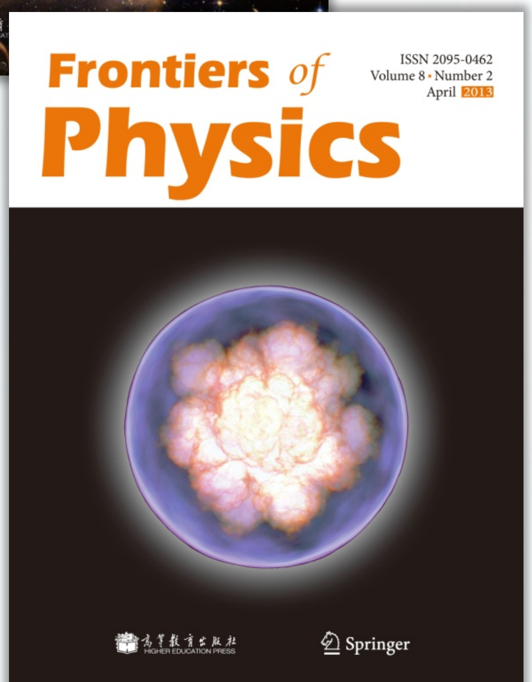

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Special Issue:

Recent Progress on High Energy Astrophysics

(**Eds.** Bing Zhang & Peter Mészáros)

Front. Phys., Vol. 8, No. 6 (2013)

Special Issue:

The Physics and Astrophysics of Type Ia Supernova Explosions

(**Eds.** Mike Guidry & Bronson Messer)

Front. Phys., Vol. 8, No. 2 (2013)

Available online:

journal.hep.com.cn/fop;

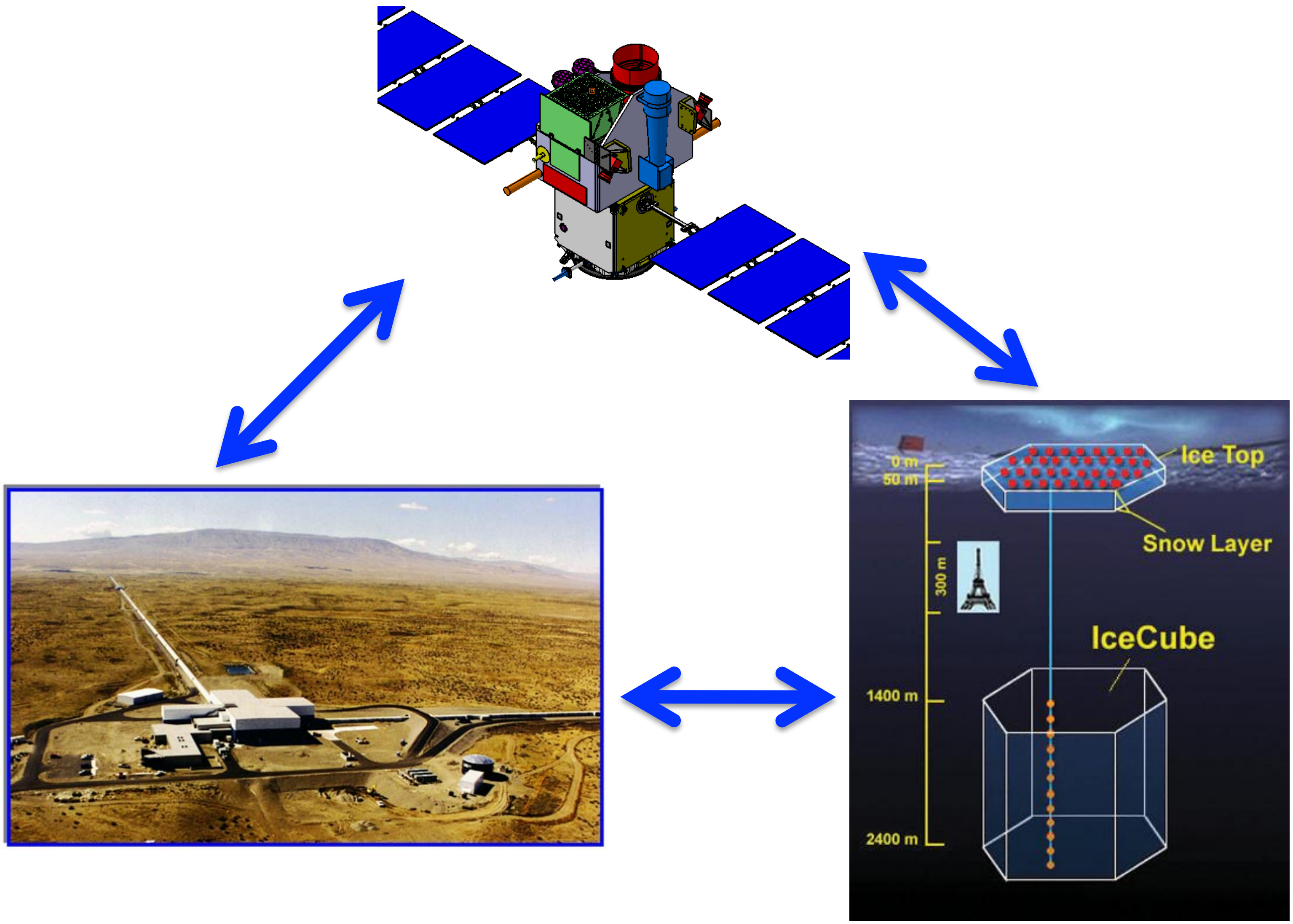
www.springer.com/11467

GRBs & multi-messenger (neutrino and gravitational wave) connection

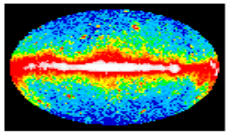
Bing Zhang (张冰)
University of Nevada Las Vegas / Peking University

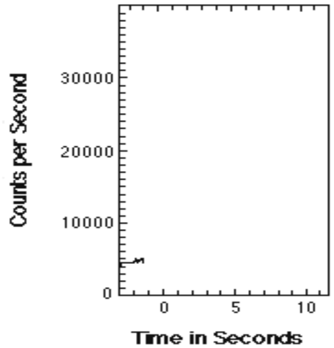
July 10, 2015,
JUNO neutrino astronomy/astrophysics workshop

