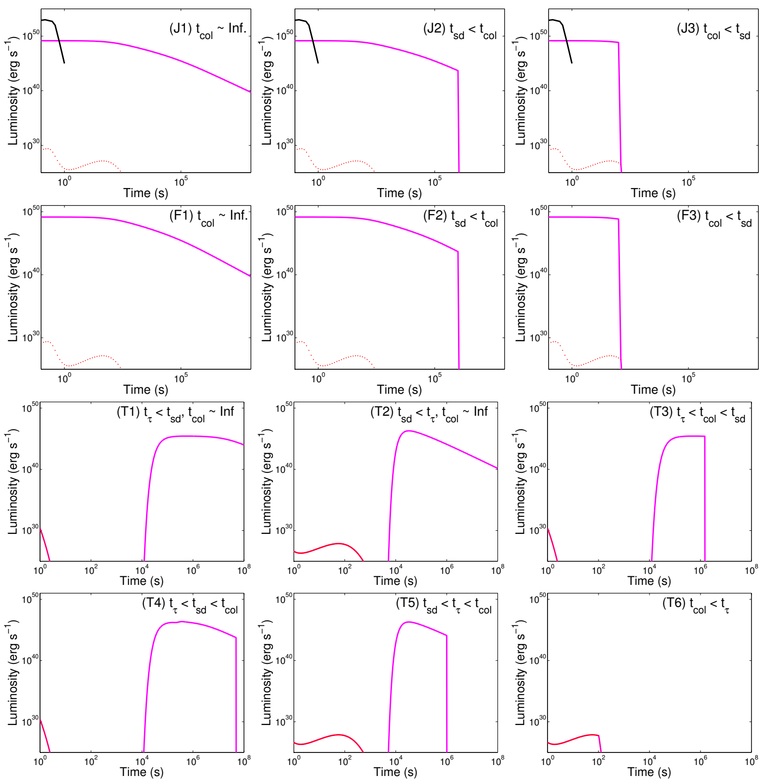
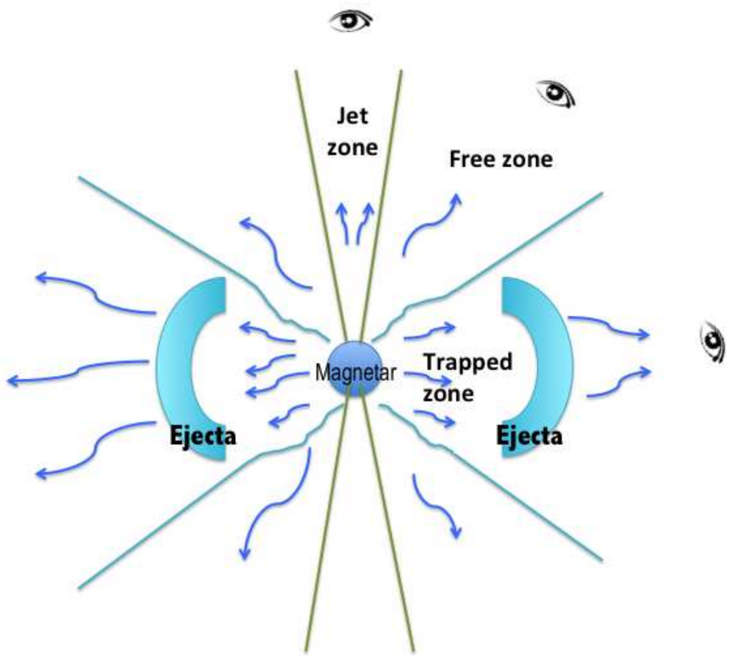




Zhang (2013, ApJL, 736, L22)

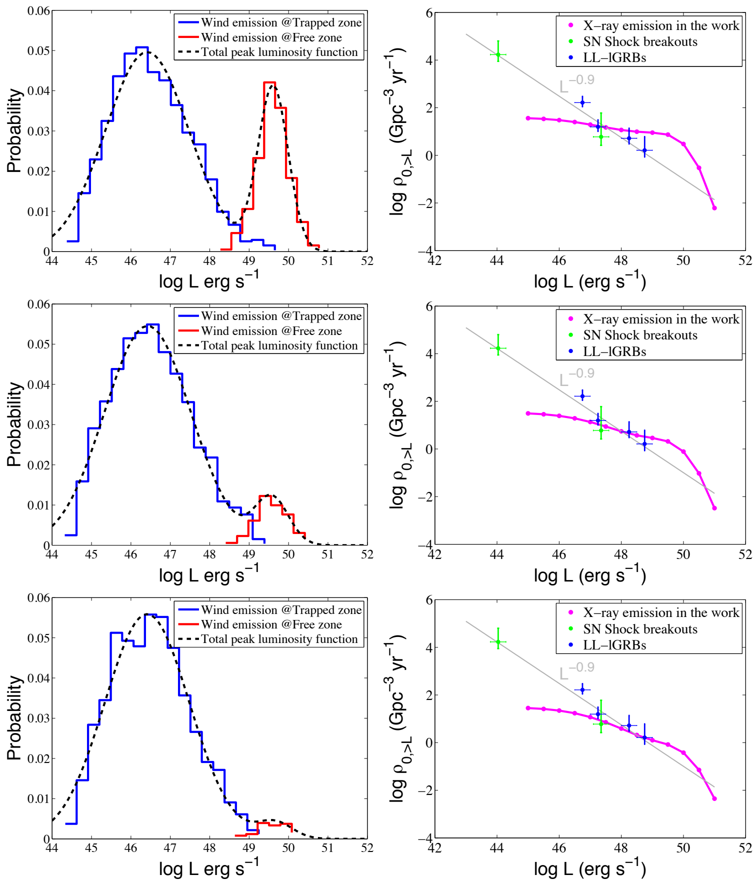
sGRB-less X-ray counterpart:
light curve gallery

