Electromagnetic Counterparts of Gravitational Wave Events

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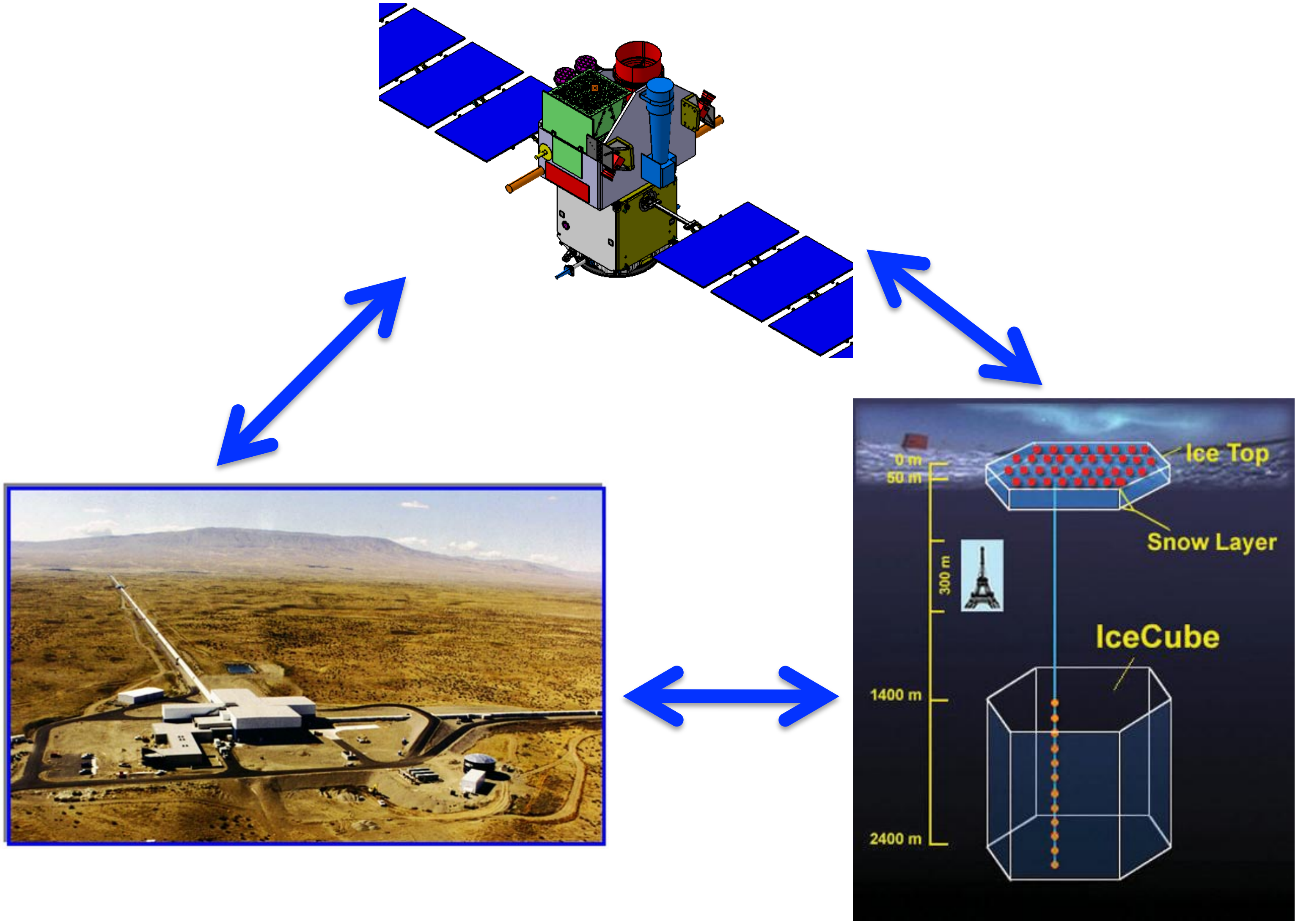
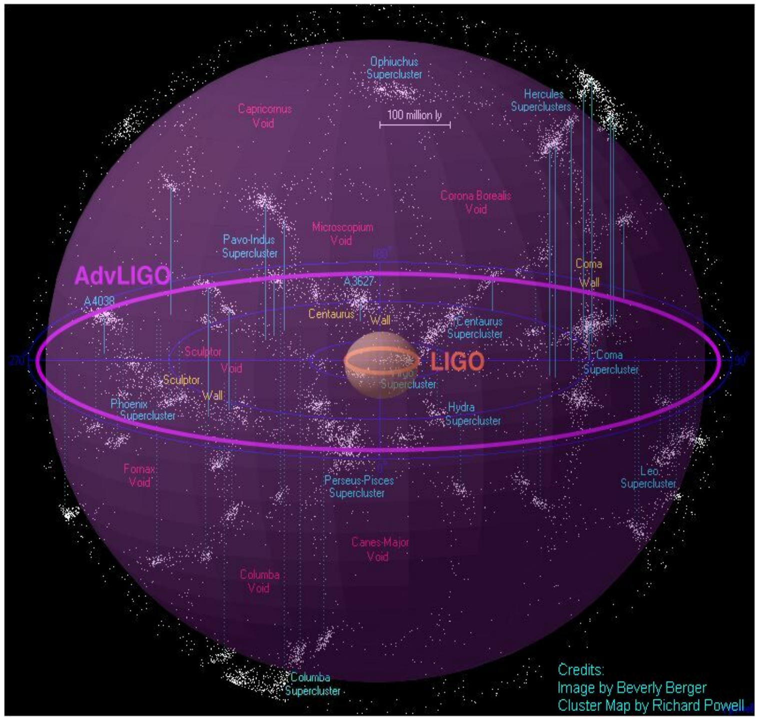
Binary Neutron Star Coalescence as a Fundamental Physics Laboratory

Collaborators: He Gao, Yun-Wei Yu, Xue-Feng Wu et al.

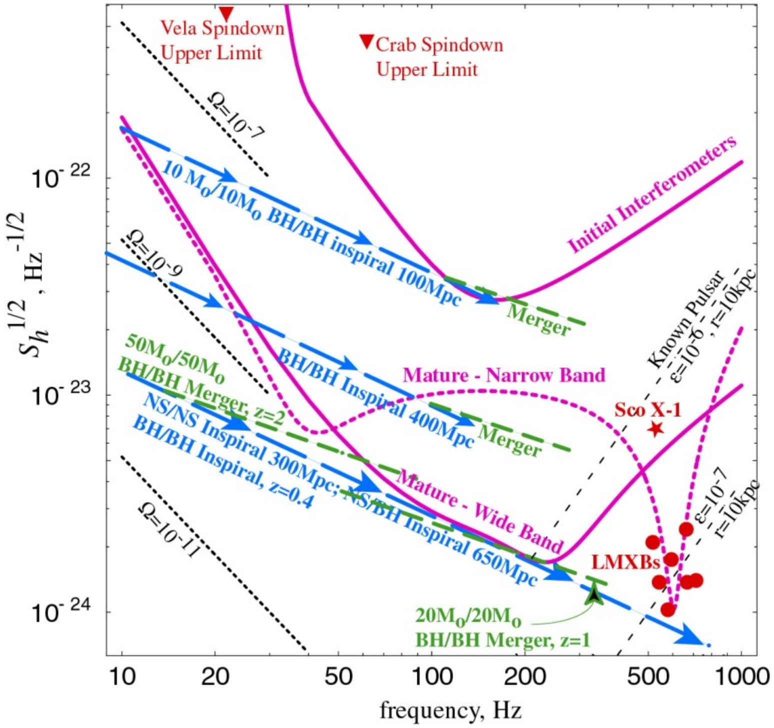
Transient Astrophysics in the Multi-Wavelength & Multi-messenger Era



Detection of gravitational wave is around the corner



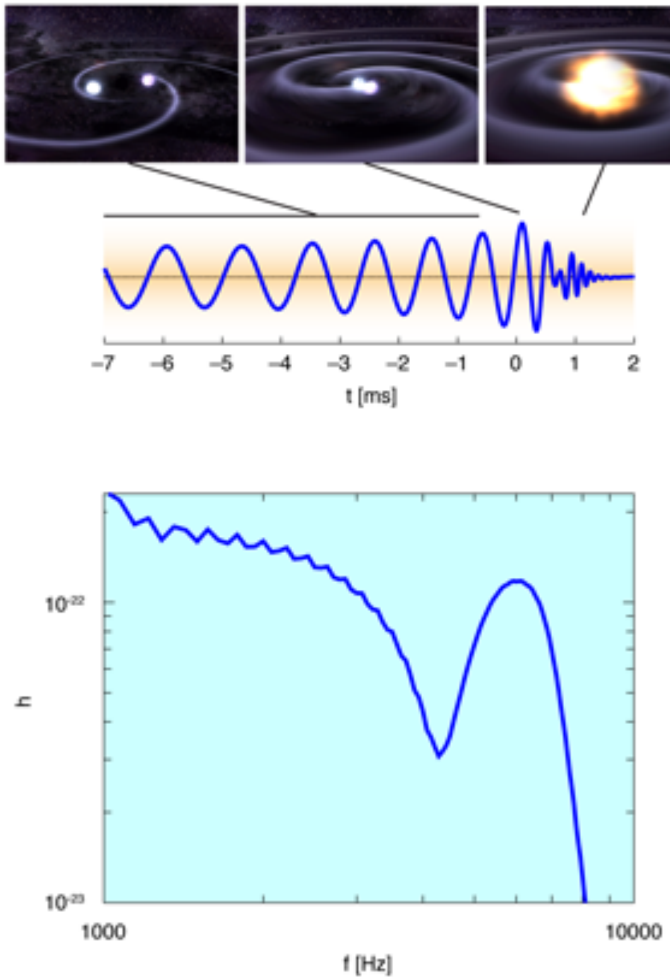
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell



NS+NS $\sim 300 Mpc \, (z \approx 0.1)$

Event Rate $0.2 \sim 2000 \, yr^{-1}$

Candidates: NS-NS & NS-BH mergers

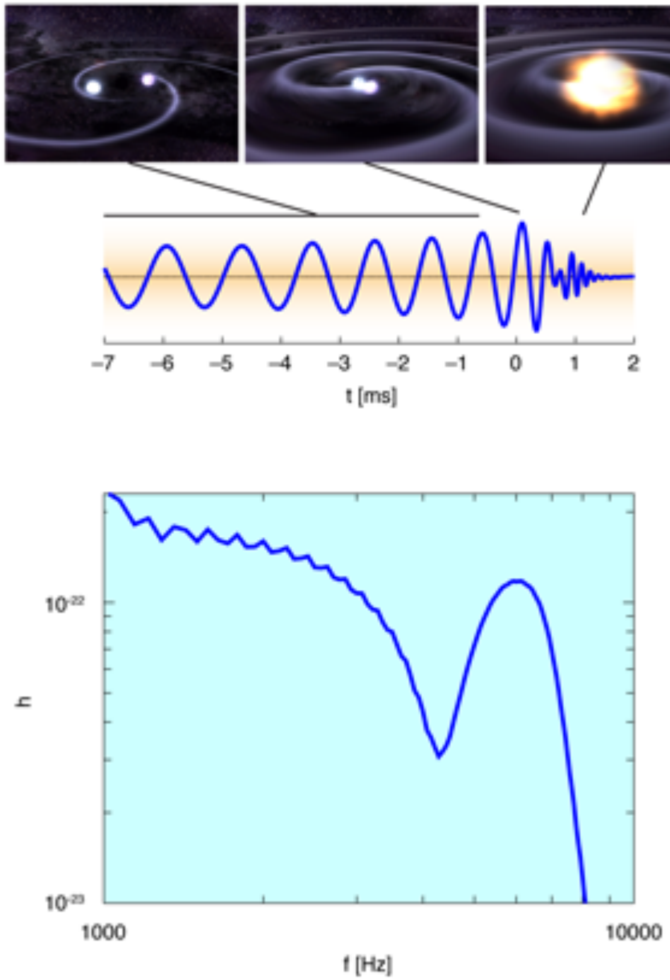


- Known NS-NS systems in the Galaxy
- Indirect evidence of GW emission from PSR 1913+16 system
- Well studied "chirp" signals

- What EM signals accompany with these events?

http://physics.aps.org/articles/v3/29 (adapted from Kiuchi et al. 2010, PRL, 104, 141101)