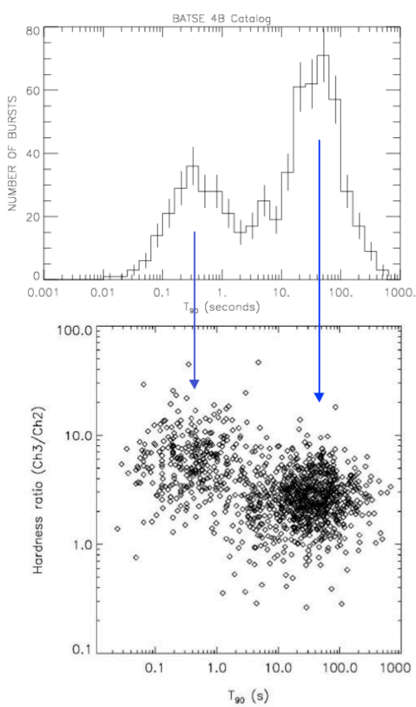
Future: Multi-messenger Era

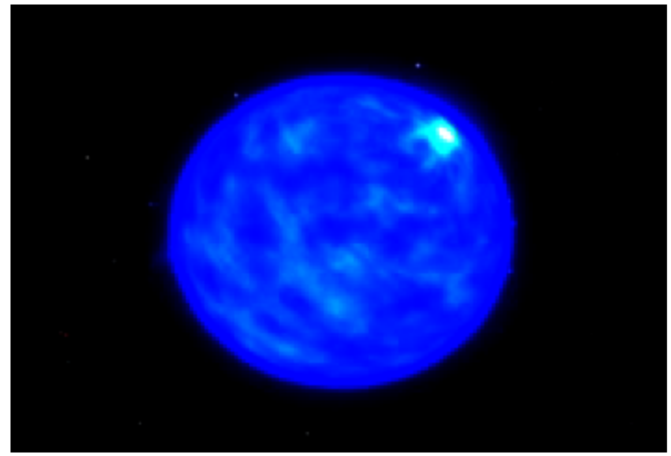


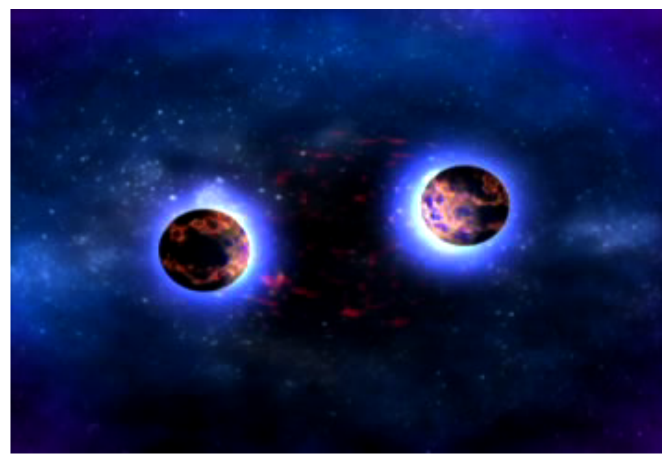
Gamma-Ray Bursts on one slide



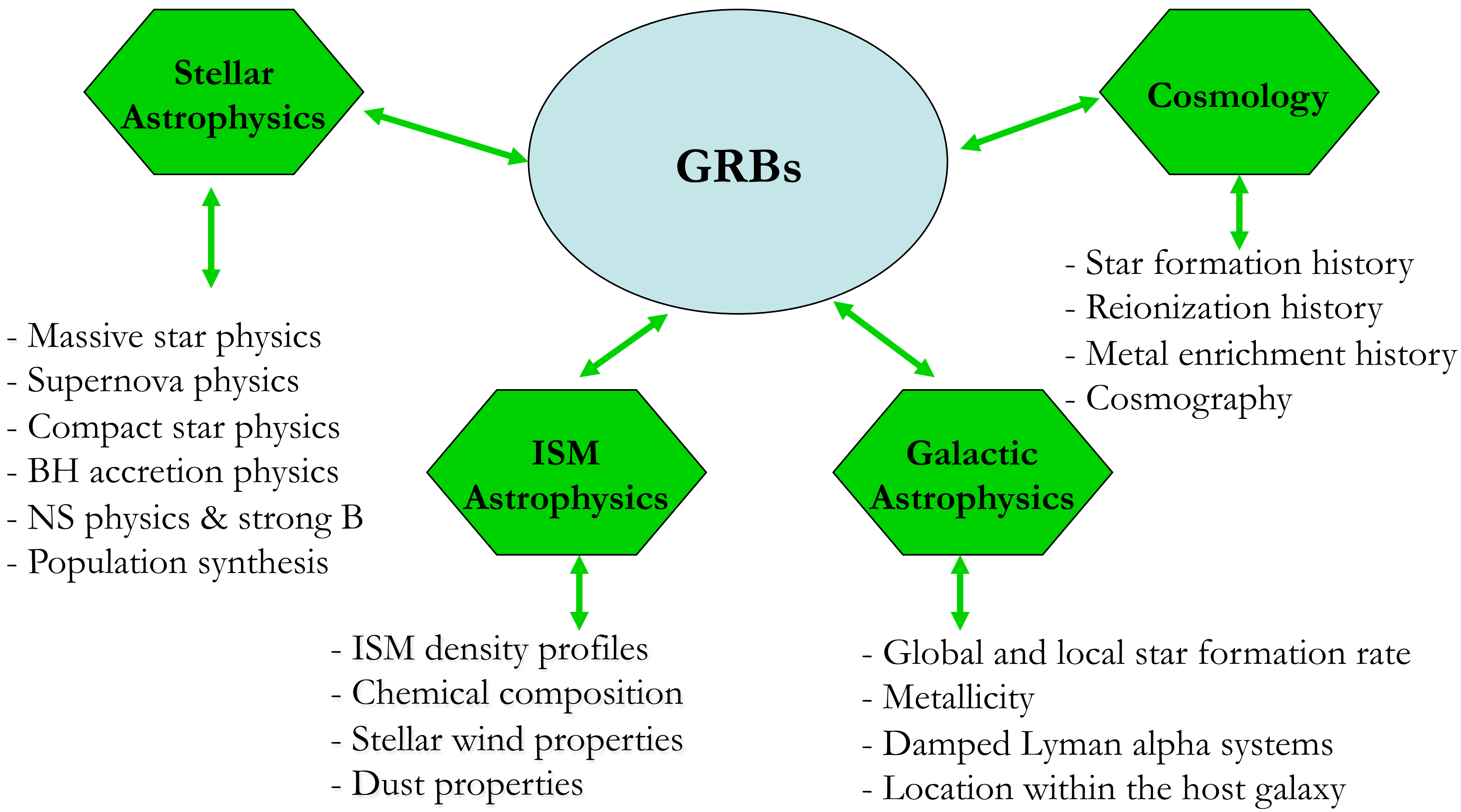




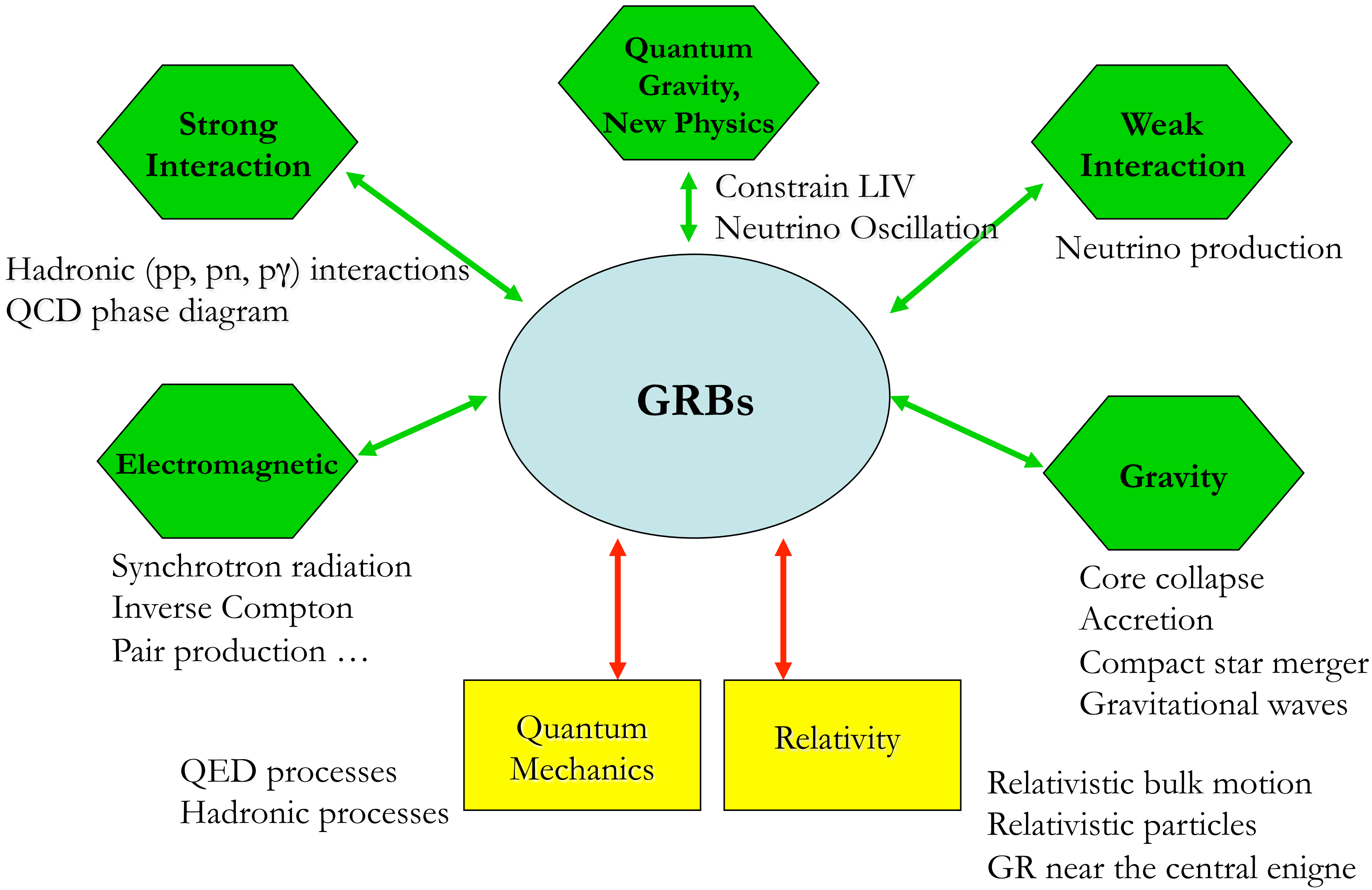




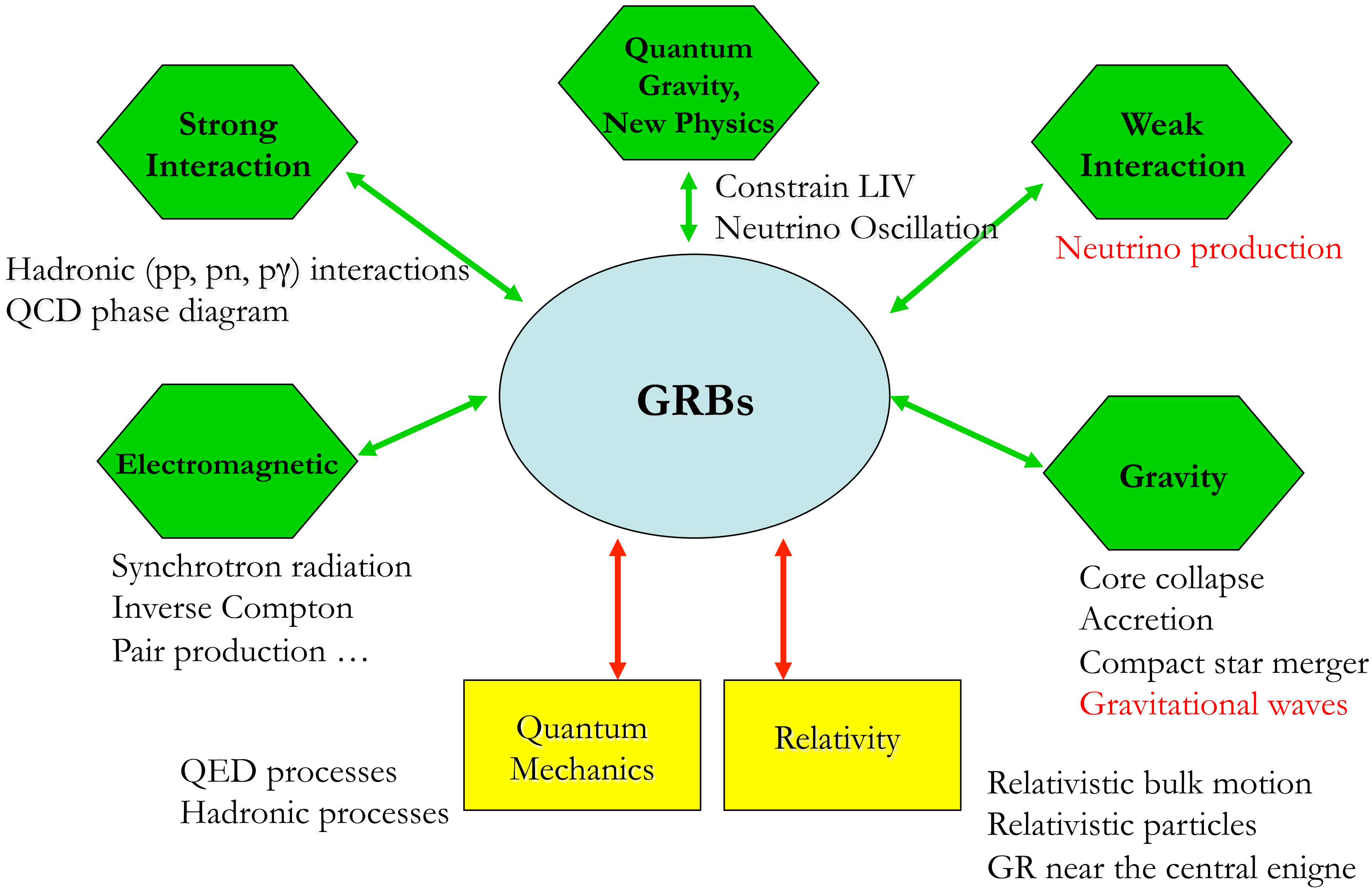
GRBs & Astrophysics



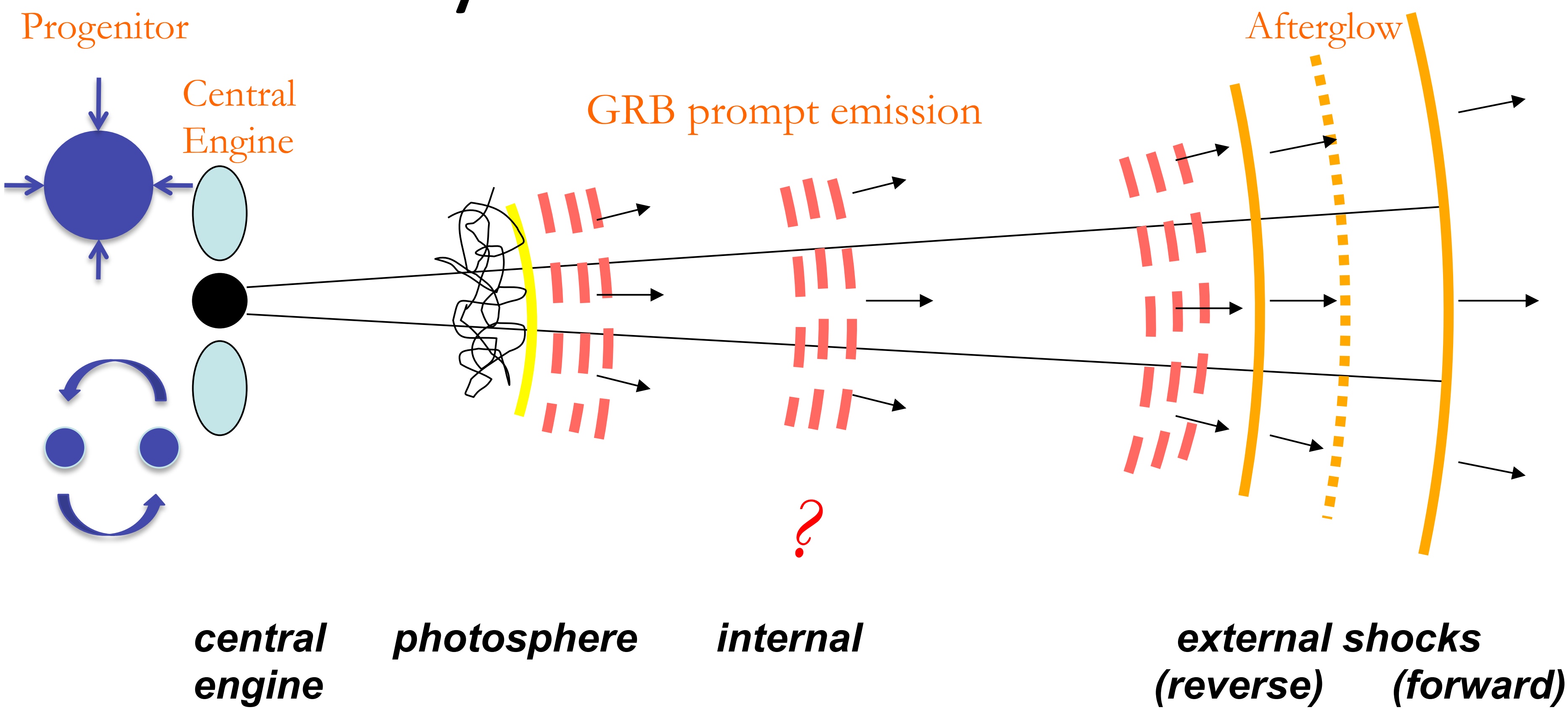
GRBs & Physics



GRBs & Physics



Physical Sketch of GRBs



Uncertainties in GRB Prompt Emission:

What is the jet composition (baryonic vs. Poynting flux)?

Where is (are) the dissipation radius (radii)? – three possible locations

How is the radiation generated (synchrotron, Compton scattering, thermal)?

Multi-Messenger Observations can address:

Open Questions in GRB Physics

- Progenitors & classification (massive stars vs. compact stars; others? how many physically distinct types?)
- Central engine (black hole, magnetar?)
- Ejecta composition (baryonic, leptonic, magnetic?)
- Energy dissipation mechanism (shock vs. magnetic reconnection)
- Particle acceleration & radiation mechanisms (synchrotron, inverse Compton, quasi-thermal)
- Afterglow physics (medium interaction vs. long-term engine activity)

Topic 1:

Neutrinos from GRBs:

“Thermal” neutrinos

- Core collapse (talks by Qian & Li)
- Neutrino dominated accretion flow (NDAF)
  - Electron capture & neutronization

    $p+e^{-} \rightarrow n+\nu_e$
  - β-decay:

    $n \rightarrow e^{-}+p+\overline{\nu}_e$
  - Photon pair annihilation:

    $\gamma\,\gamma \rightarrow e^{-}e^{+} \rightarrow \nu_e\,\overline{\nu}_e$
  - Photo neutrino:

    $\gamma\, e^{-} \rightarrow e^{-}\nu_e\,\overline{\nu}_e$

“Non-thermal” neutrinos

- Protons are accelerated in astrophysical environment, which would interact with photons or other baryons to produce neutrinos:
  - $p\gamma$ process:
  - *pp/pn* process:

pγ

- Interaction at Δ-resonance:

$$p\gamma \to (\Delta^+ \to) \begin{cases} n\pi^+ \to n\mu^+\nu_\mu \to ne^+\nu_e\bar{\nu}_\mu\nu_\mu, & \text{fraction } 1/3 \\ p\pi^0 \to p\gamma\gamma, & \text{fraction } 2/3. \end{cases}$$

- "Matching" condition:

$$E_p E_\gamma \gtrsim \frac{m_\Delta^2 - m_p^2}{4} \left(\frac{\Gamma}{1+z}\right)^2 = 0.16\ \mathrm{GeV}^2 \left(\frac{\Gamma}{1+z}\right)^2$$

$m_\Delta = 1.23$ GeV

$m_p = 0.938$ GeV

Γ: Lorentz factor

z: redshift

- Cross section:

$$\sigma_{p\gamma} \simeq 5 \times 10^{-28}\ \mathrm{cm}^2 \simeq 500\mu\mathrm{b}.$$

- Important in intense photon field

pp/pn

- Interaction (no resonance):

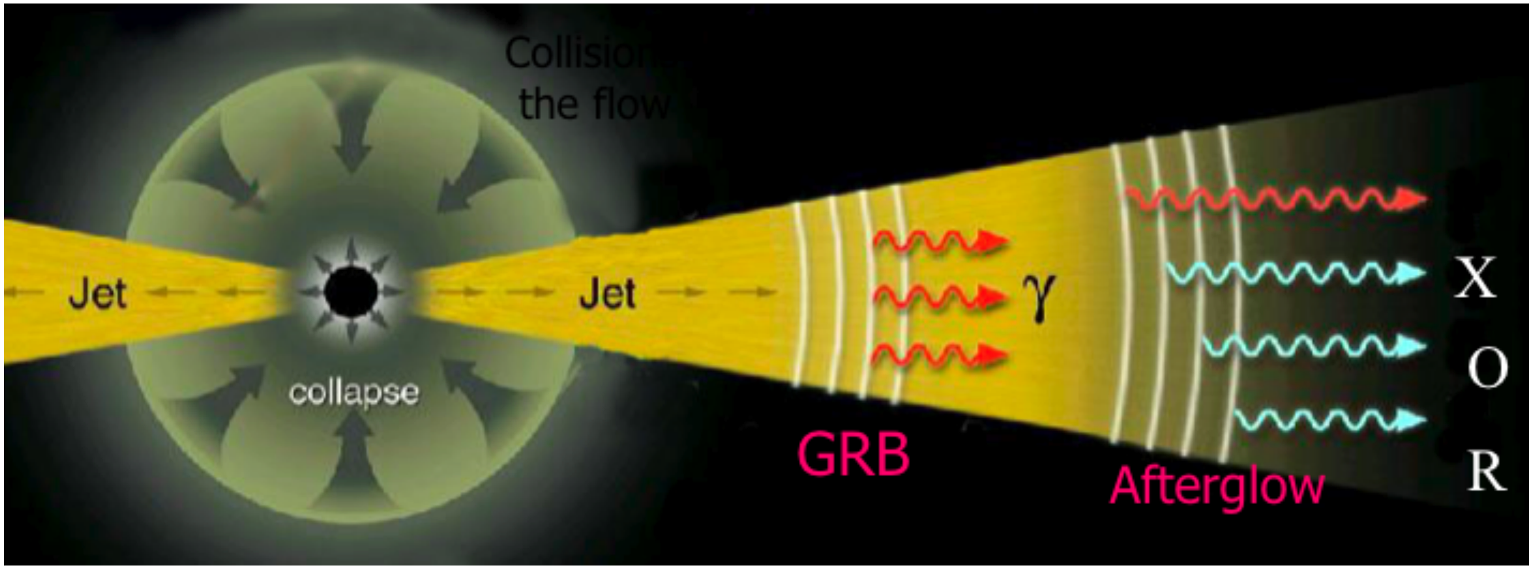
$$pp(pn) \rightarrow \pi^{\pm}/K^{\pm}... \rightarrow \begin{cases} \mu^{+}\nu_{\mu}... \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu}\nu_{\mu}... \\ \mu^{-}\bar{\nu}_{\mu}... \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}\bar{\nu}_{\mu}... \end{cases}$$

- Cross section:

$$< \sigma_{pp} > \quad \simeq 6 \times 10^{-26}\ \mathrm{cm}^2,$$

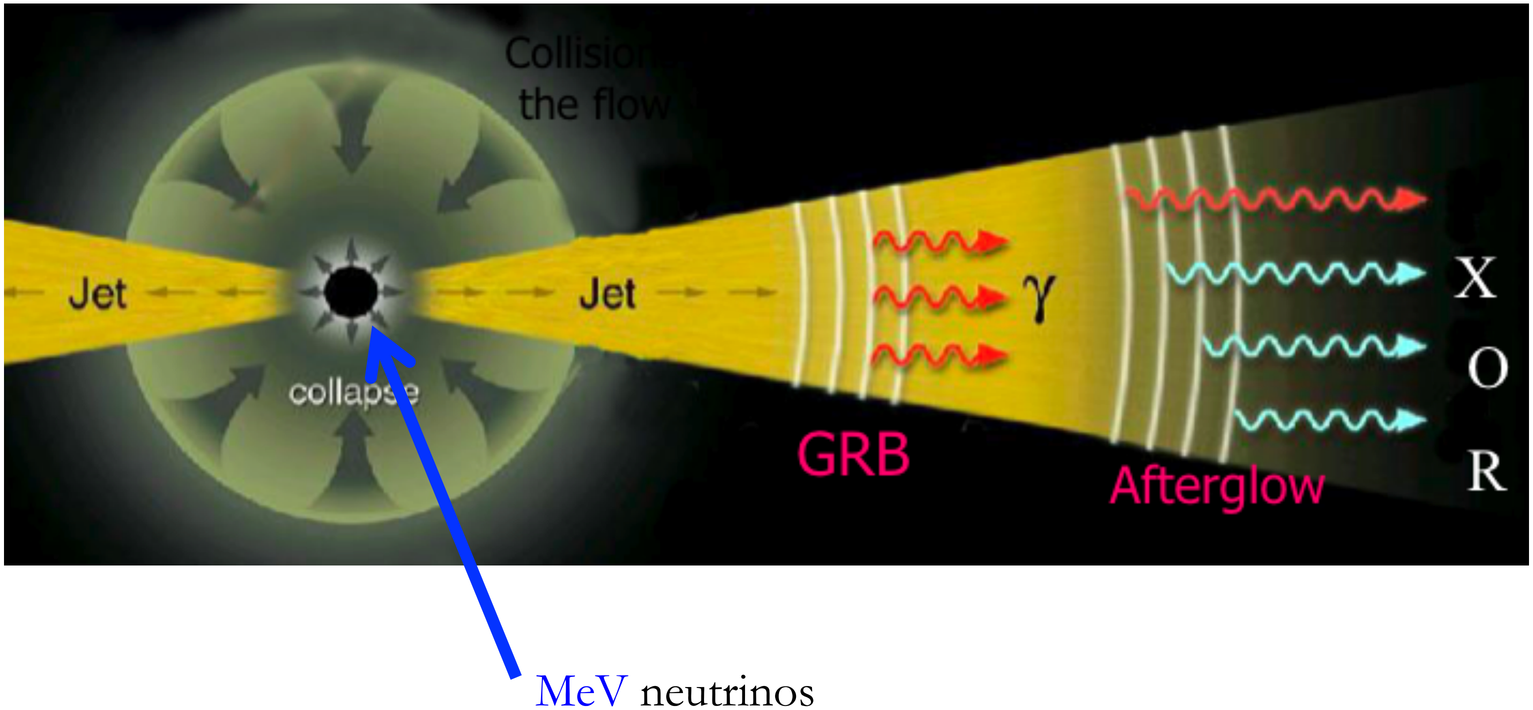
- Important in dense environments

Neutrinos from GRBs



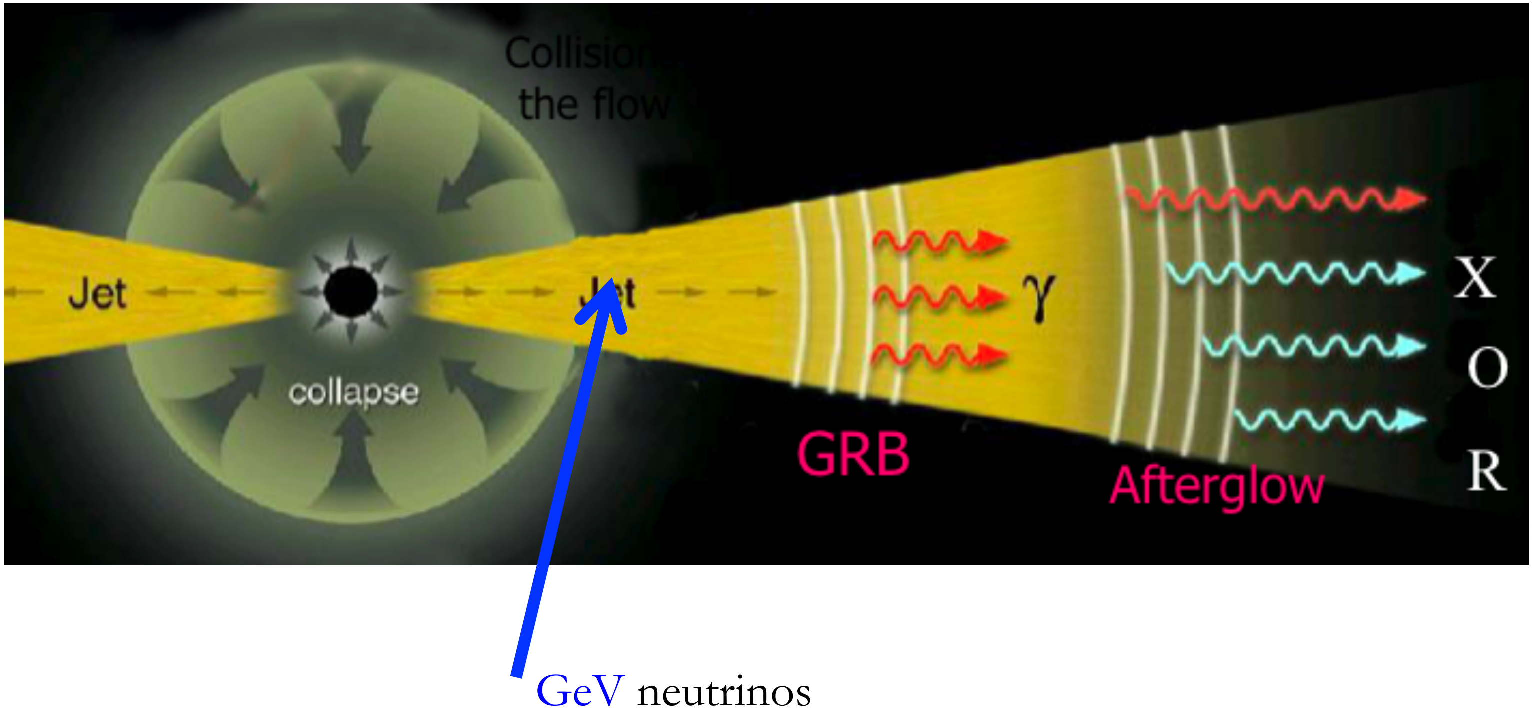
- MeV: core collapse, central engine
- GeV: fireball acceleration phase, pn collision (Bahcall & Meszaros 2000)
- TeV: Jet in star for both successful and choked GRBs; or in dissipative photosphere (Meszaros & Waxman 2001; Razzaque et al. 2003; Ando & Beacom 2005; Wang & Dai 2009; Murase & Ioka 2013)
- PeV: Internal shocks or magnetic dissipation (Waxman & Bahcall 1997; Li 2012; He et al. 2012; Zhang & Kumar 2013)
- EeV: External shock (Waxman & Bahcall 2000; Dai & Lu 2001); Low luminosity GRBs (Murase et al. 2006; Gupta & Zhang 2007)

MeV Neutrinos from GRBs



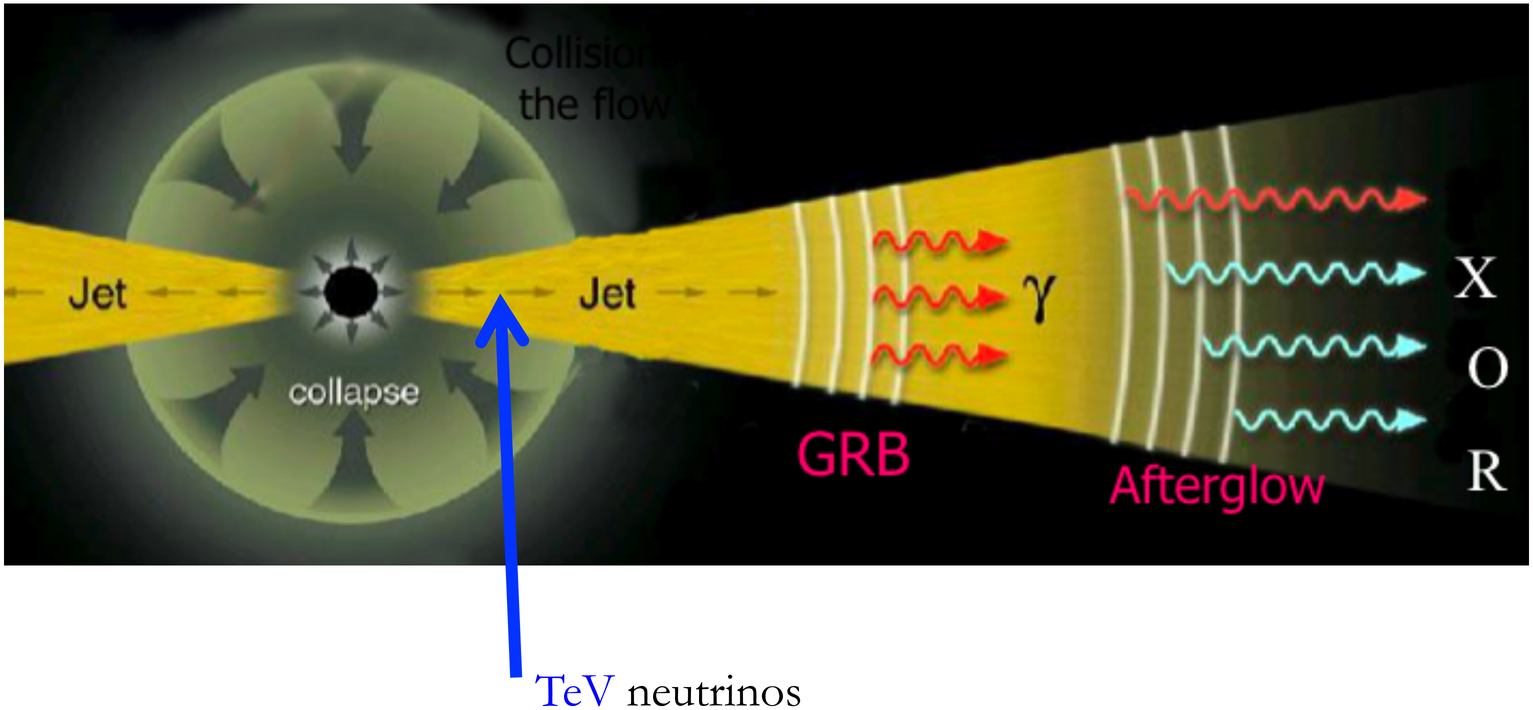
- From central engine (proto neutron star, accretion disk)
- Thermal, temperature ~ MeV, produce MeV neutrinos
- Very low flux, detectable only when a GRB is very close (in nearby galaxies)

GeV Neutrinos from GRBs



- During the fireball acceleration phase
- Relative motion between protons and neutrons
- Inelastic collisions among protons and neutrons to produce GeV neutrinos