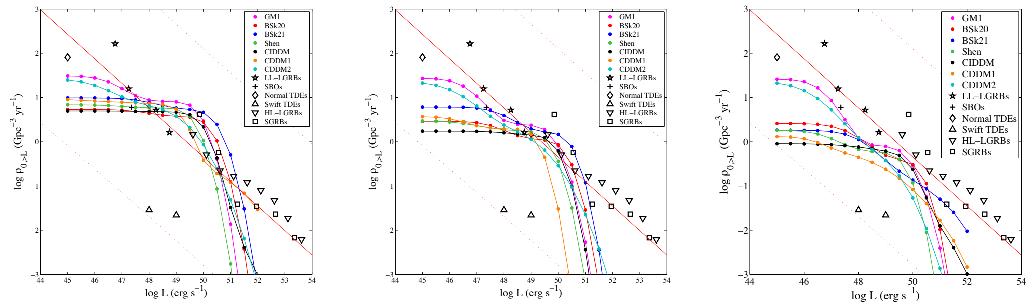


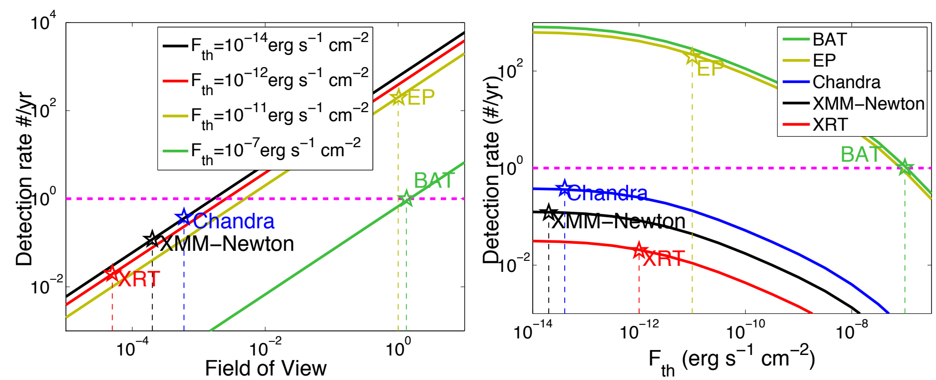


Sun, Zhang & Gao, 2017, ApJ, 835, 7

sGRB-less X-ray counterpart:
luminosity function & event rate density



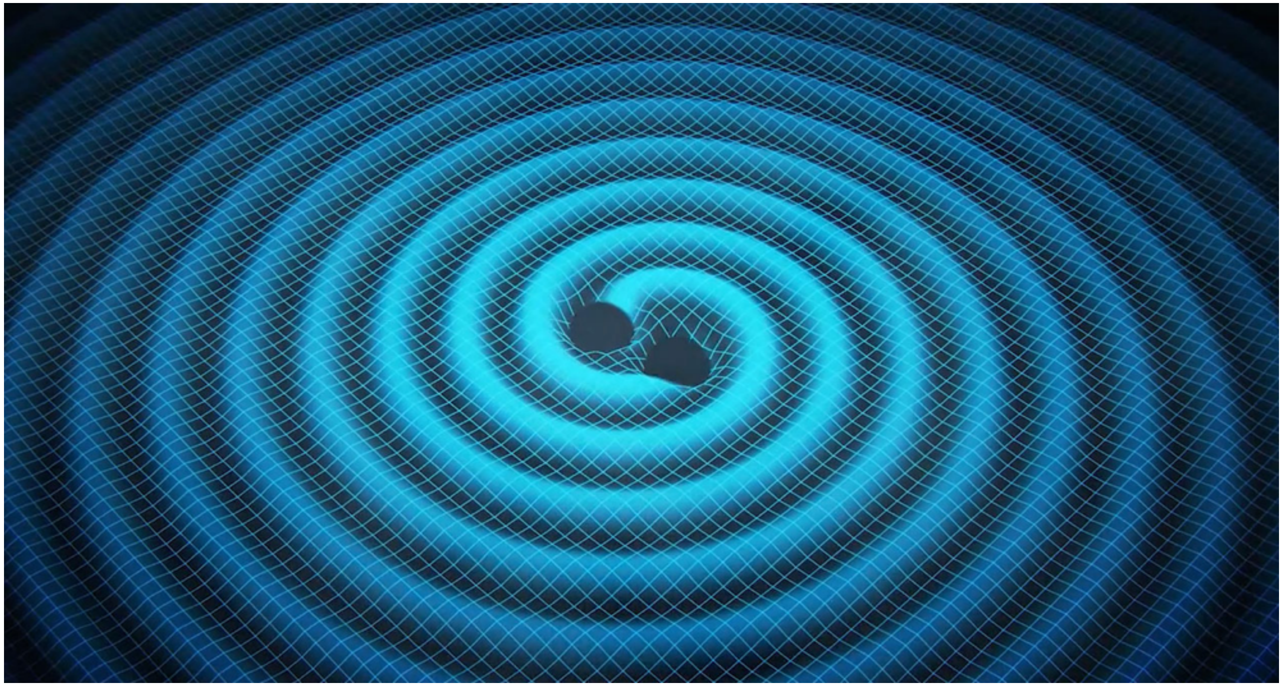




Sun, Zhang & Gao, 2017, ApJ, 835, 7

Candidate(s) found from Swift archives - great targets for SVOM & EP!