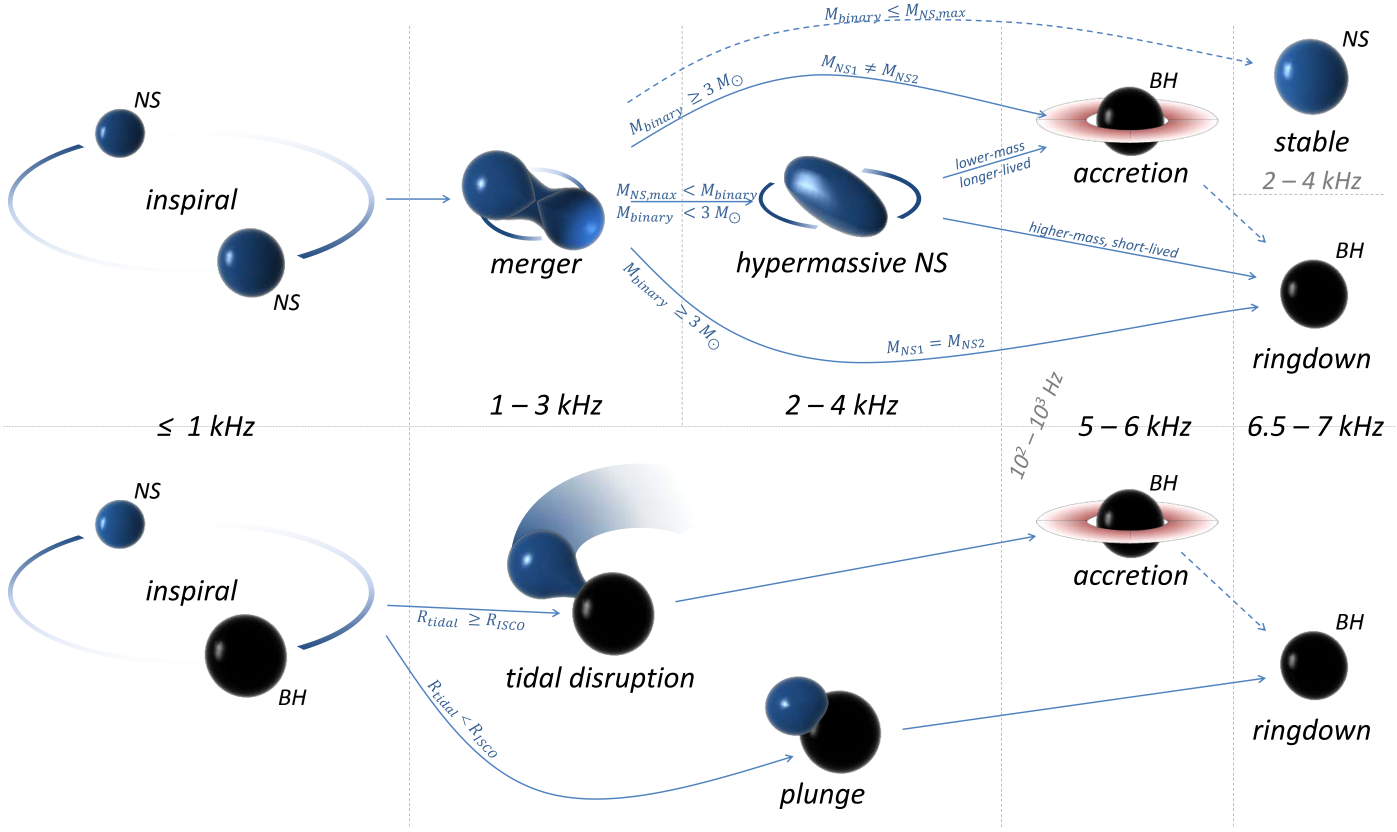
Why EM signals are essential?



http://physics.aps.org/articles/v3/29 (adapted from Kiuchi et al. 2010, PRL, 104, 141101)

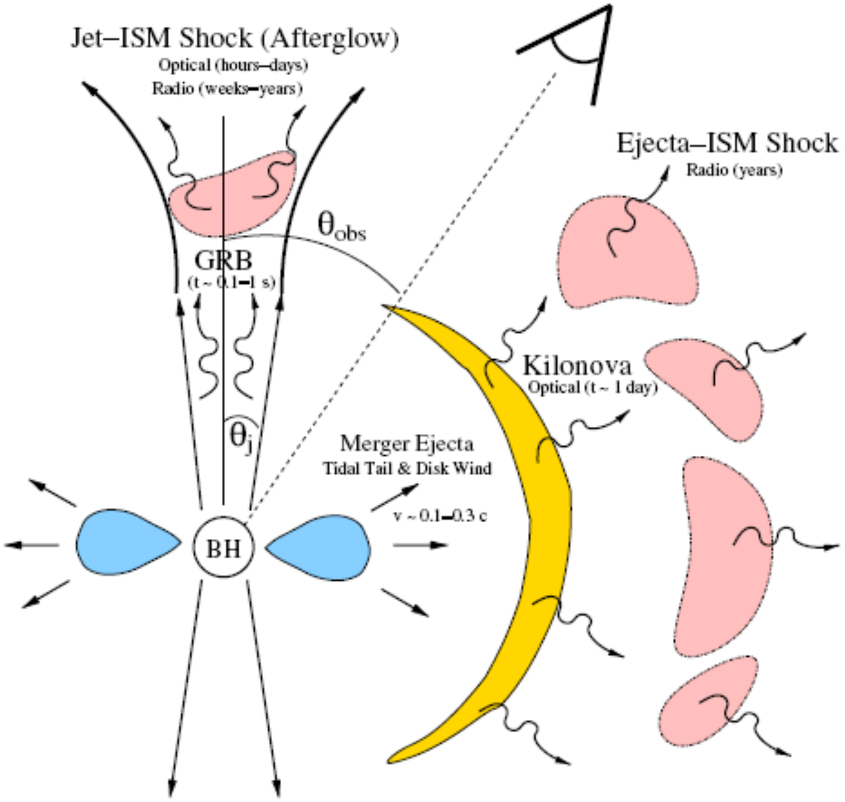
- Confirm the astrophysical origin of the GW signals
- Study the astrophysical physical origin of the GW sources (e.g. host galaxy, distance, etc)
- Study the detailed physics involved in GW events (e.g. equation of state of nuclear matter)

NS-NS and NS-BH mergers: Two types of merger products



Bartos, I., Brady, P., Marka, S. 2013, CQGrav., 30, 123001

EM signals
for a BH post-merger product



Metzger & Berger (2012)

SGRB

Multi-wavelength afterglow
~hours, days

Merger Nova
(Macronova, Kilonova)

Li & Paczyński, 1998 …

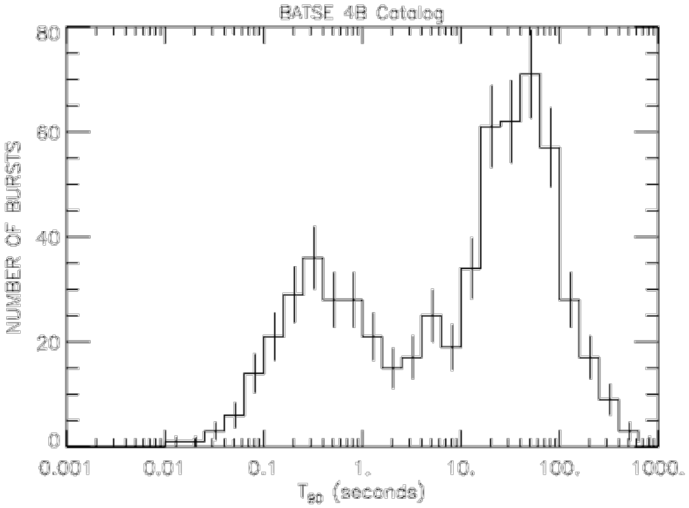
Opical/IR flare
~ 1 day

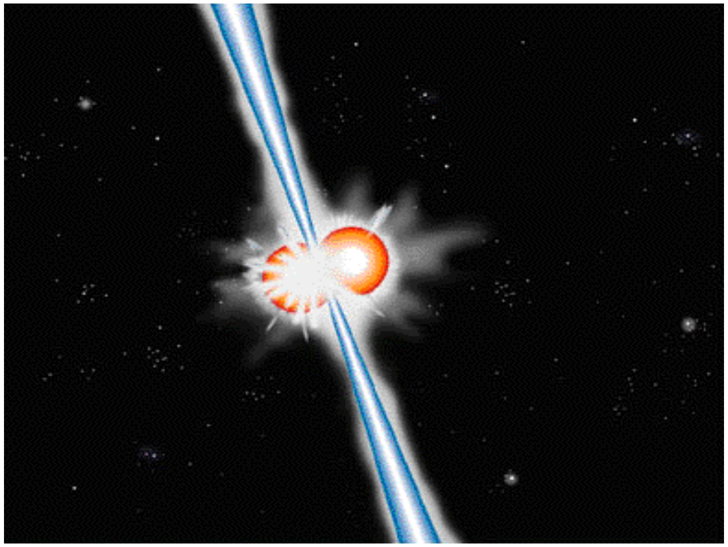
Ejecta-ISM interaction shock

Nakar& Piran, 2011

Radio
~years

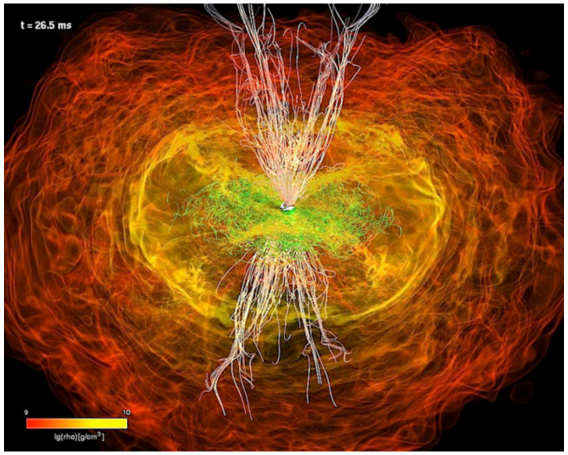
Short GRBs





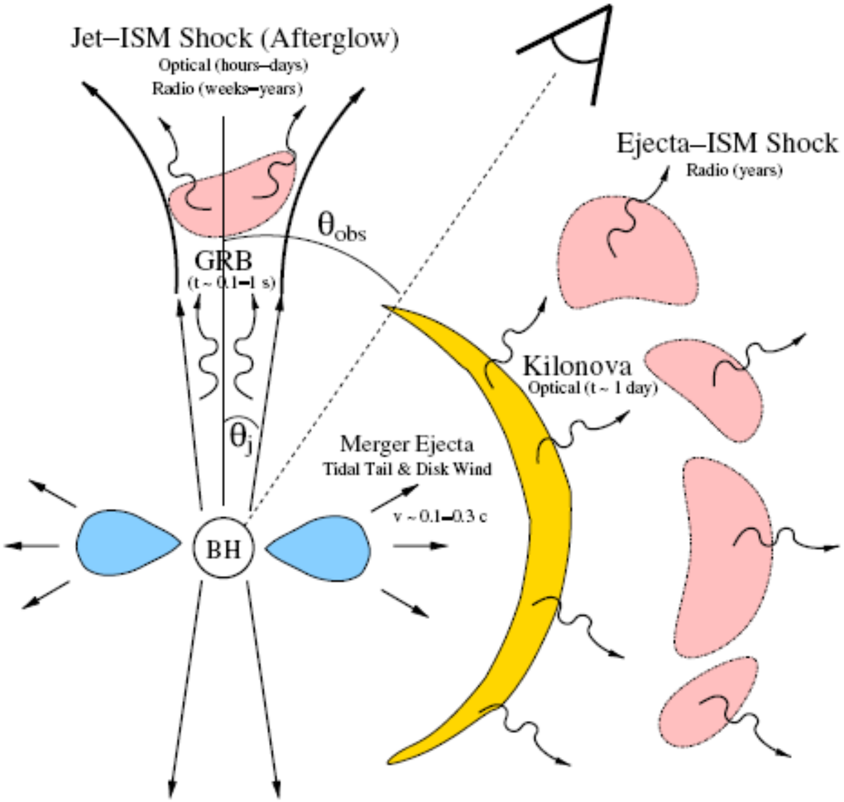
- In different types of host galaxies, including a few in elliptical/early-type galaxies, but most in star-forming galaxies
- Large offsets, in regions of low star formation rate in the host galaxy. Some are outside the galaxy.