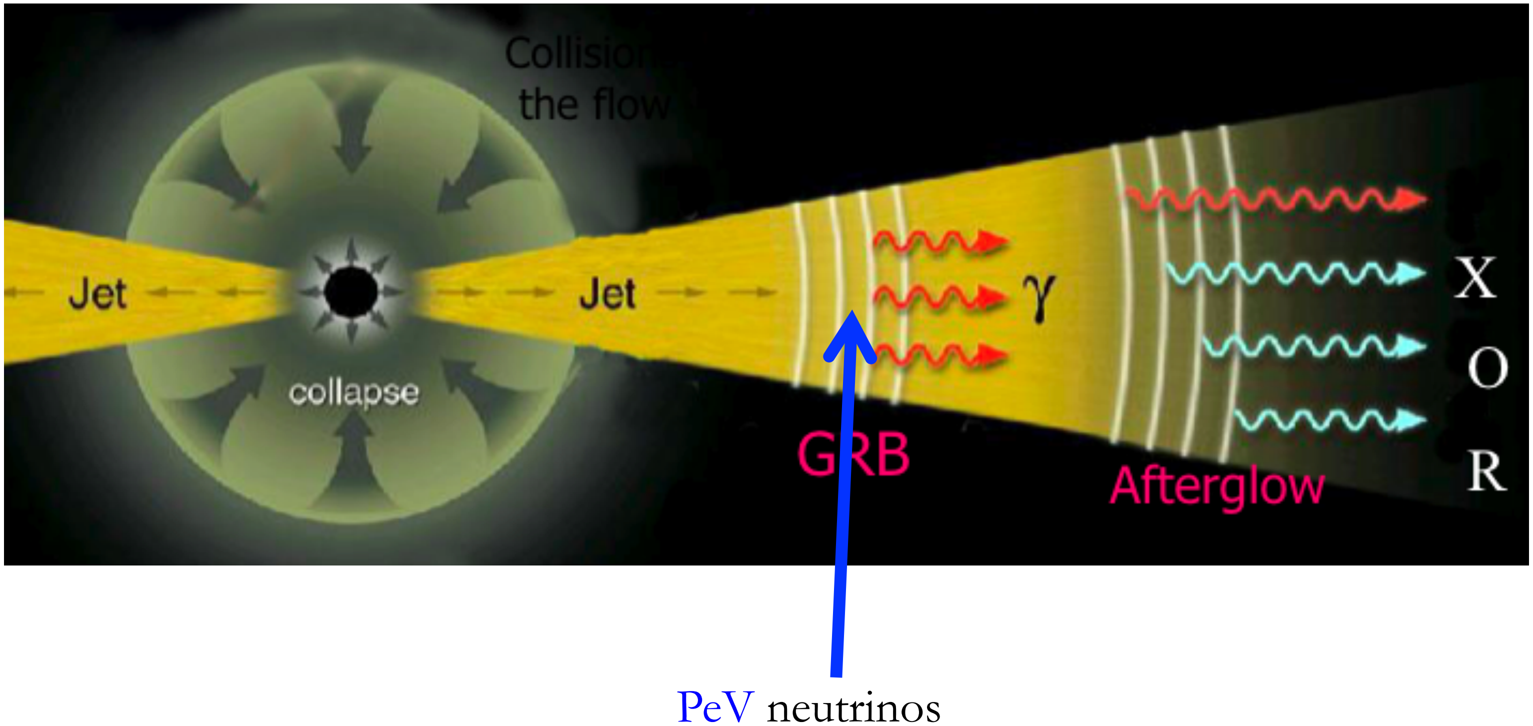
TeV Neutrinos from GRBs



- Jet propagating inside the progenitor star
- X-rays in the cocoon
- Protons interacting with X-rays to produce TeV neutrinos

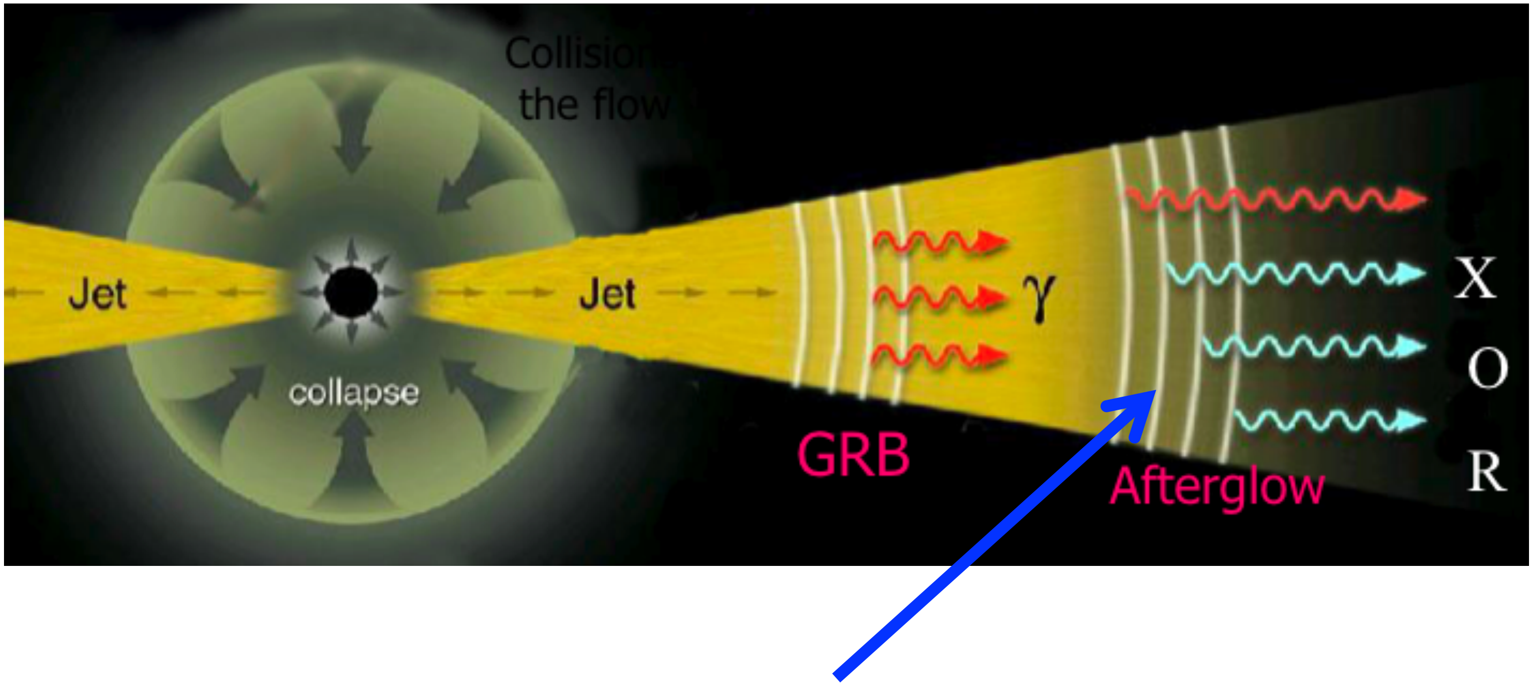
- Photosphere

PeV Neutrinos from GRBs



- Gamma-rays from the GRB emission site (internal shocks)
- Protons are also accelerated in the internal shocks
- Protons interact with gamma-ray photons to produce PeV neutrinos
- For soft, low-luminosity GRBs, peak shifts to sub EeV

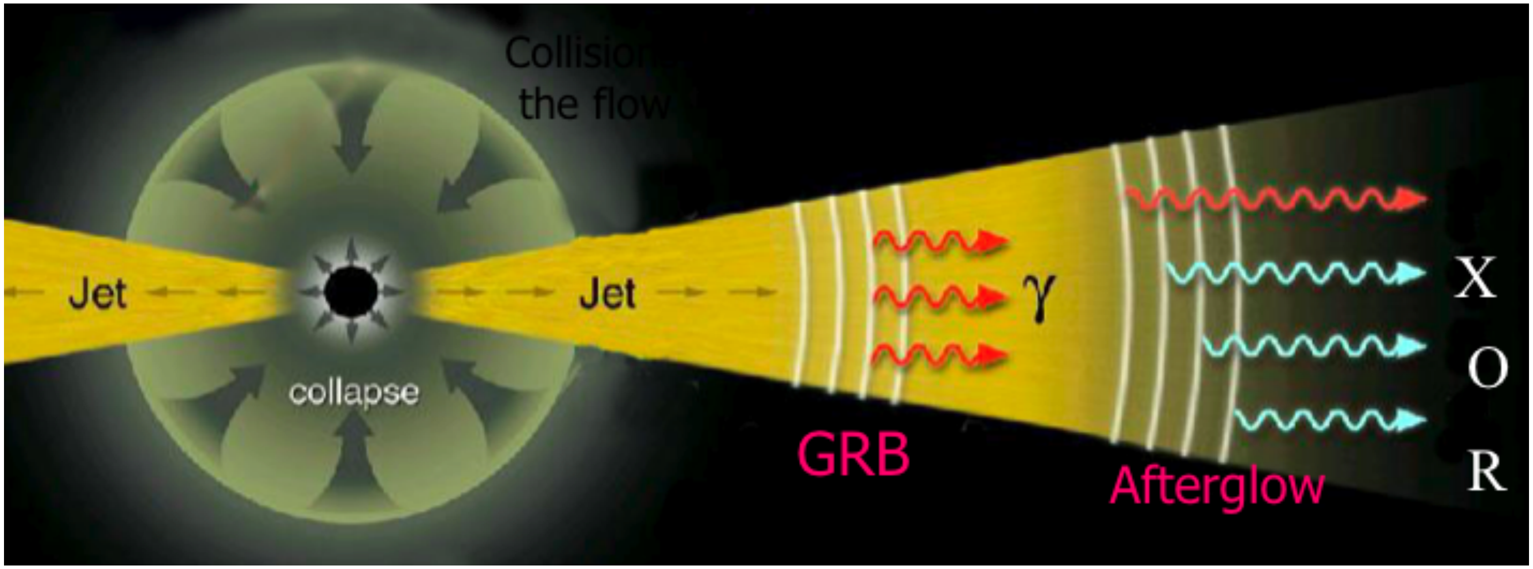
EeV Neutrinos from GRBs



EeV neutrinos

- X-rays emitted in the external reverse/forward shock region
- Protons are also accelerated in these shocks
- Protons interact with X-rays photons to produce sub EeV neutrinos
- EeV neutrinos can be also generated in X-ray flares following GRBs