BH-BH mergers

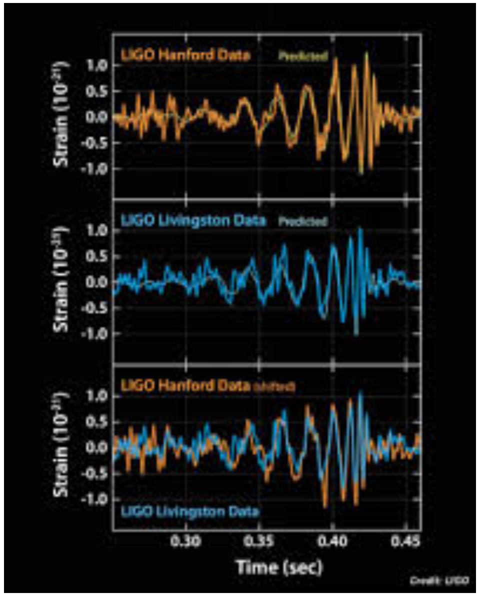


- Two naked BHs: No EM counterpart expected!
- EM counterparts can be generated if at least one BH can retain matter or EM fields

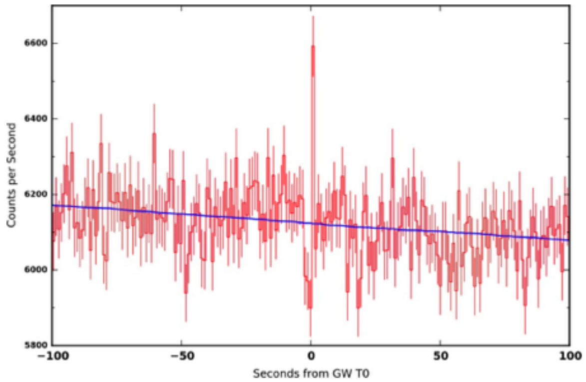
JSI Workshop debate: Can BH-BH mergers have electromagnetic counterparts?

Julian Krolik (No) vs. BZ (Yes)
Nov. 10, 2016, Annapolis, MD

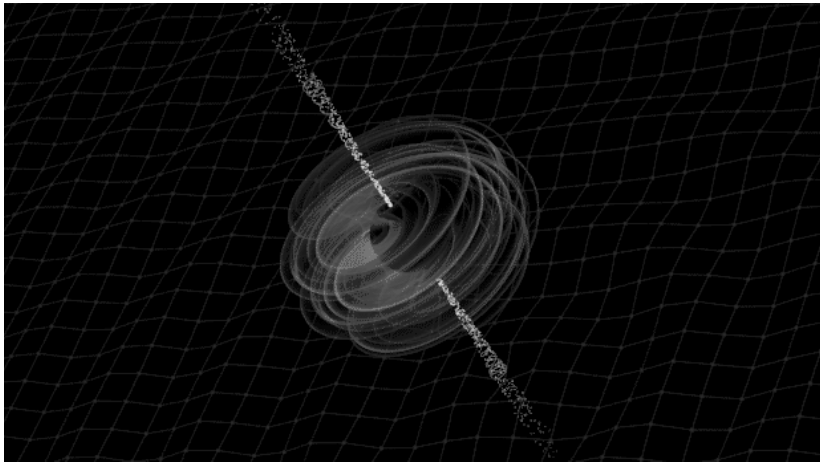
Origin of debate:
GRB following GW 150914? (GW150914-GBM)



Abbott et al. 2016)



Connaughton et al. (2016)



- Weak burst above 50 keV
- Onset time: 0.4 s after GW 150914
- Duration 1s
- Direction broadly consistent
- False alarm probability 0.0022 (2.9 σ)
- L ~ $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{-1}

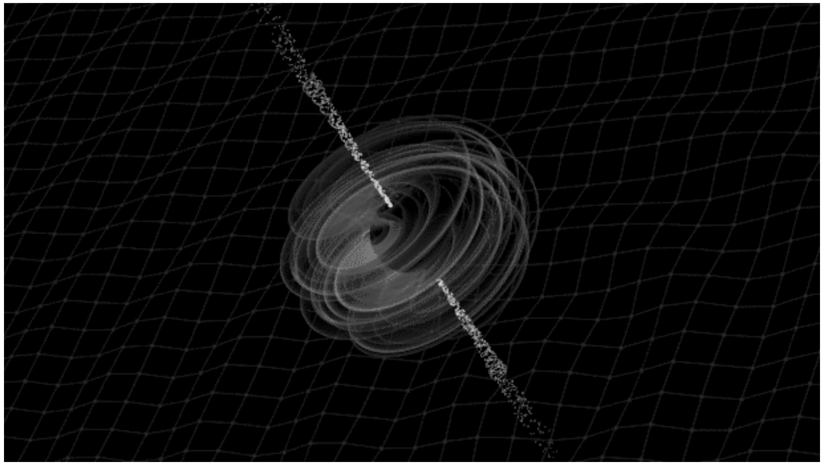
but see Savchenko et al. (2016)
Greiner et al. (2016); Xiong (2016)