- Leading model: NS-NS or NS-BH mergers



Rezzolla et al. 2011

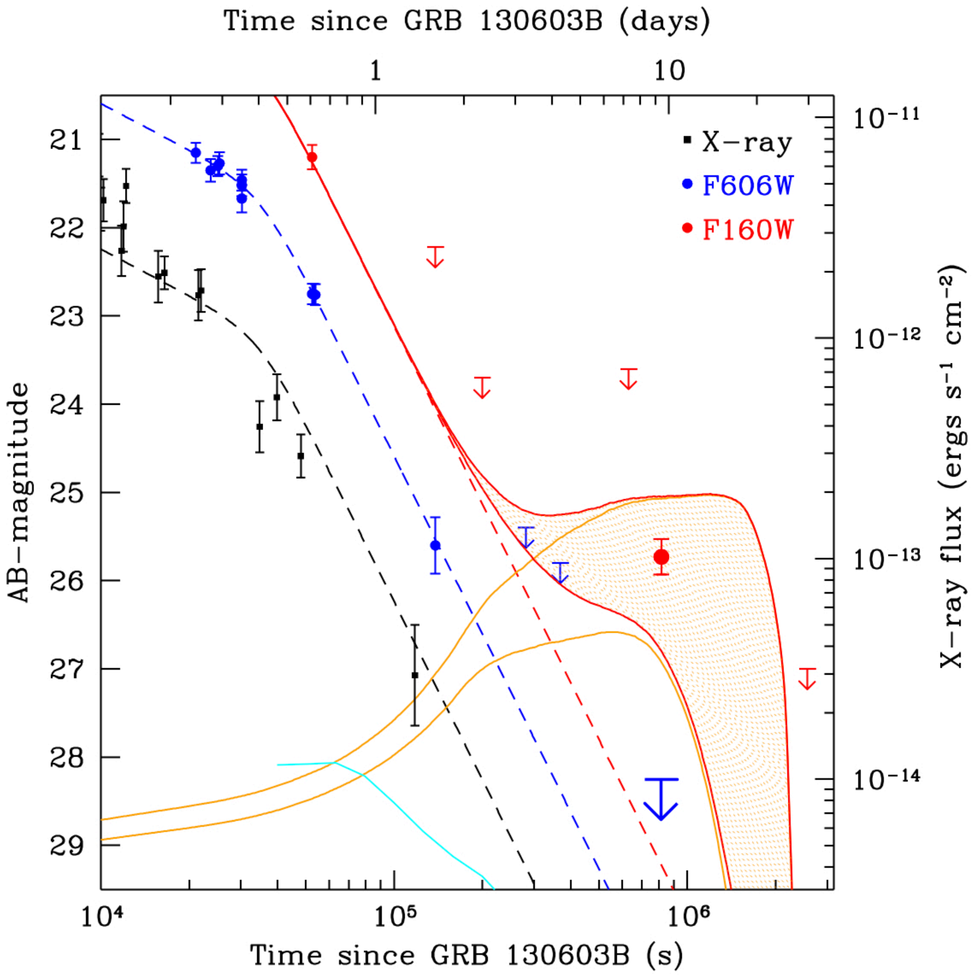
Short GRBs as GWB EM counterpart: issues



- The NS-NS and NS-BH merger models cannot simultaneously interpret the BATSE and Swift short GRB data (Virgili et al. 2012)

- Even if there is a SGRB-GW burst association, SGRBs are collimated, only a small fraction of GWBs will have SGRBs.

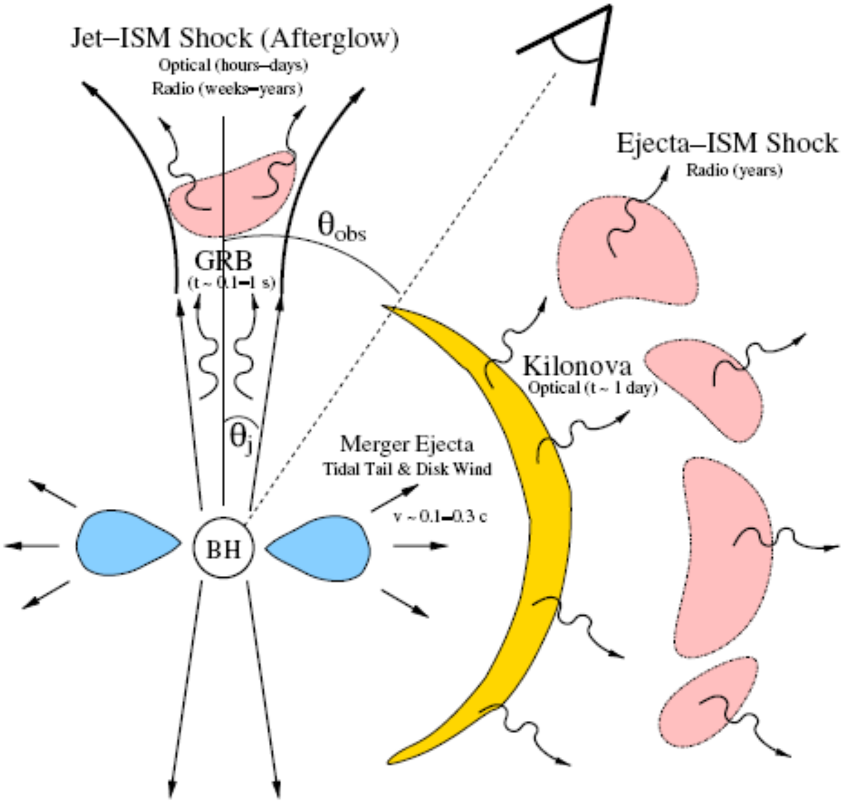
Kilo-novae: faint, in IR?



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

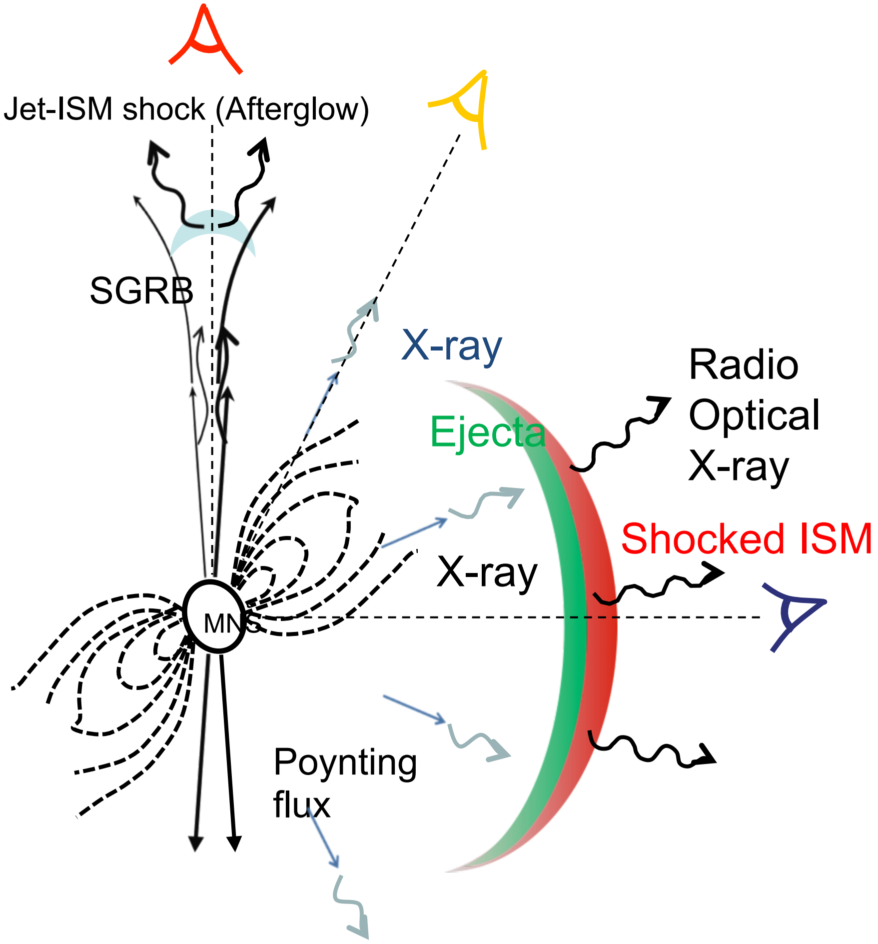
- Li-Paczynski novae: 1-day V-band luminosity: 3×10^{41} erg/s (Metzger et al. 2010): 3-5 orders of magnitude fainter than GRB afterglow
- Barnes & Kasen (2013): High opacity from heavier elements (e.g. lanthanides) – peak in IR
- Detection in GRB 130603B?

Radio afterglow



- Radio afterglow (Nakar & Piran): bright enough when $n=1\ \mathrm{cm}^{-3}$. For mergers, one may expect $n \sim 10^{-3} - 10^{-4}\ \mathrm{cm}^{-3}$, then radio afterglow not detectable

EM signals
for a (supra-massive / stable) millisecond magnetar post-merger product



Zhang (2013); Gao et al. (2013); Yu et al. (2013)

SGRB?

Late central engine activity

~Plateau & X-ray flare

Magnetic Dissipation

X-ray Afterglow

up to ~ $10^{-8} erg s^{-1} cm^{-2}$

1000 ~10000 s

Zhang, 2013

Magnetar-fed merger-novae

Yu et al, 2013;

Metzger & Piro 2014

Ejecta-ISM interaction with continuous energy injection

Multi-band transient

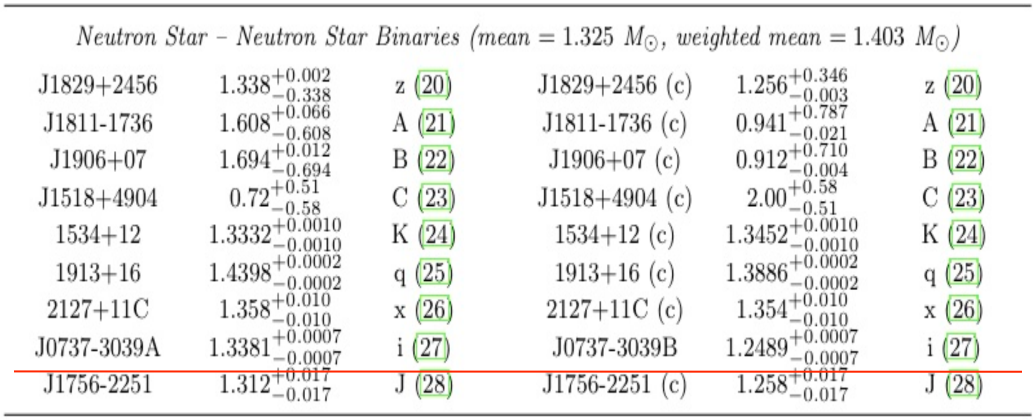
~hours, days, weeks,

or even years

Gao et al, 2013

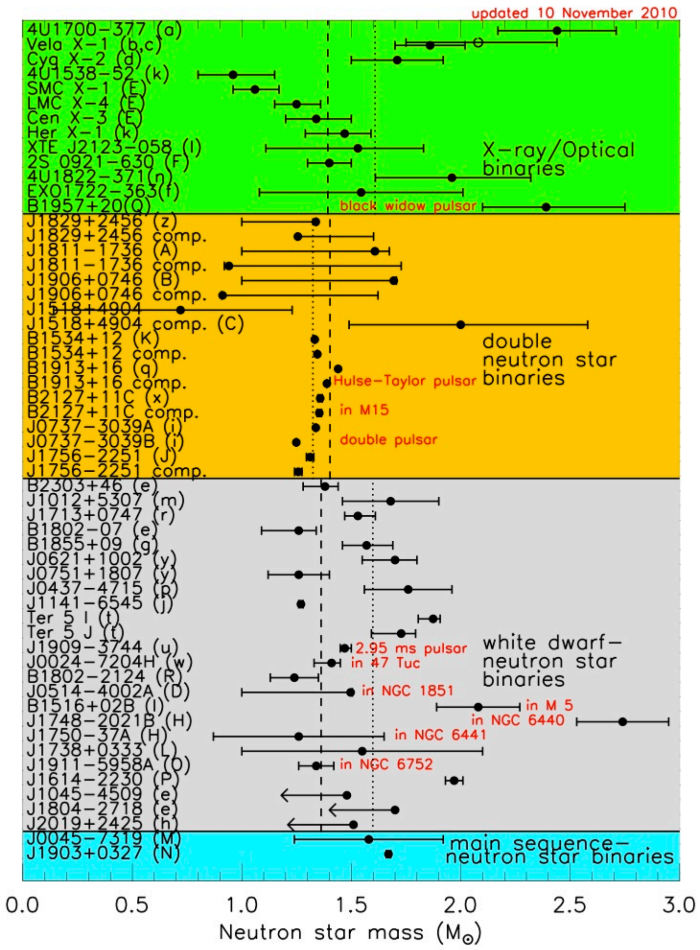
Observational hints of a (supra-massive / stable) millisecond magnetar as the post-merger product (I)

- NS with mass > 2 $M_\odot$ has been discovered
- NS-NS systems: total mass can be < 2.6 $M_\odot$