Neutrinos from GRBs



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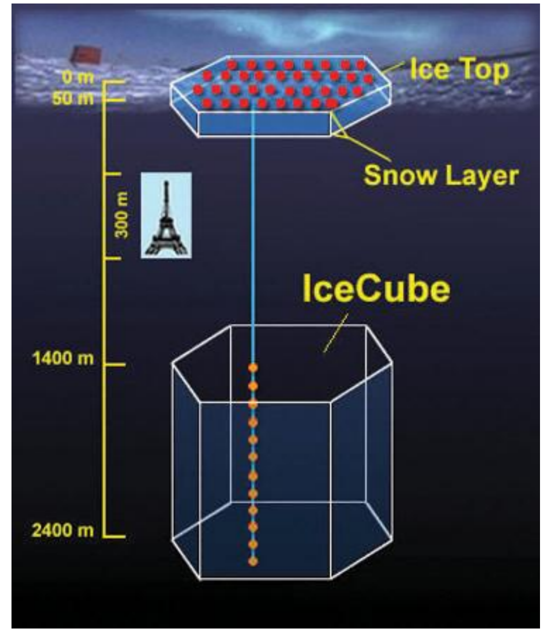
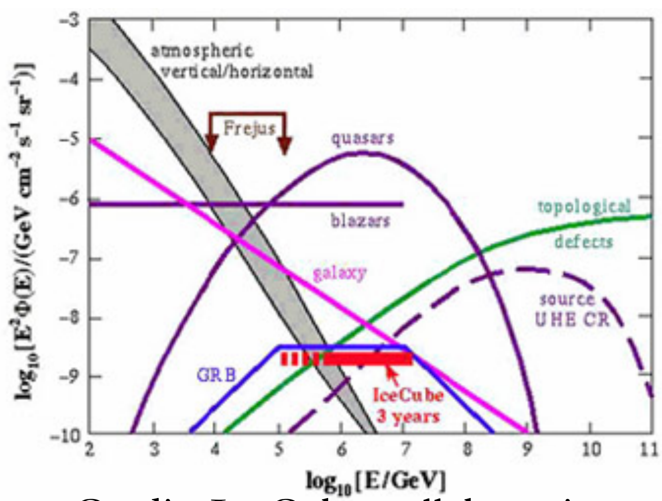
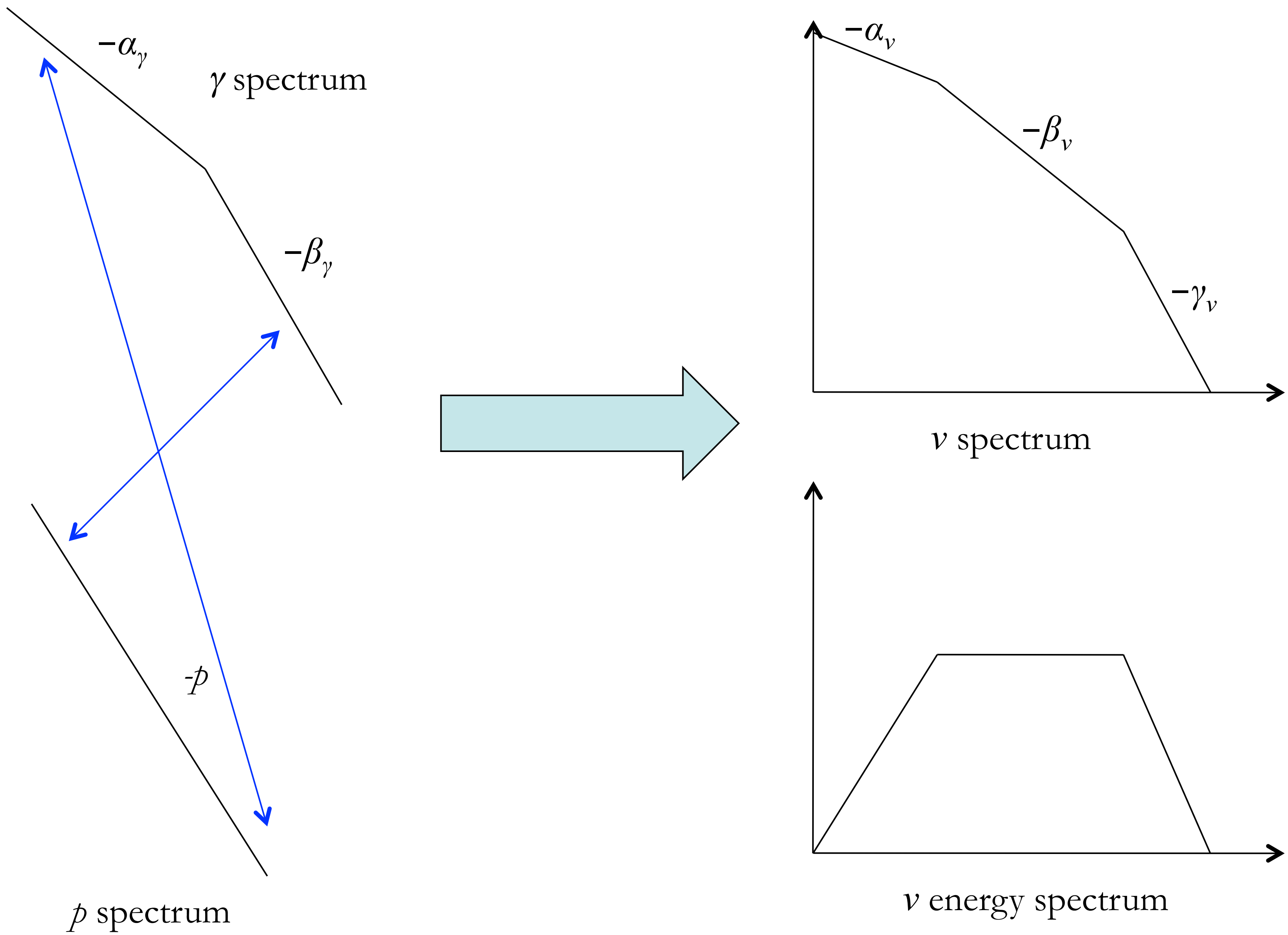
PeV neutrinos from GRBs

- Guaranteed neutrino component: photon component: ~MeV photons observed from GRBs
- If cosmic rays are accelerated in GRB sources, neutrinos must be there!
- Most favorable target for IceCube





Credit: IceCube collaboration



$$\alpha_\nu = p + 1 - \beta_\gamma, \quad \beta_\nu = p + 1 - \alpha_\gamma, \quad \gamma_\nu = \beta_\nu + 2,$$

Non-detection of neutrinos by Icecube

- IceCube did not detect neutrinos from GRBs yet, upper limit 3 times lower than the most optimistic predictions (Waxman & Bahcall)

LETTER

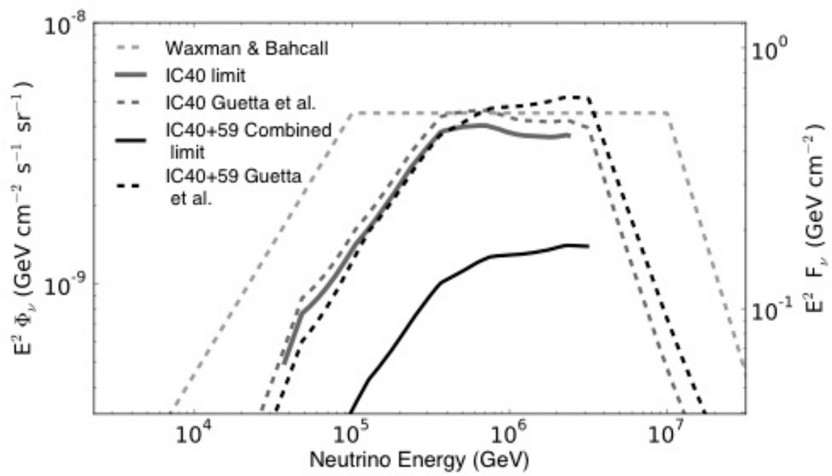
doi:10.1038/nature11068

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

IceCube Collaboration*

Very energetic astrophysical events are required to accelerate cosmic rays to above 10^{18} electronvolts. GRBs (γ-ray bursts) have been proposed as possible candidate sources[1–3]. In the GRB 'fireball' model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between the high-energy cosmic-ray protons and γ-rays[4]. Previous searches for such neutrinos found none, but the constraints were weak because the sensitivity was at best approximately equal to the predicted flux[5–7]. Here we report an upper limit on the flux of energetic neutrinos associated with GRBs that is at least a factor of 3.7 below the predictions[4,8–10]. This implies either that GRBs are not the only sources of cosmic rays with energies exceeding 10^{18} electronvolts or that the efficiency of neutrino production is much lower than has been predicted.

As in our previous study[7], we conducted two analyses of the IceCube data. In a model-dependent search, we examine data during the period of γ-ray emission reported by any satellite for neutrinos with the energy spectrum predicted from the γ-ray spectra of individual GRBs[6,9]. The model-independent analysis searches more generically for neutrinos on wider timescales, up to the limit of sensitivity to small numbers of events at ±1 day, or with different spectra. Both analyses follow the methods used in our previous work[7], with the exception of slightly changed event selection and the addition of the Southern Hemisphere to the model-independent search. Owing to the large background of downgoing muons from the southern sky, the Southern Hemisphere analysis is sensitive mainly to higher-energy events (Supplementary Fig. 3). Systematic uncertainties from detector effects have been included in the reported limits from both analyses,

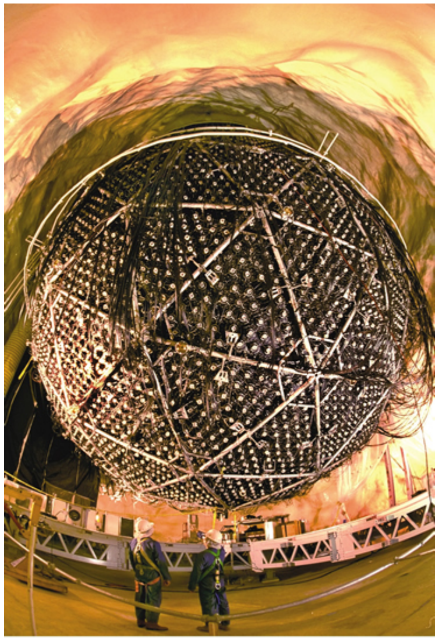


IceCube results

Solar neutrino problem

- Early searches for solar neutrinos failed to find the predicted number (about 1/3 of predicted)
- Debate:
  - Astrophysics wrong?
  - Physics wrong?
- It turns out that neutrinos oscillate – physics was wrong

Homestake Solar Neutrino Observatory

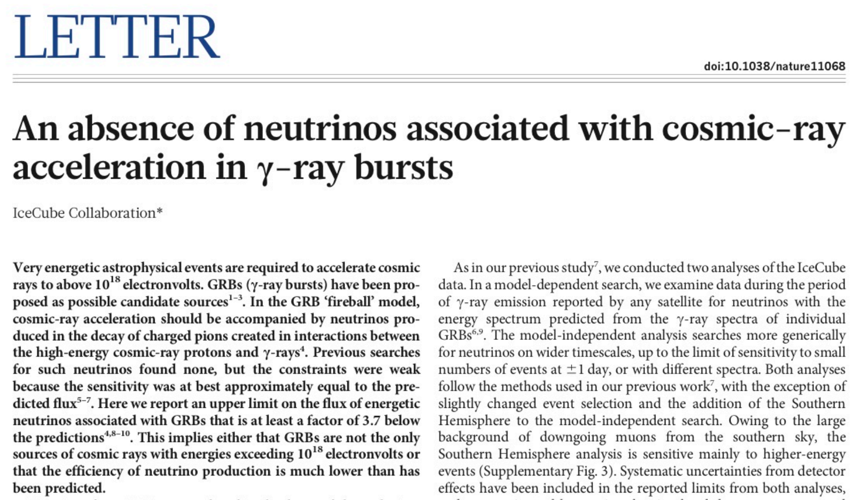


Super Kamiokande

A GRB neutrino problem?

- Icecube did not detect high energy neutrinos from GRBs as expected from the theories
- A similar question arises:
  - Astrophysics wrong?
  - Physics wrong?
- This time, very likely astrophysics is wrong!

GRB models invoke a lot more uncertainties than solar models.