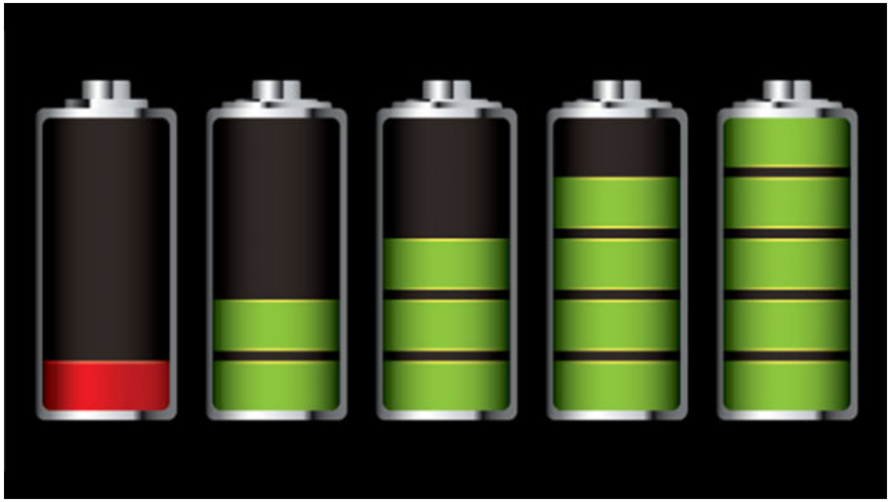
Unconventional Ideas for EM counterparts of BH-BH mergers

- Models with matter
  - Twin BHs inside one star (Loeb 2016, but see Woosley 2016; Dai et al. 2016)
  - Reactivated accretion disk (Perna et al. 2016, but see Kimura et al. 2016)
  - Merger of collapsing star & BH interactions (Janiuk et al. 2016 …)
  - Multi-body interactions (…)

- Models with EM fields
  - Charged BH-BH mergers (Zhang 2016, Liu et al. 2016; Fraschetti 2016; Liebling & Palenzuela 2016)

Charged

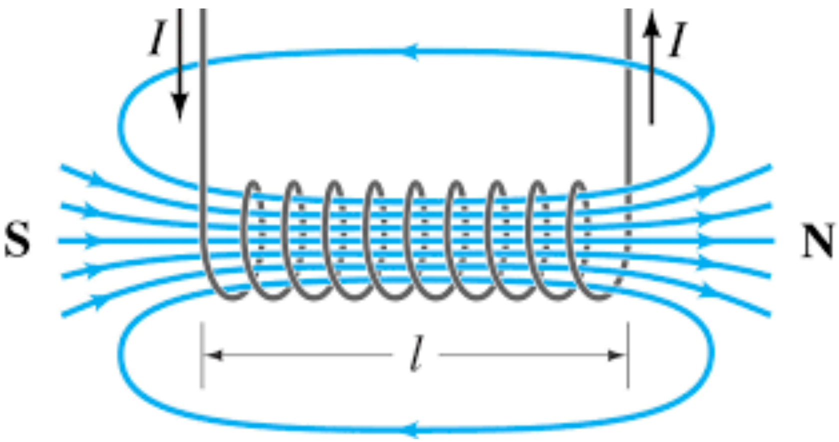


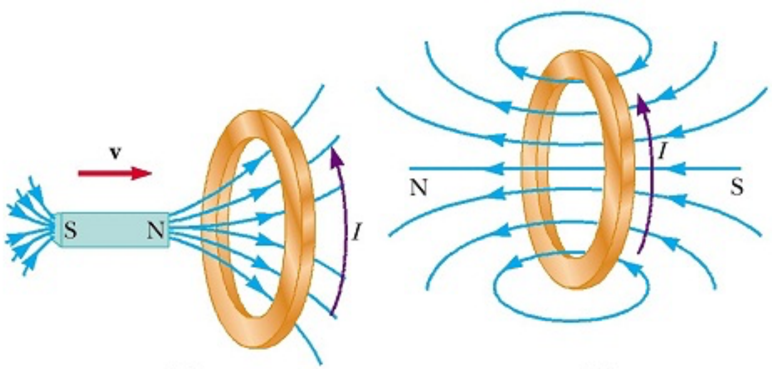


Charged BH merger model

(Zhang, ApJ, 827, L31)

Part 1: Consequence of charges





(a) (b)

1. $\nabla \cdot \mathbf{D} = \rho_V$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
4. $\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

High school E&M

Charged BH merger model

(Zhang, ApJ, 827, L31)

Part 1: Consequence of charges

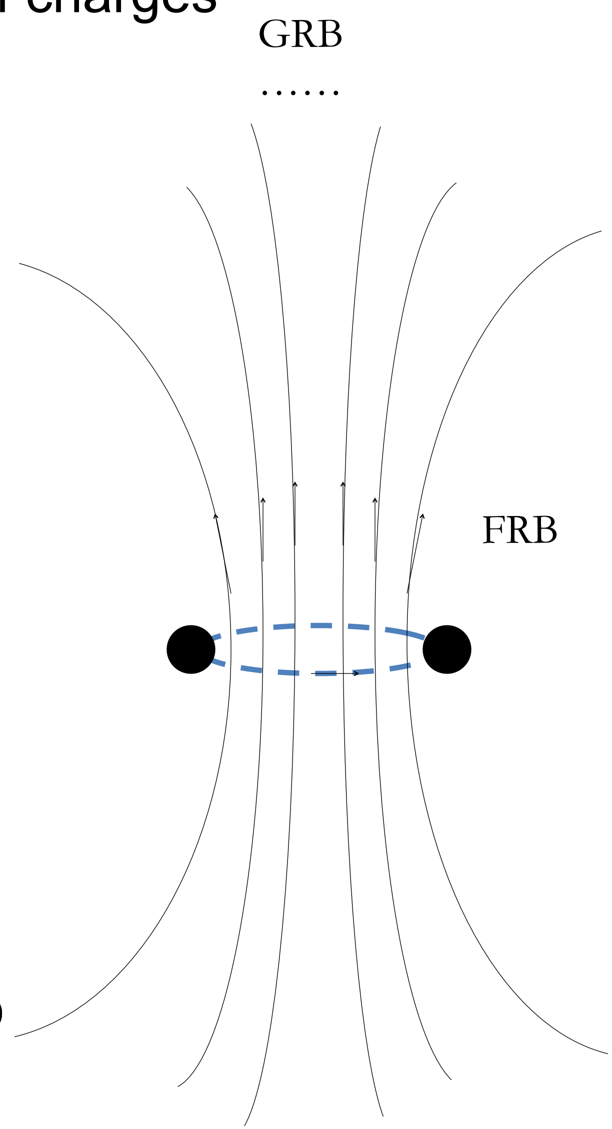
$$\mu = \frac{\pi I (a/2)^2}{c} = \frac{\sqrt{2GMa}Q}{4c} = \frac{\sqrt{2}G^{3/2}M^2}{c^2}\hat{q}\hat{a}^{1/2}$$
$$= (1.1 \times 10^{33}\ \mathrm{G\ cm^3}) \left(\frac{M}{10M_\odot}\right)^2 \hat{q}_{-4}\hat{a}^{1/2},$$