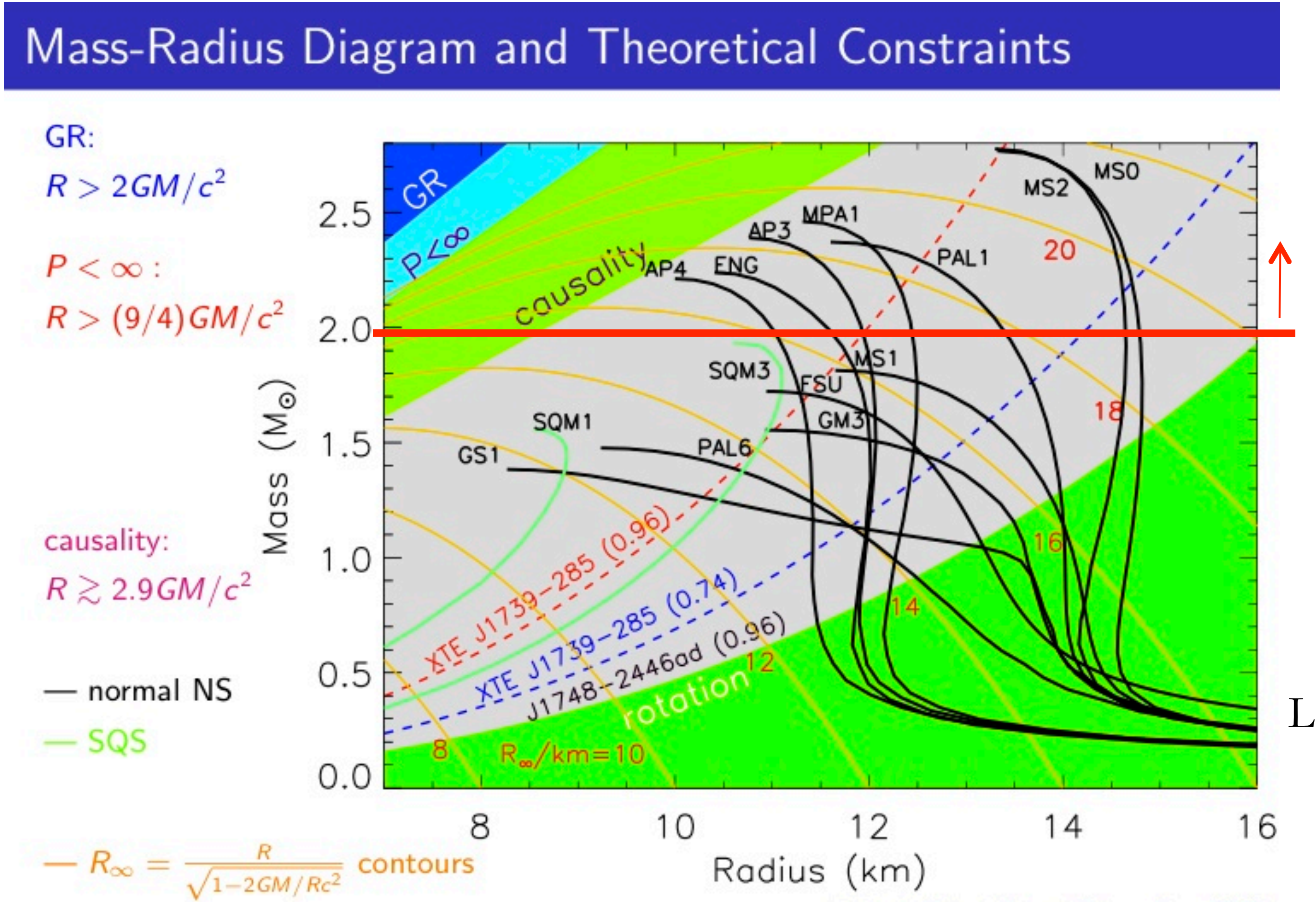
Neutron Star – Neutron Star Binaries (mean = 1.325 $M_\odot$, weighted mean = 1.403 $M_\odot$)

J1829+2456	$1.338^{+0.002}_{-0.338}$	z (20)	J1829+2456 (c)	$1.256^{+0.346}_{-0.003}$	z (20)
J1811-1736	$1.608^{+0.066}_{-0.608}$	A (21)	J1811-1736 (c)	$0.941^{+0.787}_{-0.021}$	A (21)
J1906+07	$1.694^{+0.012}_{-0.694}$	B (22)	J1906+07 (c)	$0.912^{+0.710}_{-0.004}$	B (22)
J1518+4904	$0.72^{+0.51}_{-0.58}$	C (23)	J1518+4904 (c)	$2.00^{+0.58}_{-0.51}$	C (23)
1534+12	$1.3332^{+0.0010}_{-0.0010}$	K (24)	1534+12 (c)	$1.3452^{+0.0010}_{-0.0010}$	K (24)
1913+16	$1.4398^{+0.0002}_{-0.0002}$	q (25)	1913+16 (c)	$1.3886^{+0.0002}_{-0.0002}$	q (25)
2127+11C	$1.358^{+0.010}_{-0.010}$	x (26)	2127+11C (c)	$1.354^{+0.010}_{-0.010}$	x (26)
J0737-3039A	$1.3381^{+0.0007}_{-0.0007}$	i (27)	J0737-3039B	$1.2489^{+0.0007}_{-0.0007}$	i (27)
J1756-2251	$1.312^{+0.017}_{-0.017}$	J (28)	J1756-2251 (c)	$1.258^{+0.017}_{-0.017}$	J (28)



Lattimer & Prakash (2010)

Observational hints of a (supra-massive / stable) millisecond magnetar as the post-merger product (I)



Mass-Radius Diagram and Theoretical Constraints

GR:
$R > 2GM/c^2$

$P < \infty$:
$R > (9/4)GM/c^2$

causality:
$R \gtrsim 2.9GM/c^2$

— normal NS
— SQS

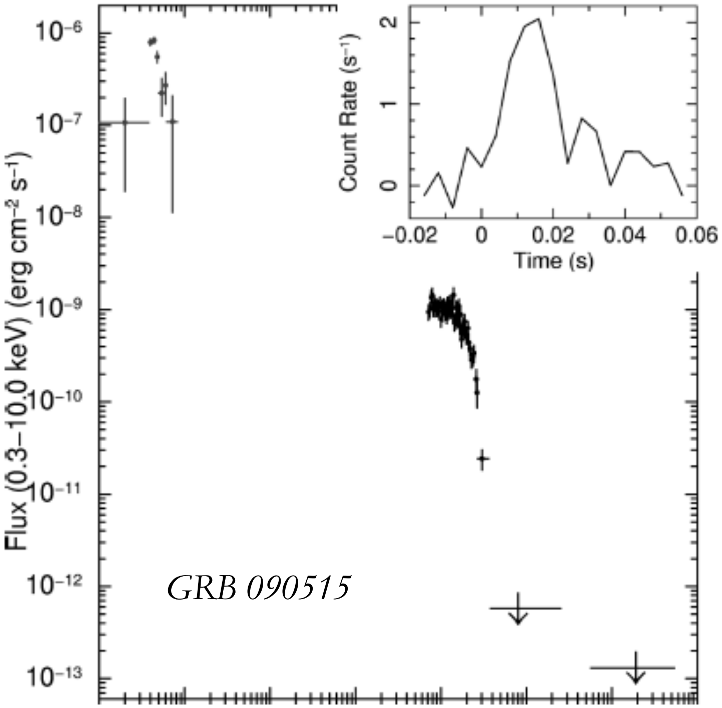
— $R_\infty = \frac{R}{\sqrt{1-2GM/Rc^2}}$ contours

Lattimer (2012)

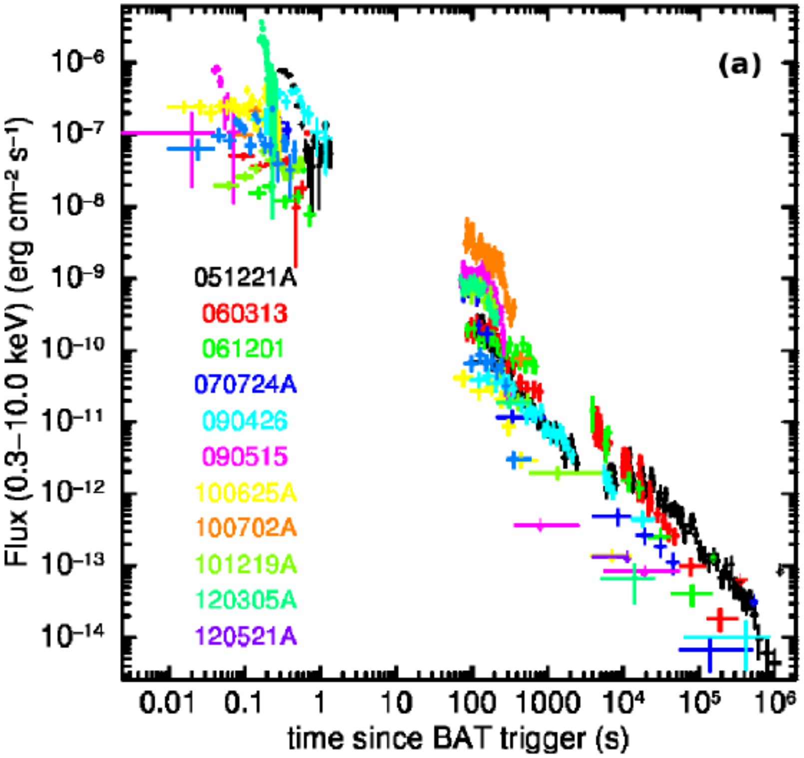
Stiff equation-of-state: maximum NS mass close to 2.5 $M_\odot$

Observational hints of a (supra-massive / stable) millisecond magnetar as the post-merger product (2)

- X-ray plateaus in some short GRB afterglows

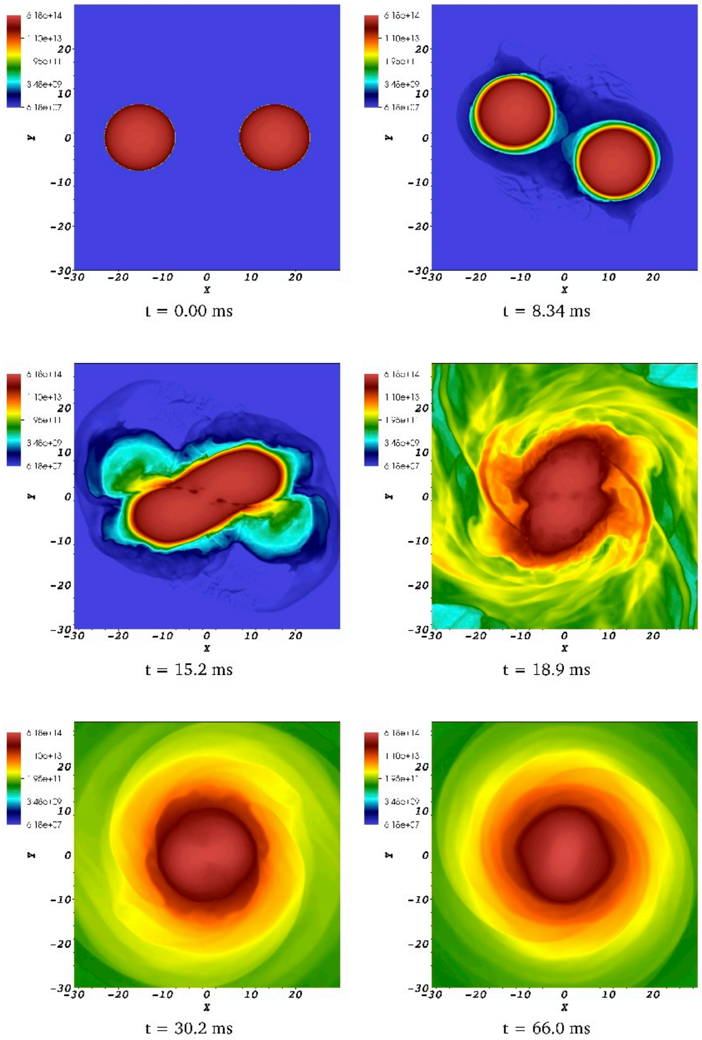


Rowlinson et al. (2010)



Rowlinson et al. (2013)

Forming a supra-massive / stable neutron star via a NS-NS merger



t = 0.00 ms

t = 8.34 ms

t = 15.2 ms

t = 18.9 ms

t = 30.2 ms

t = 66.0 ms

For small enough NS masses and a reasonable NS equation of state, a stable magnetar can survive a NS-NS merger.