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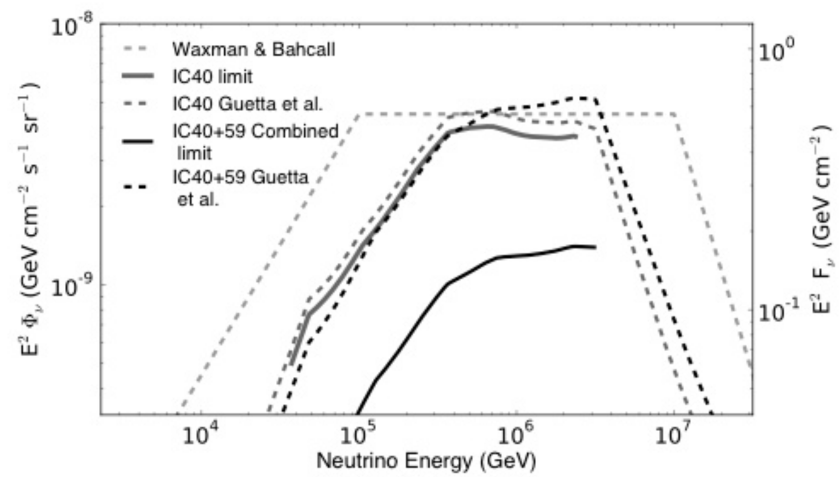
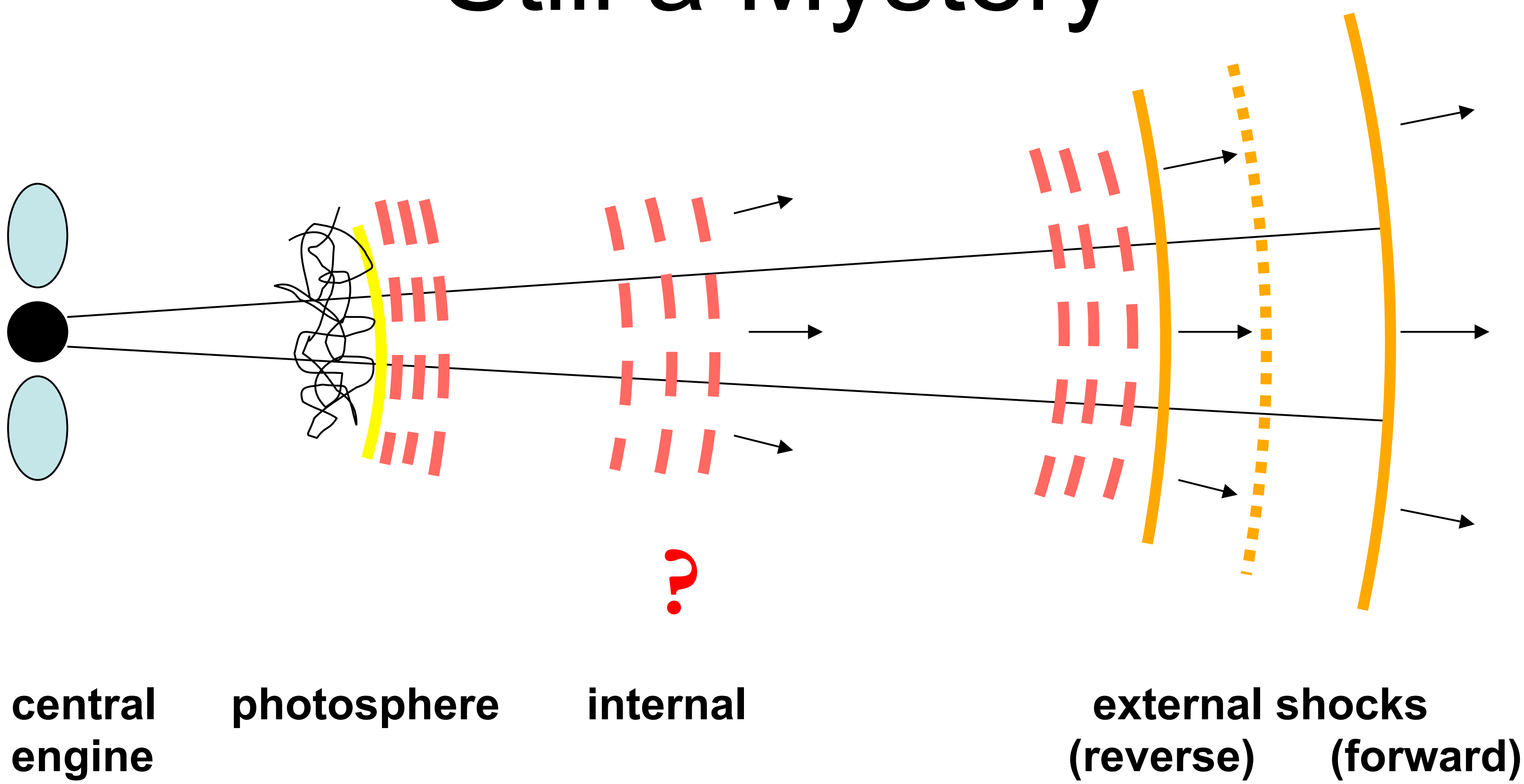


IceCube results

Prompt GRB Emission: Still a Mystery

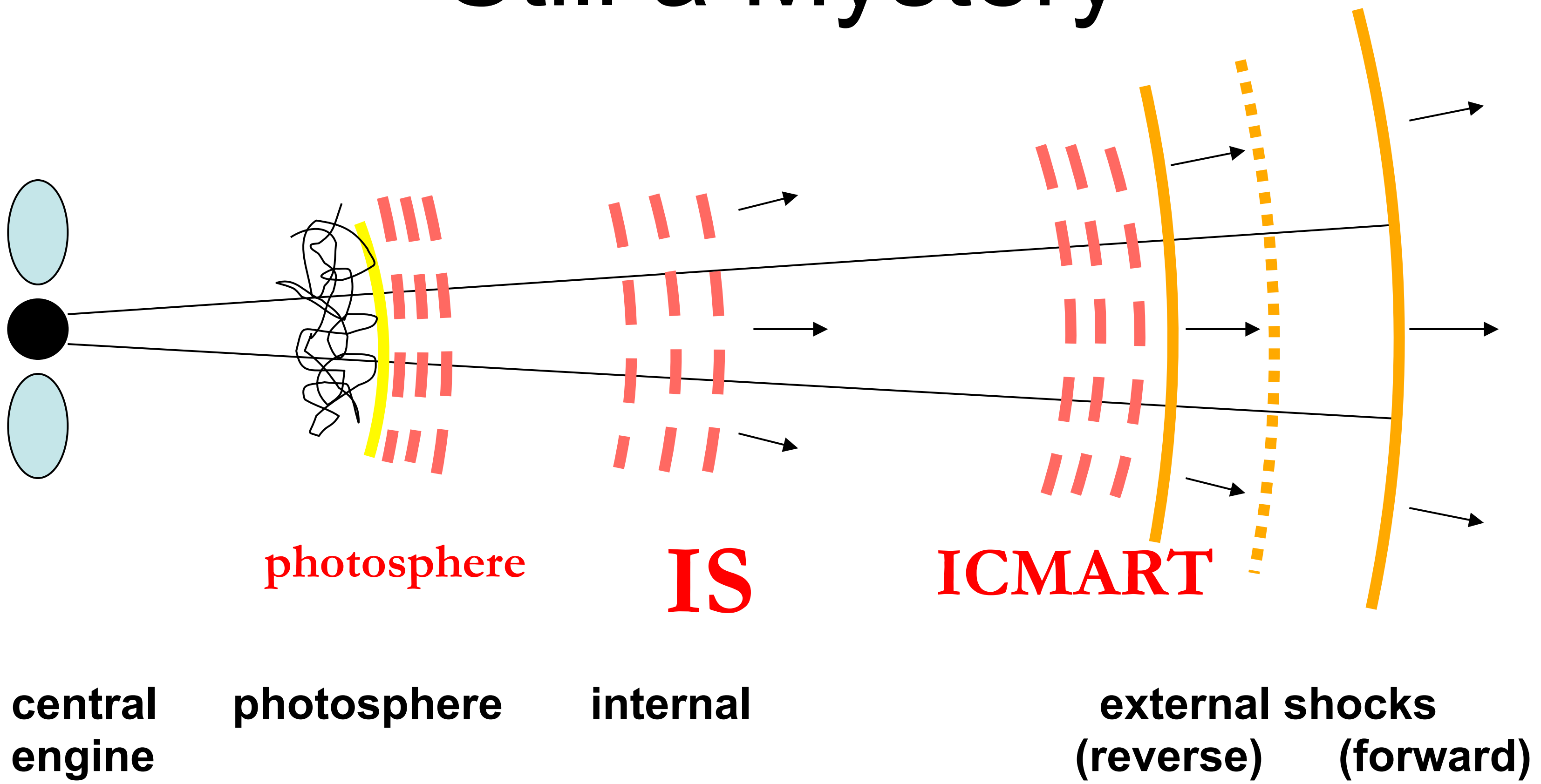


What is the jet composition (baryonic vs. Poynting flux)?
Where is (are) the dissipation radius (radii)?
How is the radiation generated (synchrotron, Compton scattering, thermal)?

Model-dependent PeV neutrino flux

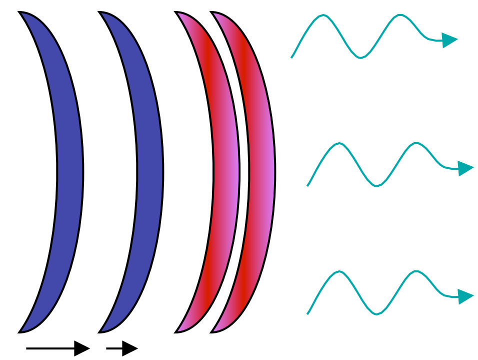
- Neutrino flux depends on proton flux and $p\gamma$ optical depth
  - Proton flux depends on L_p (normalized to L_γ)
  - Optical depth depends on L_γ, Γ and R
- Different models may have different $f_{\gamma/p} = L_\gamma / L_p$
- Given the same observed L_γ and Γ, different models invoke different R
  - Internal shock model: $R = \Gamma^2 c\, \delta t_{\rm min}$
  - Photosphere model: *probably* $R < \Gamma^2 c\, \delta t_{\rm min}$
  - Internal Collision-induced MAgnetic Reconnection and Turbulence (ICMART) model: $R = \Gamma^2 c\, \delta t_{\rm slow} > \Gamma^2 c\, \delta t_{\rm min}$

Prompt GRB Emission: Still a Mystery



Internal Shock Model

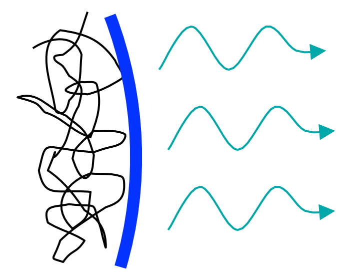
- Internal shocks develop at $R = \Gamma^2 c\, \delta t_{\min}$
- Both electrons and protons are accelerated in internal shocks; most electron energy goes to radiation (fast cooling), so $f_{\gamma/p} = L_\gamma / L_p = \varepsilon_e / \varepsilon_p \sim 0.1$
- This ratio also allows GRBs to be dominant UHECR sources (Waxman 1995)



Rees & Meszaros
Paczynski & Xu
Kobayashi, Piran & Sari
Daigne & Mochkovitch
Panaitescu, Spada, Meszaros
……