$$L_w \simeq \frac{2\ddot{\mu}^2}{3c^3} \simeq \frac{49}{120000}\frac{c^5}{G}\hat{q}^2\hat{a}^{-15}$$
$$\simeq (1.5 \times 10^{48}\ \mathrm{erg\ s^{-1}})\hat{q}_{-4}^2\hat{a}^{-15},$$

$$L_w \sim 0.03\hat{q}^2 L_{\rm GW}\hat{a}^{-10}$$

$$Q = \hat{q}Q_c, \qquad \frac{da}{dt} = -\frac{2}{5}\frac{c}{\hat{a}^3}$$

$$Q_c \equiv 2\sqrt{G}M = (1.0 \times 10^{31}\ \mathrm{e.s.u.}) \left(\frac{M}{10M_\odot}\right)$$



Can produce Fast radio bursts (FRBs) and short GRBs

$\hat{q} \sim (10^{-9}–10^{-8})$ $\qquad$ $\hat{q} \sim (10^{-5}–10^{-4})$

Charged BH merger model (Zhang, ApJ, 827, L31)

Part 2: How does a BH obtain and maintain charge?

Fair question

but, don't say:

"According to … textbook, astrophysical charged BHs are quickly neutralized."

Valid for Reissner-Nordstrom BHs

Not sure for Kerr-Newman BHs: work needed

Bottom line

- A rotating magnet is charged and remain charged - a pulsar is charged

Theory of pulsar magnetospheres

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There is a wide range of fundamental physical problems directly related to how pulsars function. Some of these are independent of the specific pulsar mechanism. Others relate directly to the physics of the pulsar and already shed some light on the properties of matter at high density ($\sim 10^{15}$ g/cc) and in strong magnetic fields ($\sim 10^{12}$ G). Pulsars are assumed to be rotating neutron stars surrounded by strong magnetic fields and energetic particles. It is somewhere within this "magnetosphere" that the pulsar action is expected to take place. Currently there has been considerable difficulty in formulating an entirely self-consistent theory of the magnetospheric behavior and there may be rapid revisions in the near future, which is all the more surprising since many of the issues involve "elementary" problems in electromagnetism. One interesting discovery is that charge-separated plasmas apparently can support stable static discontinuities.

b. The central charge

Let us now ask why there should be a huge charge associated with a point dipole. See, for example, Cohen *et al.* (1975). From E_r (outside) and Gauss's law we have a positive central charge

$$Q = 8\pi\varepsilon_0 a \Phi_0 / 3 \ ,$$

which is of the order of 10^{12} C (or about 10^7 moles of electrons!) for the Crab pulsar. This charge is actually

TABLE VIa. The vacuum solution (point dipole field).

Quantity	Expression	Surface values Equator[a]	Surface values Pole[b]
	Inside star		
Φ	$\sin^2\theta/r$	$+1$	0
E_r	$\sin^2\theta/r^2$	$+1$	0
E_θ	$-2\sin\theta\cos\theta/r^2$	0	0
q/ε_0	$2(1-3\cos^2\theta)/r^3$	$+2$	-4
$\underline{E}\cdot\underline{B}$	0	0	0
	Outside star		
Φ	$\frac{2}{3r}+\frac{1}{3r^3}(1-3\cos^2\theta)$	$+1$	0
E_r	$\frac{2}{3r^2}+\frac{1}{r^4}(1-3\cos^2\theta)$	$+\frac{5}{3}$	$-\frac{4}{3}$
E_θ	$-2\sin\theta\cos\theta/r^4$	0	0
q/ε_0	0	0	0
$\underline{E}\cdot\underline{B}$	$4\cos\theta(1-3\cos^2\theta/r^2)/3r^5$	0	$-\frac{8}{3}$
	Surface		
σ/ε_0[c]	$2(1-3\cos^2\theta)/3$	$+\frac{2}{3}$	$-\frac{4}{3}$
$\underline{E}\cdot\underline{B}$ (average)	$2\cos\theta(1-3\cos^2\theta)/3$	0	$-\frac{4}{3}$
	Everywhere		
B_r	$2\cos\theta/r^3$	0	$+2$
B_θ	$\sin\theta/r^3$	$+1$	0