Giacomazzo & Perna (2013)

Supra-massive / stable magnetar

Additional energy budget
from a millisecond magnetar: the spin energy

$$E_{rot} = 2\times 10^{52}\ erg\, I_{45} P_{0,-3}^{-2}$$

$$L_{sd,0} = 10^{49}\ erg\, s^{-1} B_{p,15}^{2} R_{6}^{6} P_{0,-3}^{-4}$$

$$T_{sd} = \frac{E_{rot}}{L_{0,sd}} \sim 10^{3}\ s\, I_{45} B_{p,15}^{-2} R_{6}^{-6} P_{0,-3}^{2}$$

A **postmerger magnetar** would be **initially rotating** near the **Keplerian velocity P~1ms**.

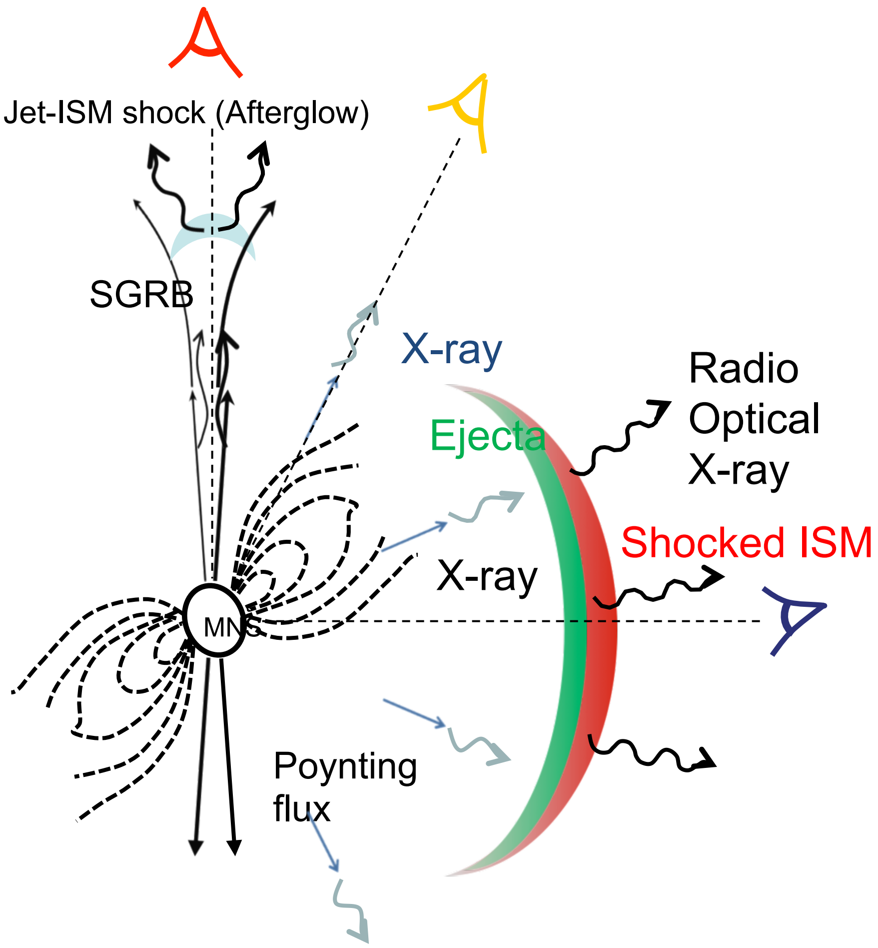
A huge energy budget: released in the EM form in different channels

Early EM afterglow of GWBs

(Zhang, 2013, ApJ, 763, L22)

- Magnetar wind is essentially isotropic
- If the post-merger product of NS-NS coalescence is a millisecond magnetar, essentially every GWB would be accompanied by a bright early EM afterglow
- This applies regardless of whether NS-NS mergers are accompanied by short GRBs

EM signals for a (supra-massive / stable) millisecond magnetar post-merger product



Zhang (2013); Gao et al. (2013); Yu et al. (2013)

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~Plateau & X-ray flare

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X-ray Afterglow

up to ~ $10^{-8} ergs\, s^{-1}\, cm^{-2}$

1000 ~10000 s

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Yu et al, 2013;
Metzger & Piro 2014

Ejecta-ISM interaction with continuous energy injection

Multi-band transient

~hours, days, weeks,
or even years

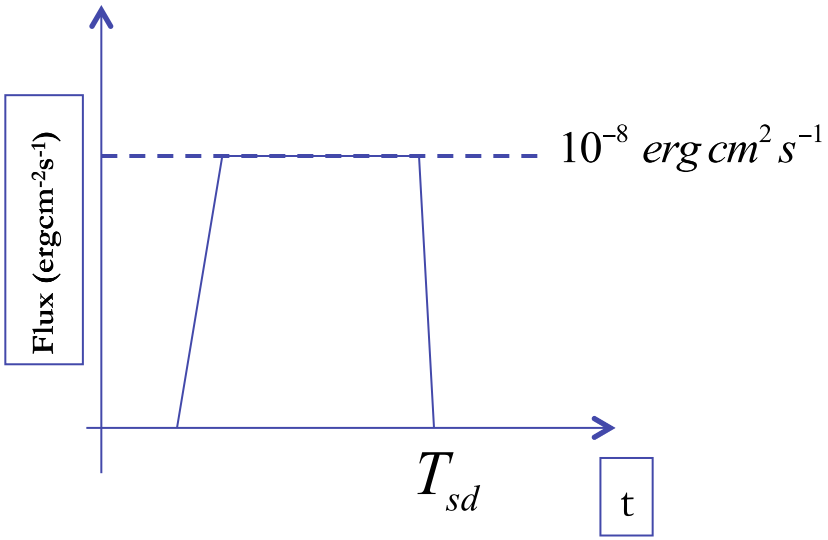
Gao et al, 2013

Bright early X-ray Afterglow from NS-NS mergers

Zhang, 2013, ApJ, 763, L22

$$F_x = \frac{\eta_x L_{\rm sd}}{4\pi f_{b,w} D_L^2} \simeq 2 \times 10^{-8}\,{\rm erg\,s^{-1}\,cm^{-2}} \times \eta_{x,-2} f_{b,w}^{-1} \left(\frac{D_L}{300\,{\rm Mpc}}\right)^{-2} I_{45}\, P_{0,3}^{-2}\, T_{{\rm sd},3}^{-1}$$

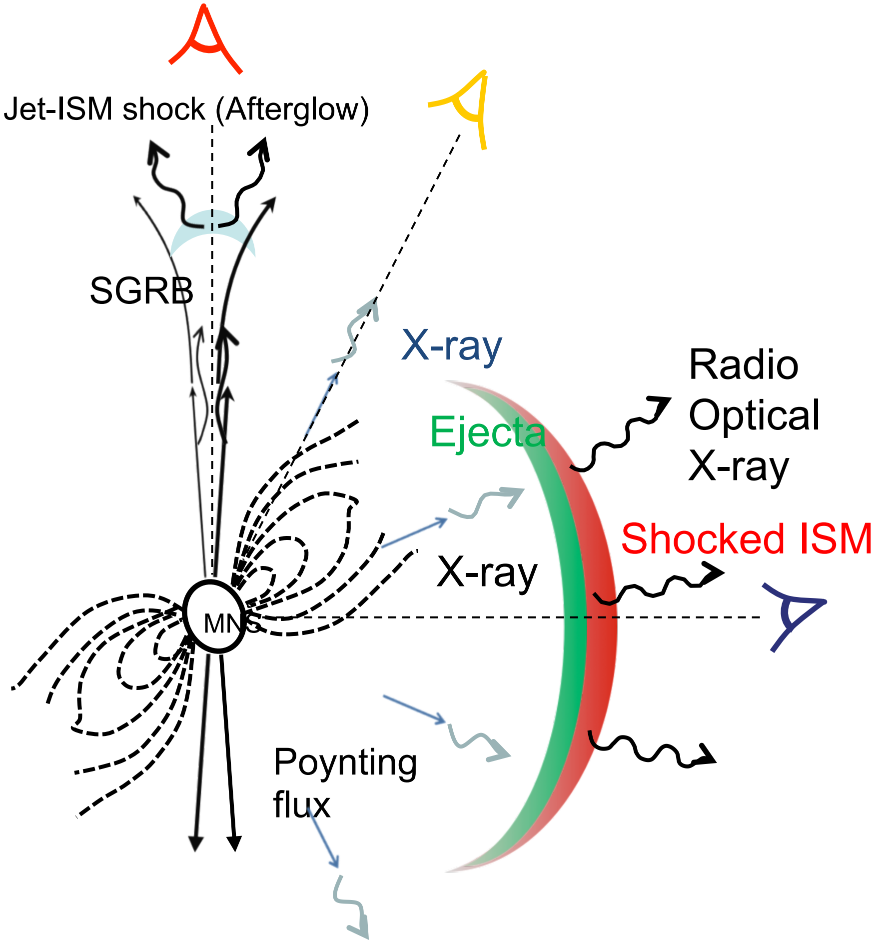
$$E_p \sim 5\,{\rm keV}\, L_{w,49}^{1/4} (R/(3 \times 10^{10}\,{\rm cm}))^{-1/2}$$



The proto-magnetar would eject a wide-beam wind, whose dissipation would power an X-ray afterglow as bright as~ **10^{-8} erg cm^{-2} s^{-1}.**
The duration is typically **10^3–10^4s**.

With $F_\nu \propto \nu^{1/3}$, one can roughly estimate that the optical flux could be as bright as **17th magnitude in** R *band.*

EM signals
for a (supra-massive / stable) millisecond magnetar post-merger product



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Gao et al, 2013

Enhanced (Magnetar powered) Merger Novae

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

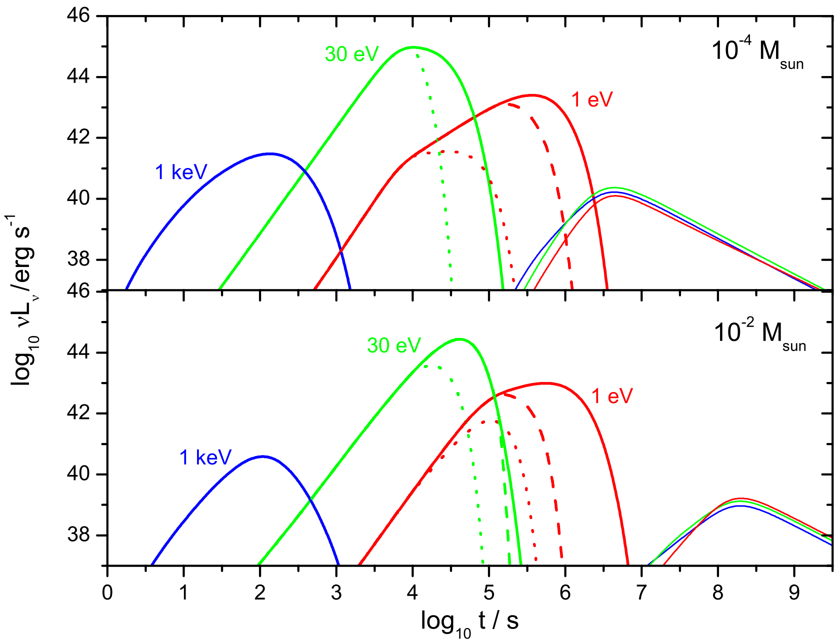


Figure 2. Light curves of the merger-nova (thick) and afterglow (thin) emissions at different observational frequencies as labeled. The dashed and dotted lines are obtained for an optionally taken magnetar collapsing time as $t_{\rm col} = 2t_{\rm md}$ and $t_{\rm col} = 10^4$ s, respectively. The ambient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

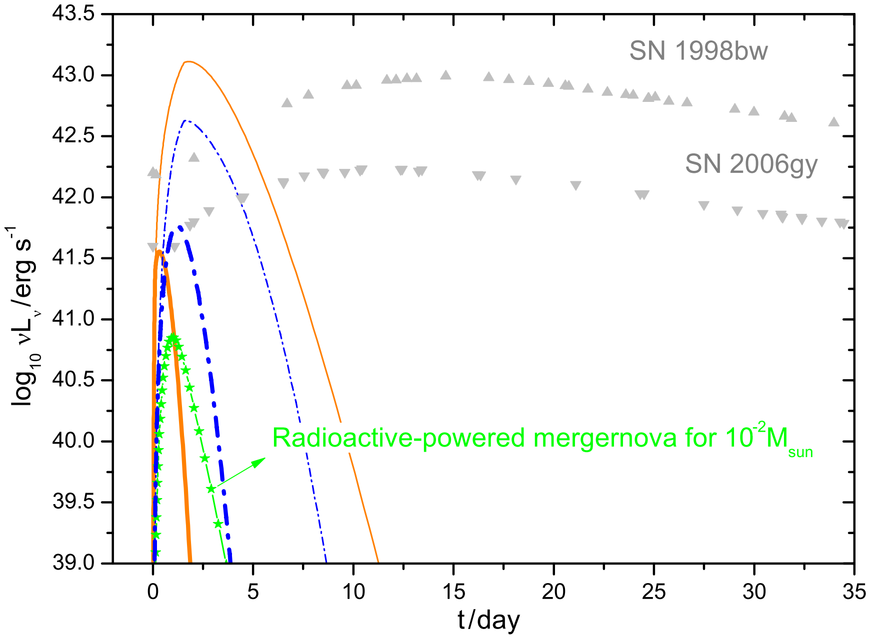
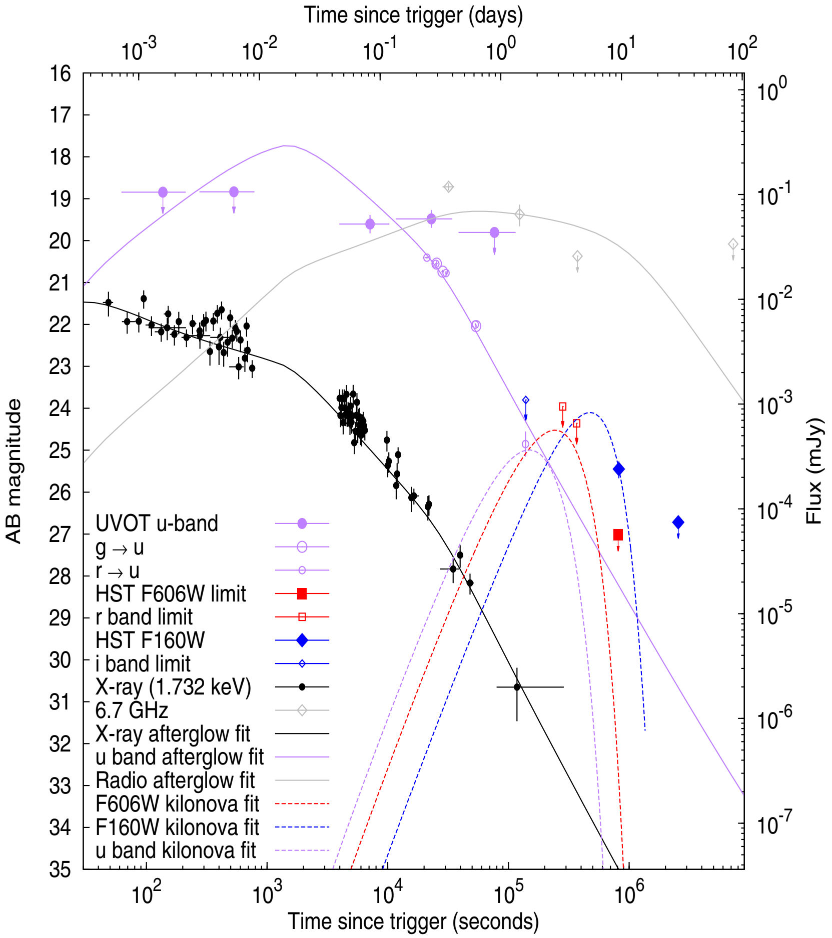


Figure 3. Optical (∼1 eV) light curves of the millisecond-magnetar-powered merger-nova, in comparison with the light curves of two supernovae (bolometric) and one radioactive-powered merger-nova (as labeled). The dash-dotted (blue) and solid (orange) lines represent $M_{\rm ej} = 10^{-2}\,M_\odot$ and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

See also Metzger & Piro (2014)

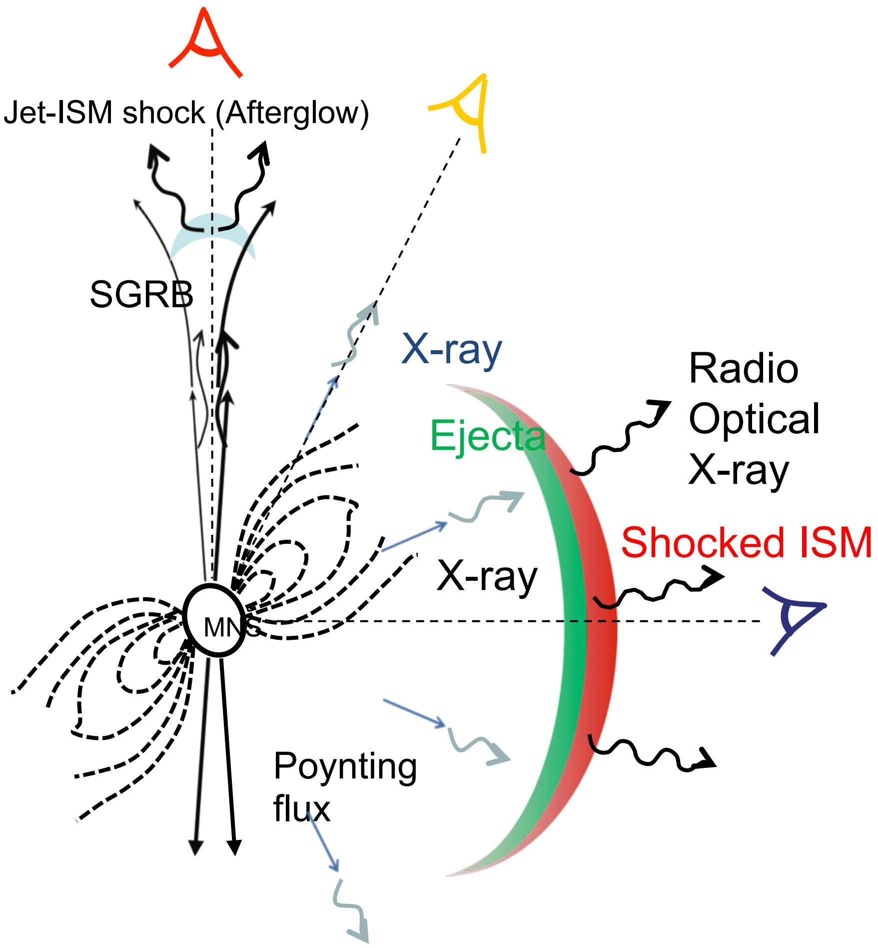
Kilo-novae in GRB 130603B:



Fan et al. (2013, ApJL)

- Can be magnetar-powered also, but the kinetic energy is small (10^{51} erg), birth period is long: near 5 ms
- Gravitational wave loss of the supra-massive NS?

EM signals
for a (supra-massive / stable) millisecond magnetar post-merger product



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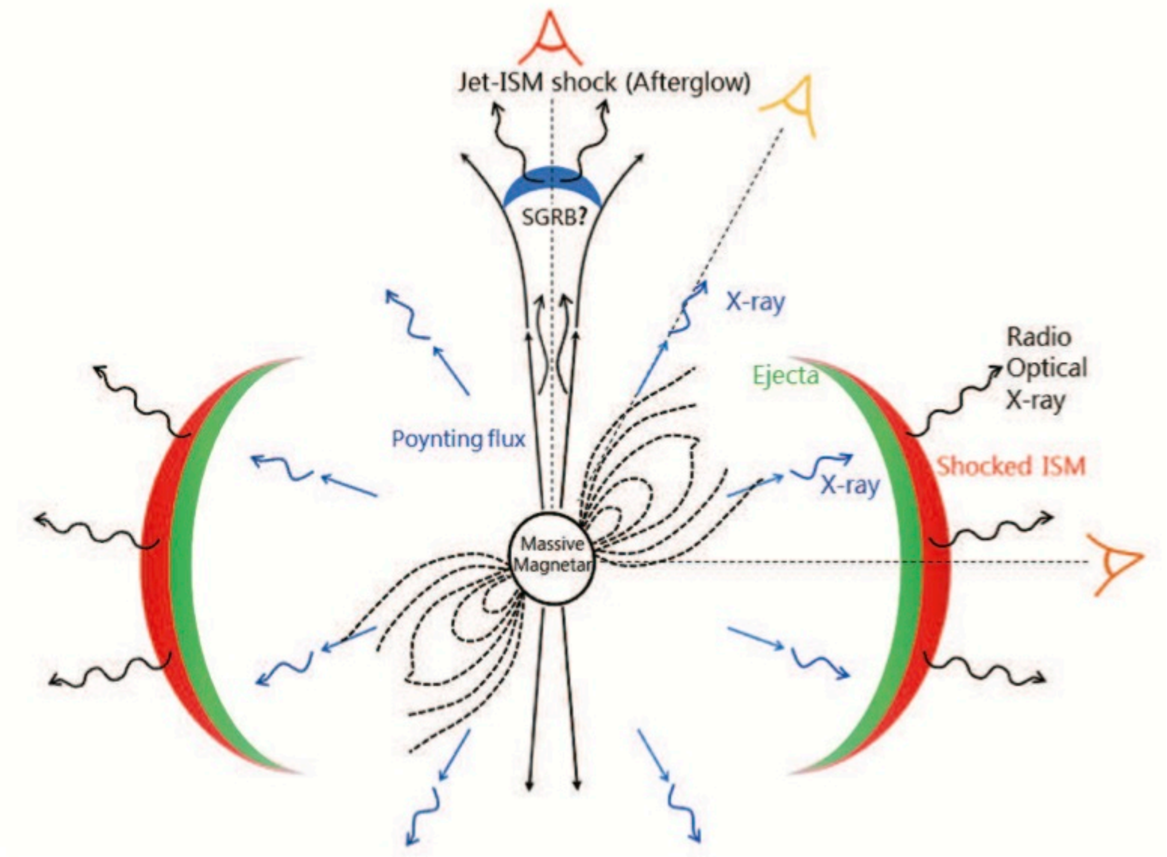
Gao et al, 2013

Later afterglow due to ejecta-medium interaction



Gao et al, 2013, ApJ, 771, 86

Ejecta-ISM shock with Energy Injection

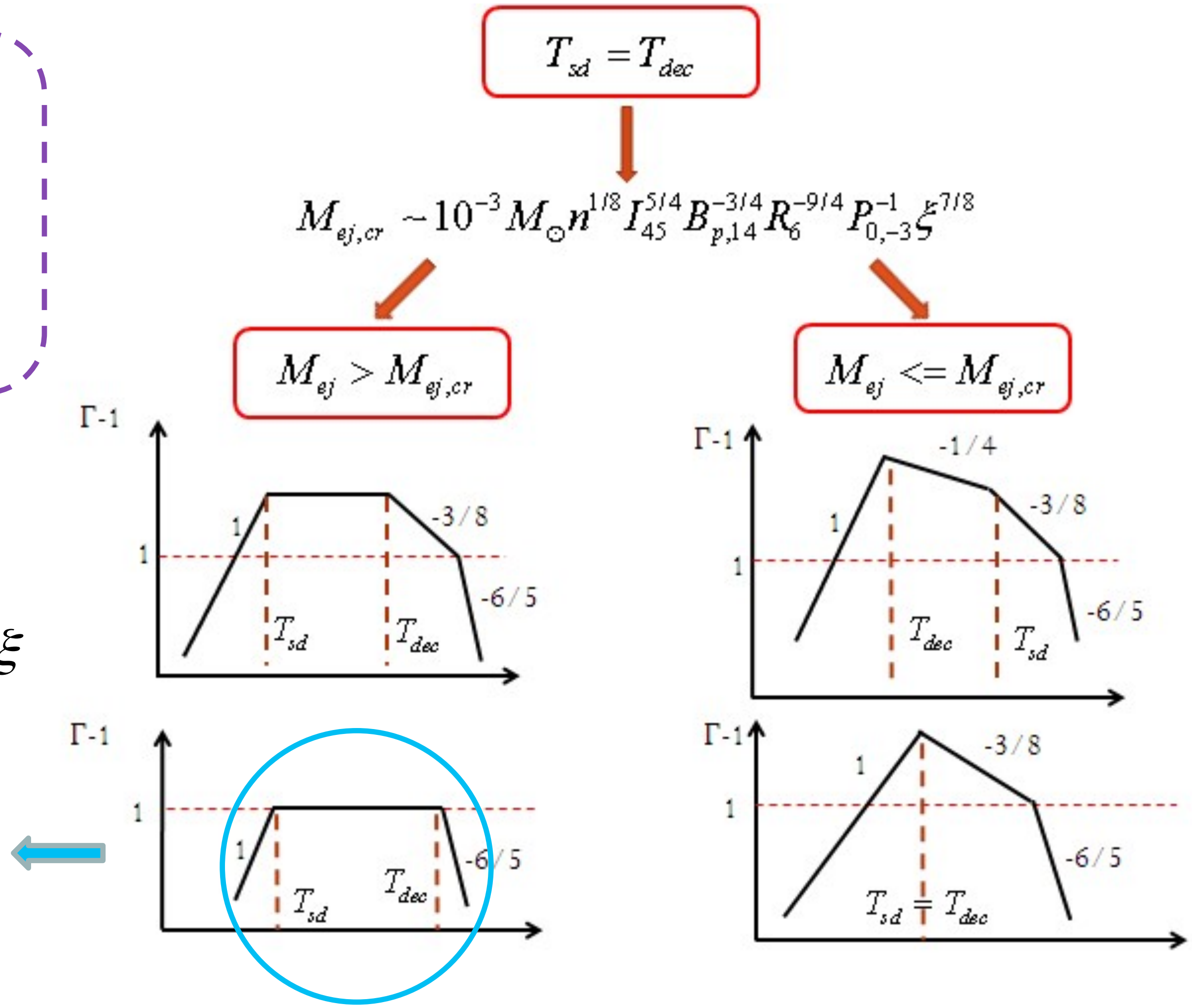
Gao et al. 2013, ApJ, 771, 86

Different M_{ej} leads to different dynamics cases.