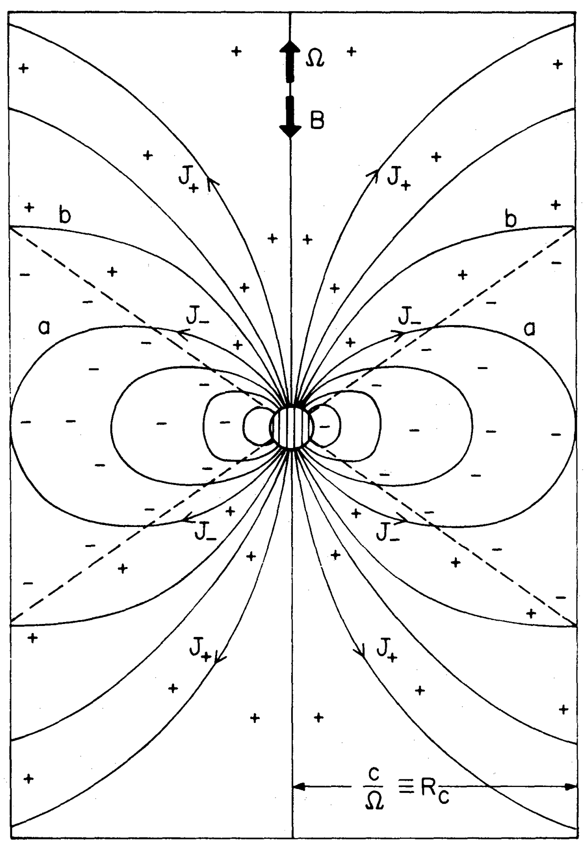
[a]Here $f=1$, $\theta=\pi/2$.
[b]Here $f=0$, $\theta=0$.
[c]The surface charge density σ is given from E_r(out) $-E_r$(in).

Charged pulsars

THE ASTROPHYSICAL JOURNAL, 196:51–72, 1975 February 15

THEORY OF PULSARS: POLAR GAPS, SPARKS, AND COHERENT MICROWAVE RADIATION

M. A. RUDERMAN*
AND
P. G. SUTHERLAND†



Goldreich and Julian (1969) elucidated the characteristics of the corotating magnetosphere surrounding an axisymmetric neutron star with aligned magnetic moment and rotation axes. They assumed that (*a*) the neutron star can supply the necessary negative charges (electrons) and positive charges (ions and positrons) required to fill and maintain the magnetosphere with $\boldsymbol{E}\cdot\boldsymbol{B} \sim 0$, and (*b*) the currents in the magnetosphere are negligible. They showed that the magnetosphere would then corotate with a local charge density

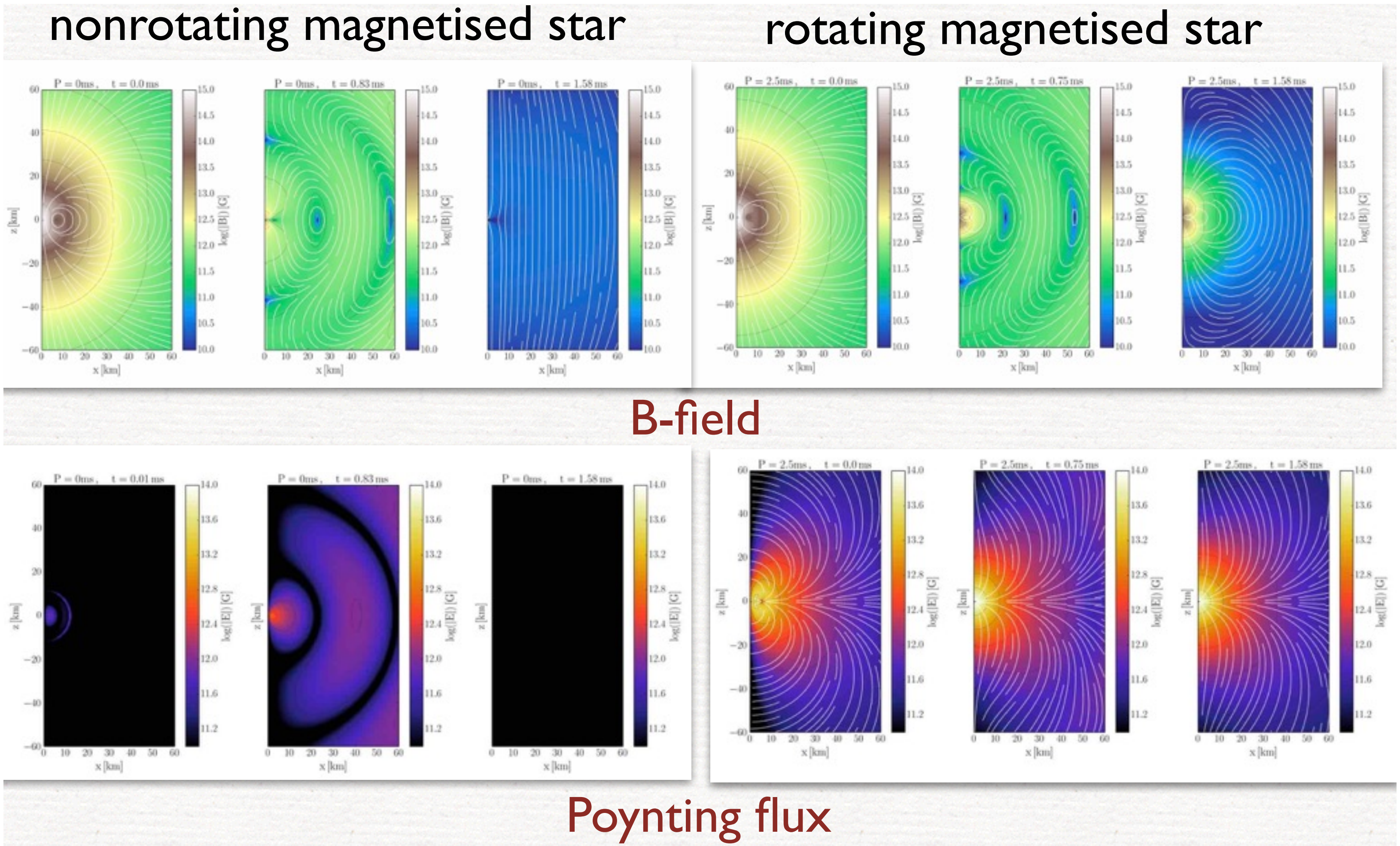
$$\rho_e = -\frac{\boldsymbol{\Omega}\cdot\boldsymbol{B}}{2\pi c}\frac{1}{1 - \Omega^2 r_\perp{}^2/c^2} \qquad (1)$$