$$M_{ej,cr,2} \sim 6\times10^{-3} M_{\rm e}\, I_{45} P_{0,-3}^{-2}\xi$$

If M_{ej} >= $M_{ej,cr,2}$

Non-relativistic



$T_{sd} = T_{dec}$

$$M_{ej,cr} \sim 10^{-3} M_\odot n^{1/8} I_{45}^{5/4} B_{p,14}^{-3/4} R_6^{-9/4} P_{0,-3}^{-1} \xi^{7/8}$$

$M_{ej} > M_{ej,cr}$

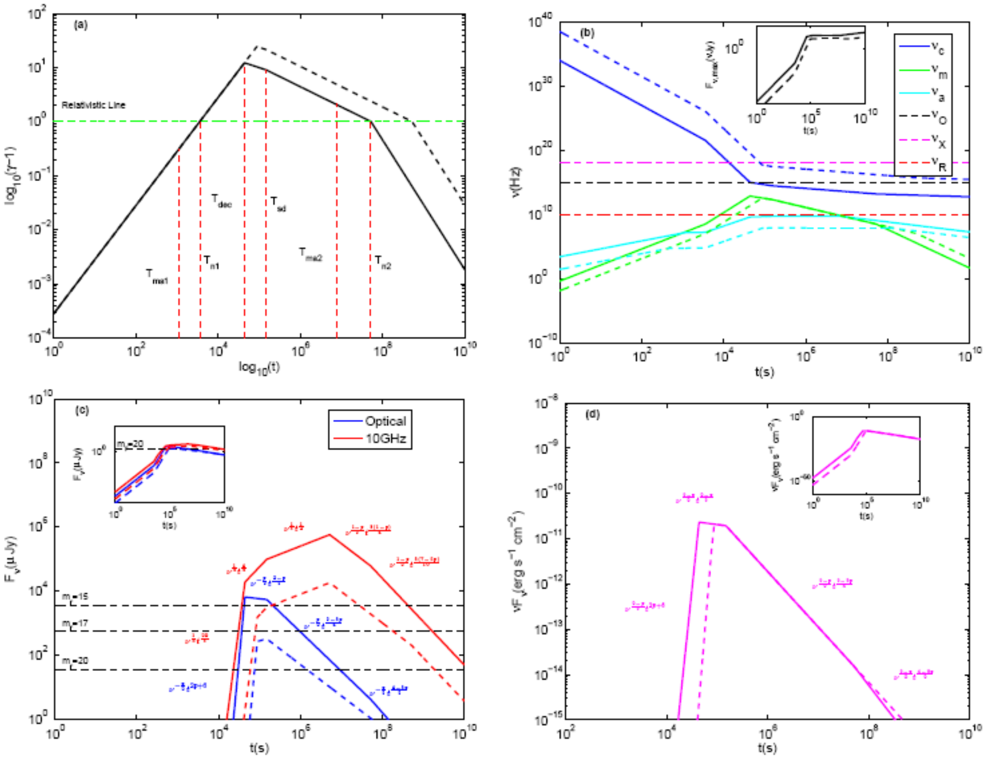
$M_{ej} <= M_{ej,cr}$

Ejecta-ISM shock with Energy Injection

Gao et al. 2013, ApJ, 771, 86

$$B_{\perp} \sim 10^{14}\, G, \quad M_{ej} \sim 10^{-4} M_{\mathrm{e}}$$

$$\boxed{T_{sd} > T_{dec}}$$



X-ray: $T_{peak} \sim T_{sd} \sim 10^4\, s$

$F_{peak} \sim 10^{-11}\, erg\, cm^{-2} s^{-1}$

Opt: $T_{peak} \sim T_{sd} \sim 10^4\, s$

$F_{peak} \sim 10 mJy$

Radio: $T_{peak} \sim 10^7\, s$

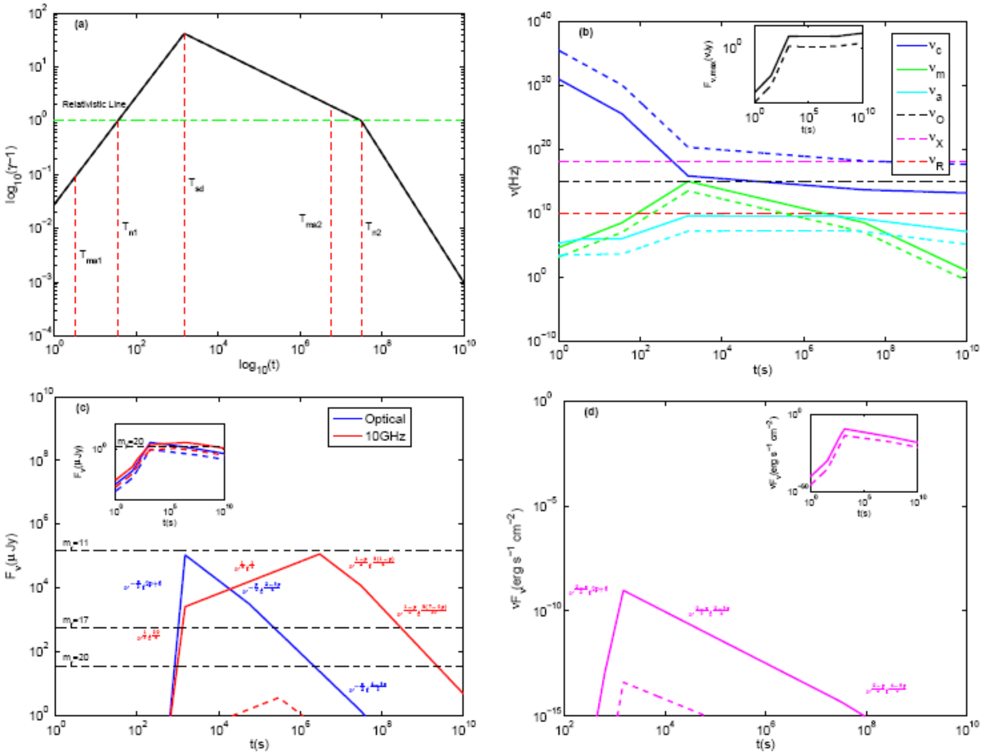
$F_{peak} \sim 1 Jy$

Ejecta-ISM shock with Energy Injection

Gao et al. 2013, ApJ, 771, 86

$$B_{\perp} \sim 10^{15}\, G, \quad M_{ej} \sim 10^{-4}\, M_{\mathrm{e}}$$

$$\boxed{T_{sd} \sim T_{dec}}$$



X-ray: $T_{peak} \sim T_{sd} \sim 10^{3}\, s$

$F_{peak} \sim 10^{-9}\, erg\, cm^{-2} s^{-1}$

Opt: $T_{peak} \sim T_{sd} \sim 10^{3}\, s$

$F_{peak} \sim 100 mJy$

Radio: $T_{peak} \sim 10^{7}\, s$

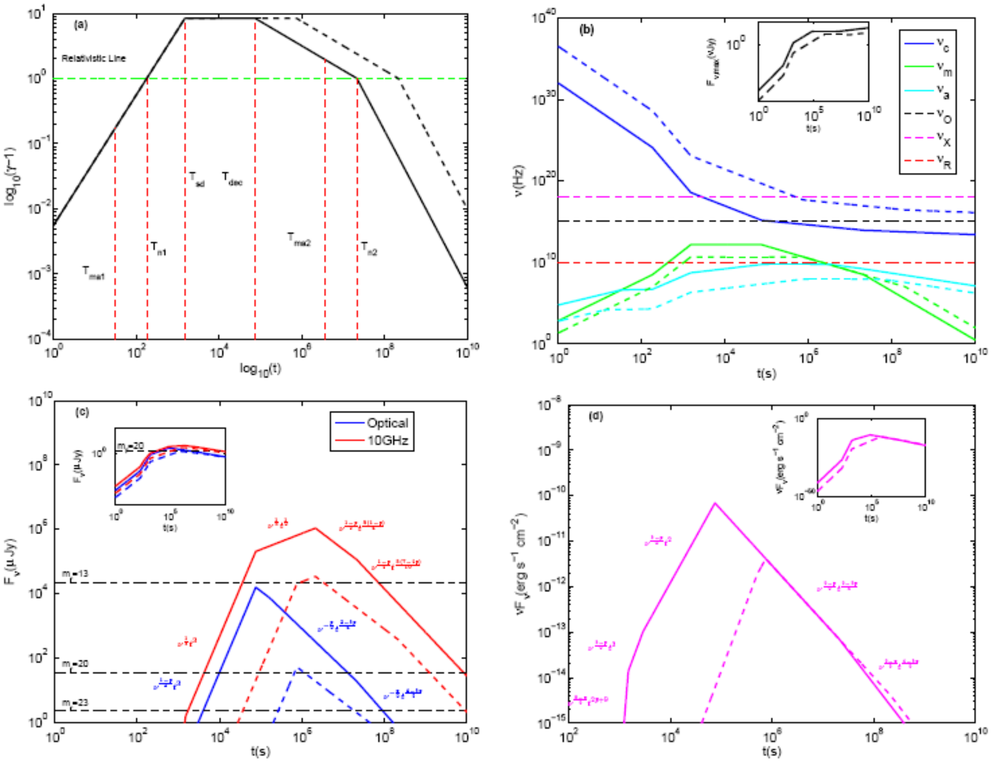
$F_{peak} \sim 100 mJy$

Ejecta-ISM shock with Energy Injection

Gao et al. 2013, ApJ, 771, 86

$$B_\perp \sim 10^{15} G, \quad M_{ej} \sim 10^{-3} M_e$$

$$T_{sd} < T_{dec}$$



X-ray: $T_{peak} \sim T_{sd} \sim 10^3 s$

$F_{peak} \sim 10^{-10} erg\, cm^{-2} s^{-1}$

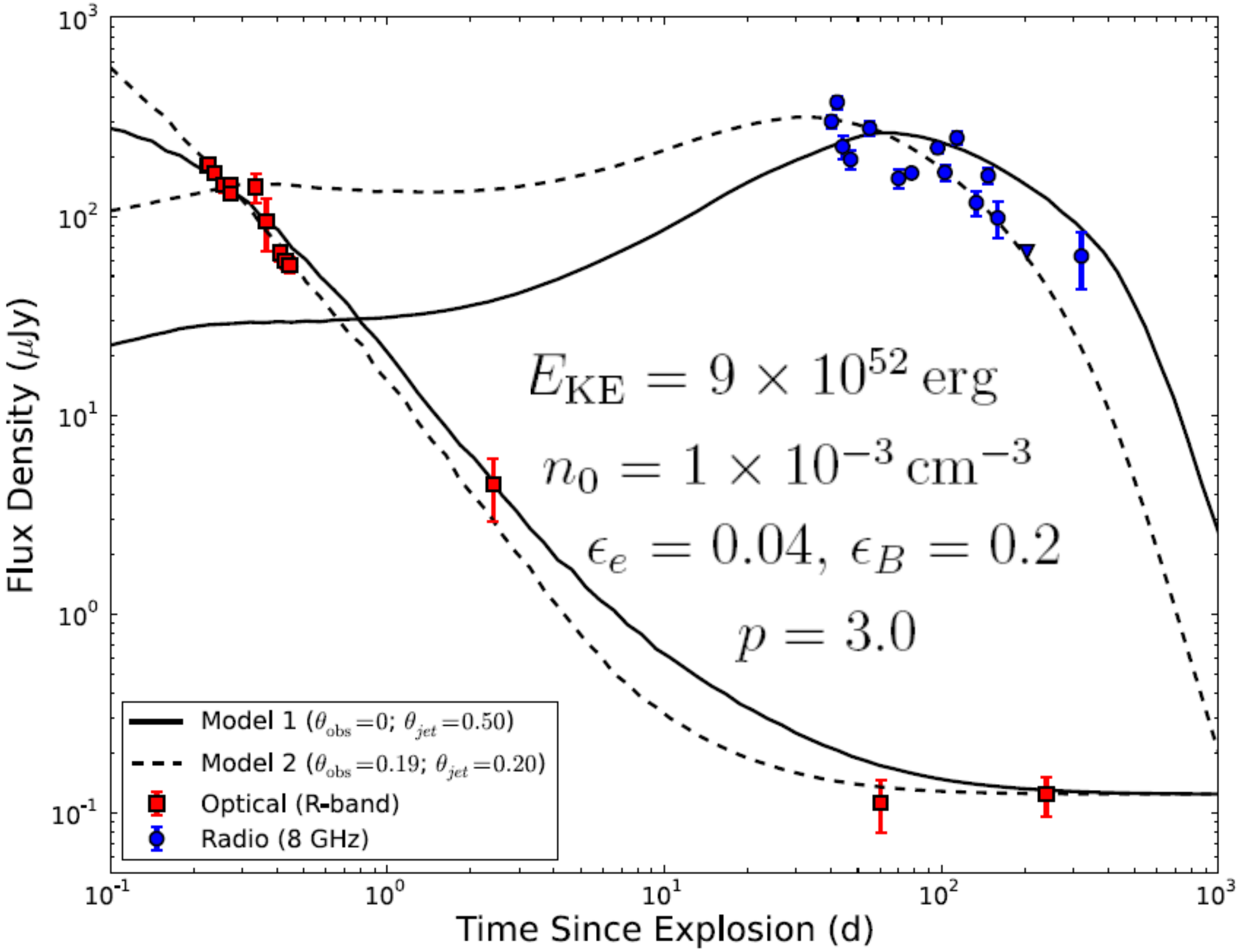
Opt: $T_{peak} \sim T_{sd} \sim 10^3 s$

$F_{peak} \sim 10 mJy$

Radio: $T_{peak} \sim 10^7 s$

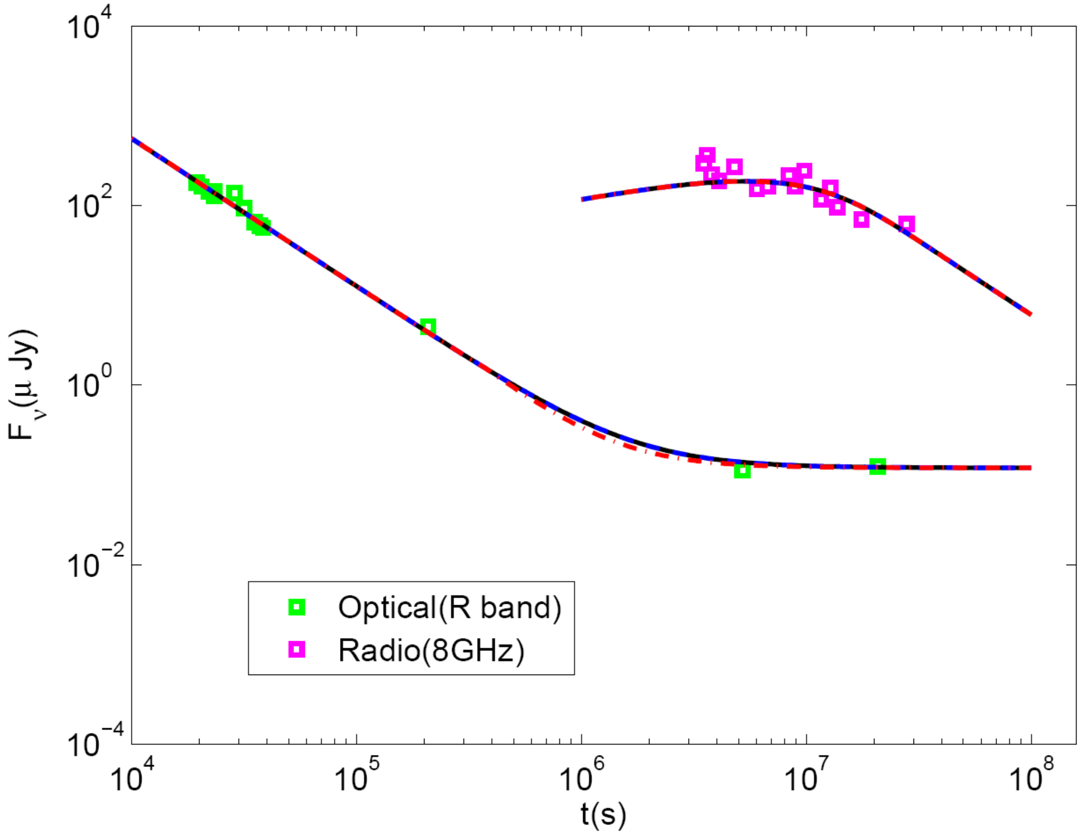
$F_{peak} \sim 1 Jy$

Candidate 1: PTF11agg



Cenko et al. (2013)

Model fits to PTF11agg



z	$n\,(\mathrm{cm}^{-3})$	ϵ_e	ϵ_B	η	ξ	p
0.5	1.0×10^{-4}	0.4	0.08	0.09	0.3	3.2
1	2.4×10^{-3}	0.4	0.06	0.09	0.3	3.2
3	0.26	0.4	0.03	0.09	0.3	3.2

Wu, et al., 2014, ApJL, 781, L10; See also Wang & Dai (2013)

Event Rate

- NS-NS merger: $2\text{-}2\times10^4$ Gpc^{-3} yr^{-1}
- Within advanced LIGO horizon ~ 300 Mpc:
  $R_{\mathrm{GWB\text{-}ag}} \sim (0.2 - 2000)\,(f_{\mathrm{NS}})\,(f_{\mathrm{bw}})\ \mathrm{yr}^{-1}$

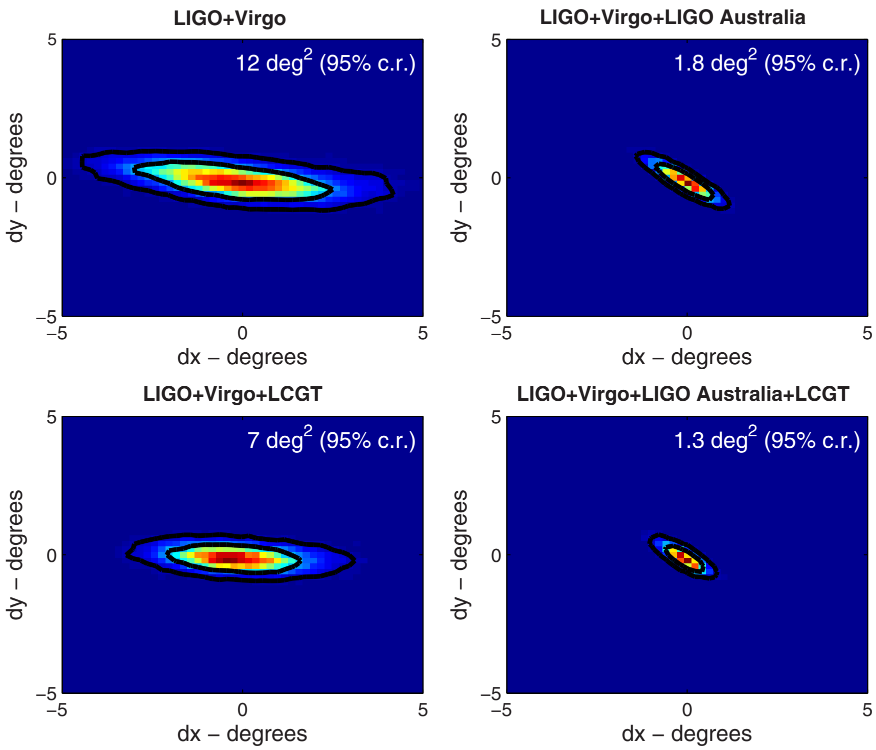
Most probable values:

~ 20 per year for NS-NS mergers

~ 2-10 per year for NS-NS mergers
with a supra-massive millisecond magnetar engine?

Observational strategy

GWB Localization Error Box



LIGO+Virgo

LIGO+Virgo+LIGO Australia

LIGO+Virgo+LCGT

LIGO+Virgo+LIGO Australia+LCGT

Nissanke et al. 2011

X-ray observational strategy

1) **Small field of view (e.g. Swift XRT), requires fast-slew to search for the entire error box in 10^3-10^4 s**

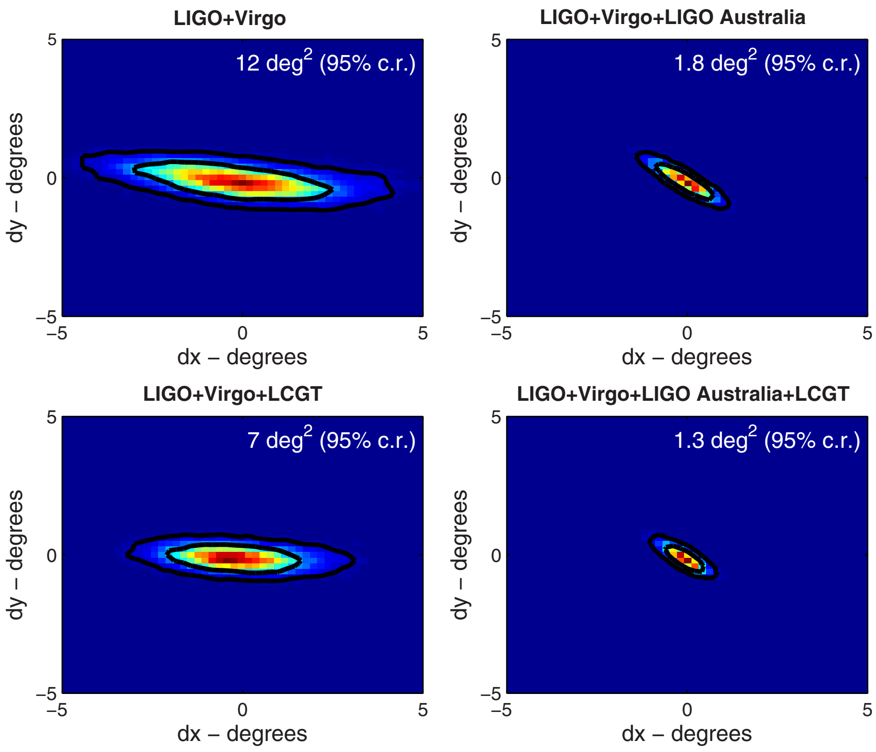
Not easy

2) **Large field of view with moderate sensitivity, rapid-slew to increase chance coincidence with GWB triggers**

e.g. Einstein Probe, Lobster, ASTAR …

Observational strategy

GWB Localization Error Box



Nissanke et al. 2011

Optical observational strategy

Large field of view, look for chance coincidence with GWB triggers;
Follow-up observations if X-ray triggers are made

Radio observational strategy

No need of prompt follow up;
All-sky radio survey important

If all the required observations can be made, how likely can we discover these early afterglows?

- We don’t know
- Because we do not know the NS equation-of-state and total mass distribution of NS-NS systems, so that we do not know what fraction of NS-NS mergers will leave behind a stable magnetar rather than a black hole
- If a supra-massive millisecond magnetar forms, essentially every one would have a bright X-ray early afterglow
- The brightness of the multi-wavelength afterglow depends on viewing angle, ejecta mass, and medium density

Story I

- Imagine some time beyond 2020
- Advanced LIGO sends an alert to the EM community about a “chirp” GWB signal
- Einstein Probe / Lobster / ASTAR happens to cover the error box of advanced LIGO, but no bright X-ray emission is discovered
- The magnetar possibility is essentially ruled out. The upper limit of NS maximum mass constraints NS equation of state
- Deep searches of optical signal in the error box did not reveal a bright optical transient
- Deep searches of radio signal one year after the GWB trigger revealed a very faint object. It takes years to figure out whether it is a variable source, and hence, whether it is related to the NS-NS merger.

Story II

- Imagine some time beyond 2020
- Advanced LIGO sends an alert to the EM community about a “chirp” GWB signal
- Einstein Probe / Lobster / ASTAR happens to cover the error box of advanced LIGO, and a bright X-ray emission is discovered
- Optical and radio telescopes immediately slews to the error box provided by the X-ray detector, and discovers a bright afterglow
- Follow-up GW signal analysis reveals a phase of secular bar-mode instability signal of a hyper-massive neutron star
- From the duration of the X-ray plateau, the magnetar magnetic field is constrained.
- Combining GW analysis and afterglow analysis, one is able to derive many interesting physical parameters: the mass of the two parent NSs, ejecta mass, maximum mass of the survived NS, maximum mass of a non-spinning NS, equation-of-state of nuclear matter …

Look Early!

Both positive and negative detections are of great interest!

Only observations will make breakthrough!