The magnetic fields inside/outside a NS is co-rotating with the NS, so charged

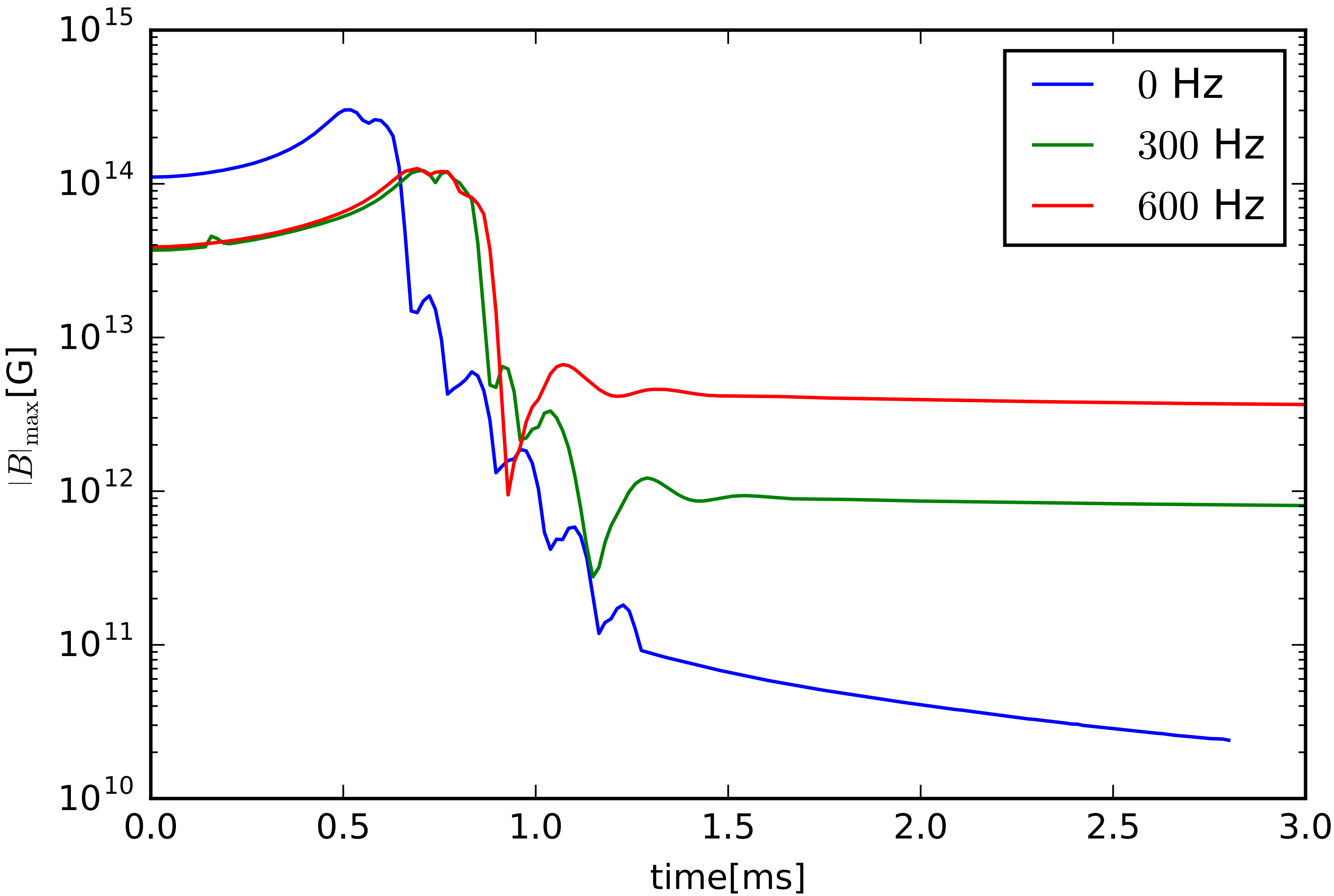
When a NS collapses to a BH, the BH is a spinning, charged BH - Kerr Newman

Formation of charged BHs

(Nathanail, Mosy & Rezzolla, 2017, MNRAS)



Rezzolla's talk in Kyoto meeting



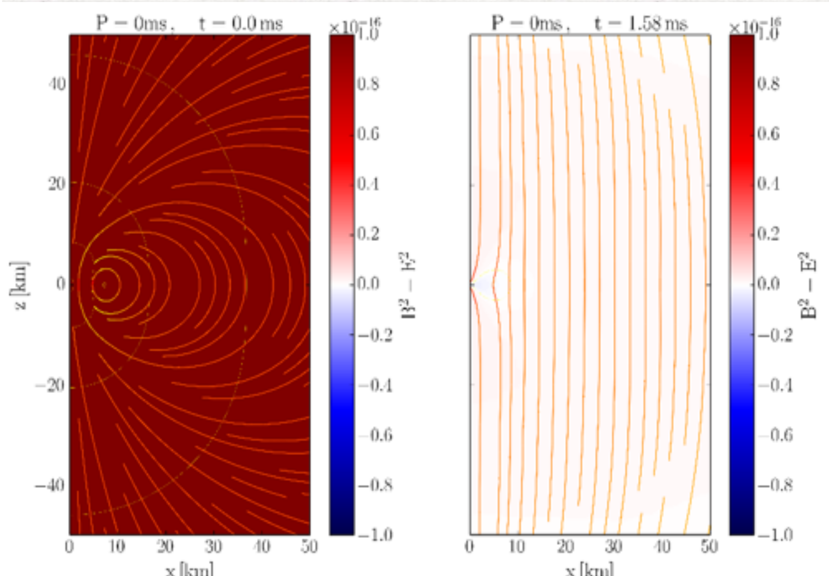
Most, Nathanail & Rezzolla (2016)

Rezzolla's talk in Kyoto meeting

Collapse to what?

Nathanail, Most, LR 2016

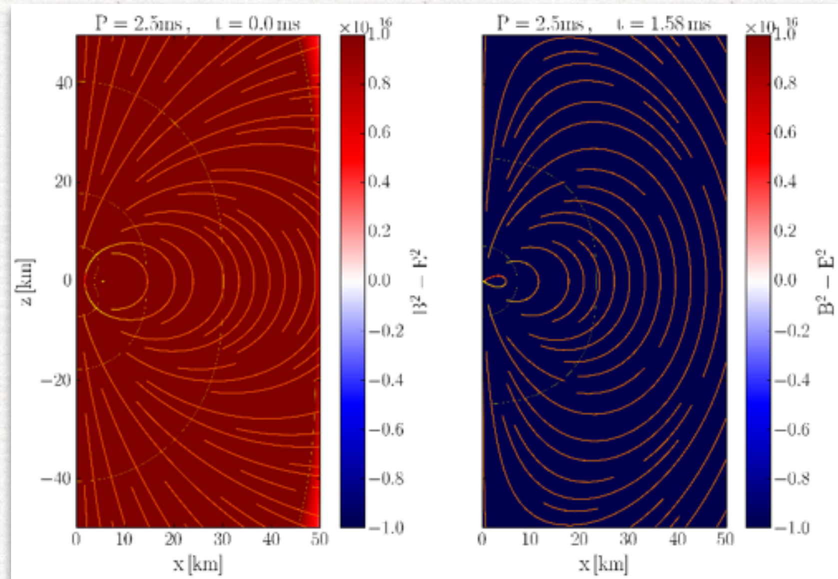
nonrotating magnetised star



$$\frac{1}{2}F^{\mu\nu}F_{\mu\nu} = \boldsymbol{B}^2 - \boldsymbol{E}^2 = 0$$

collapse to **Schwarzschild BH**

rotating magnetised star



$$\frac{1}{2}F^{\mu\nu}F_{\mu\nu} = \boldsymbol{B}^2 - \boldsymbol{E}^2 < 0$$

collapse to **Kerr-Newman BH**

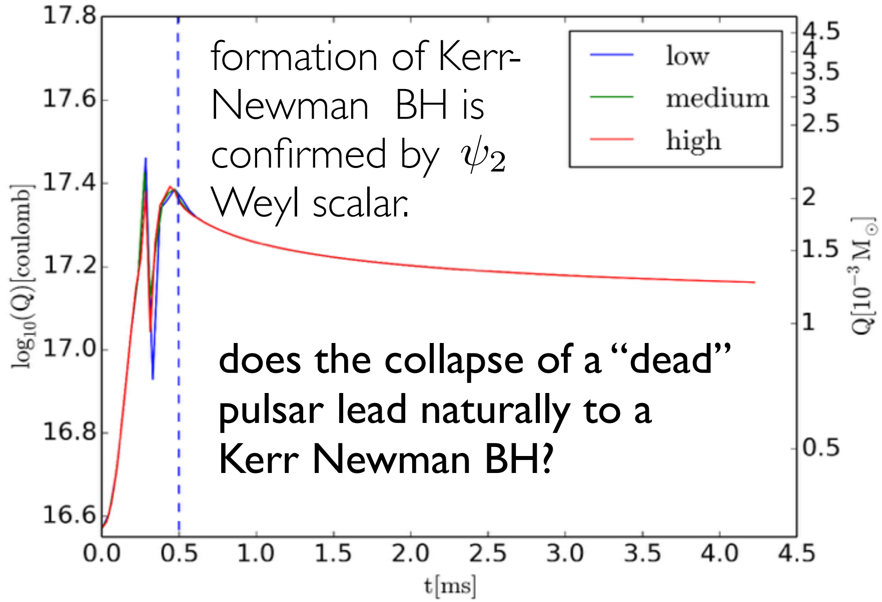
Rezzolla's talk in Kyoto meeting

How long does a Kerr-Newman BH sustain?

I don't know. More work is needed.

But not easy to neutralize because of the pulsar-like magnetosphere activities.

If the BHs merge before discharged, then an FRB or even a GRB would be produced



Observationally testable!

Search for simultaneous short signals (sGRB, FRB, or even FOB) coincident with BH-BH mergers - one can constrain the amount of charge carried by merging BHs!

Summary: Possible EM counterparts of GW events

- **Short GRBs** (gamma-rays) **and afterglows** (multi-wavelength)
  - NS-NS mergers, BH-NS mergers
  - BH-BH mergers?
- **Kilonova/Macronova/Mergernova** (optical/IR) and **afterglows** (multi-wavelength, strongest in radio)
  - BH-NS mergers, NS-NS mergers
  - Enhanced in some NS-NS mergers with a supra-massive/ stable NS
- **Early X-ray emission** (X-rays)
  - NS-NS mergers with a supra-massive/stable NS
- **Fast radio bursts** (radio)
  - NS-NS mergers with a supra-massive NS
  - Mergers of charged BH-BH systems (also NS-NS, BH-NS?)