Dissipative Photosphere Model

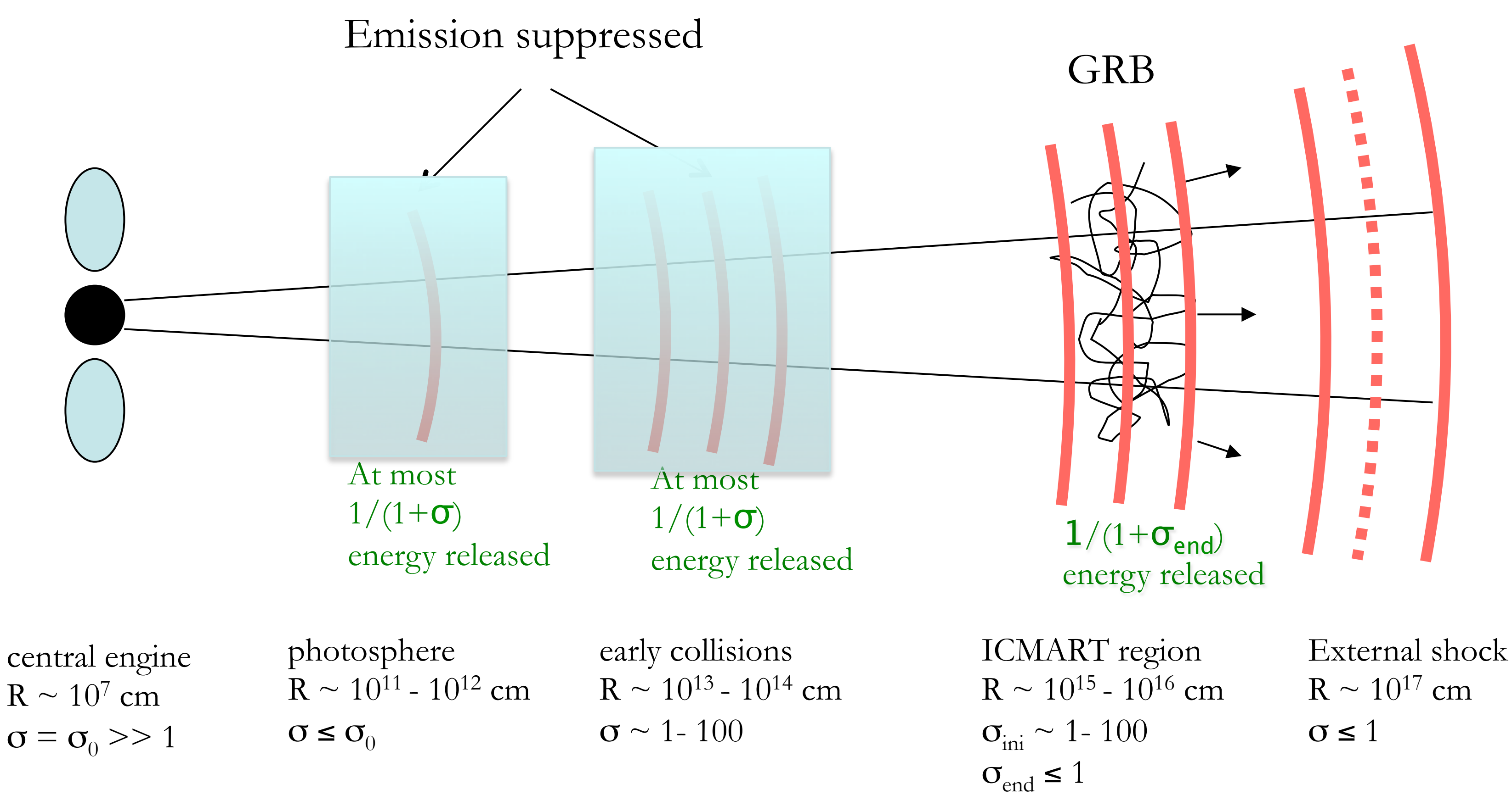
- At photosphere quasi-thermal photons are released. Dissipation and particle acceleration are envisaged around the photosphere, so that a non-thermal spectrum emerges
- $R \leq \Gamma^2 c\, \delta t_{\min}$, $\delta t_{\min}$ can be defined by minimum central engine activity, not necessarily $R / \Gamma^2 c$.
- Can be rich of photons, so that $f_{\gamma/p} = L_\gamma / L_p$ can be larger than 0.1
- GRBs are not dominant UHECR sources



Rees & Meszaros
Thompson et al.
Beloborodov
Giannios
Ioka
Lazzati
Toma, Veres
……

ICMART Model

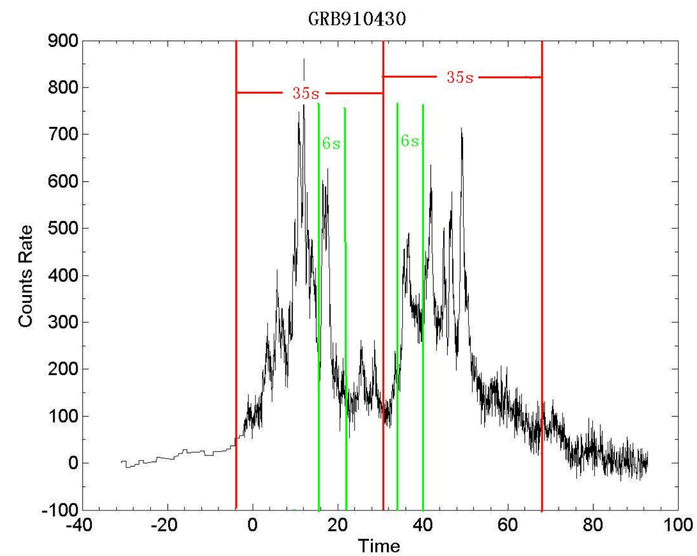
(Internal Collision-induced MAgnetic Reconnection & Turbulence)



Zhang & Yan (2011)

ICMART Model

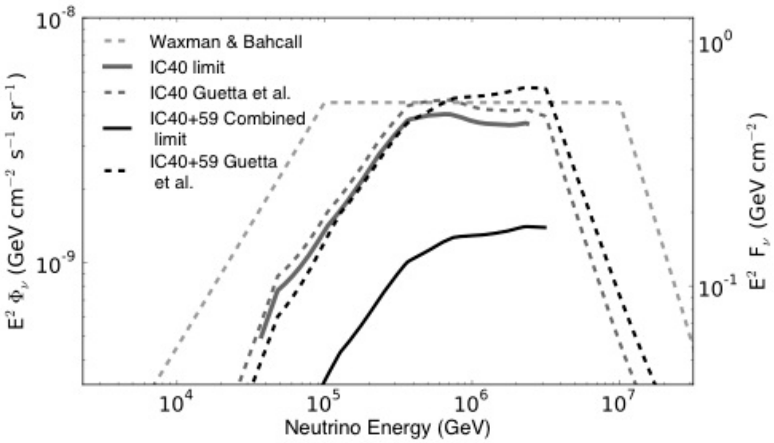
- ICMART radius is at $R = \Gamma^2 c\, \delta t_{\rm slow} > \Gamma^2 c\, \delta t_{\rm min}$
- $f_{\gamma/p} = L_\gamma / L_p$ can be $= \varepsilon_e / \varepsilon_p \sim 0.1$ (no pair) or > 0.1 (pair-rich dissipation)
- GRBs can either be or not be dominant UHECR sources



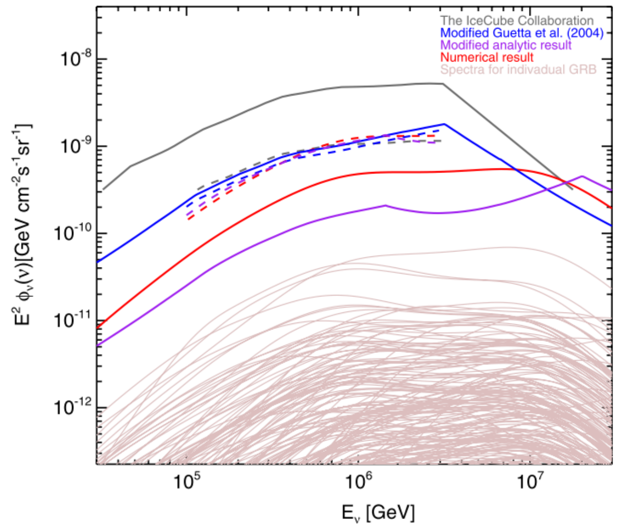
H. Gao et al. 2012

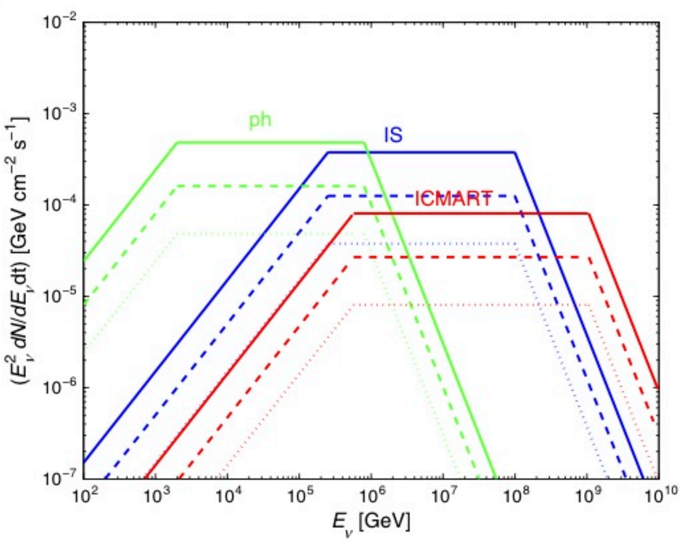
Zhang & Yan 2011

Non-detection of neutrinos by Icecube

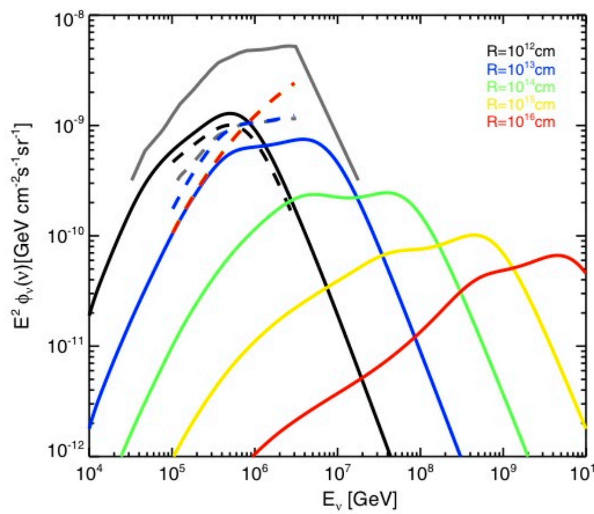


IceCube (2012) results





Zhang & Kumar (2013)



He et al. (2012)

Latest Constraints from the IceCube Team

THE ASTROPHYSICAL JOURNAL LETTERS, 805:L5 (7pp), 2015 May 10 AARTSEN ET AL.

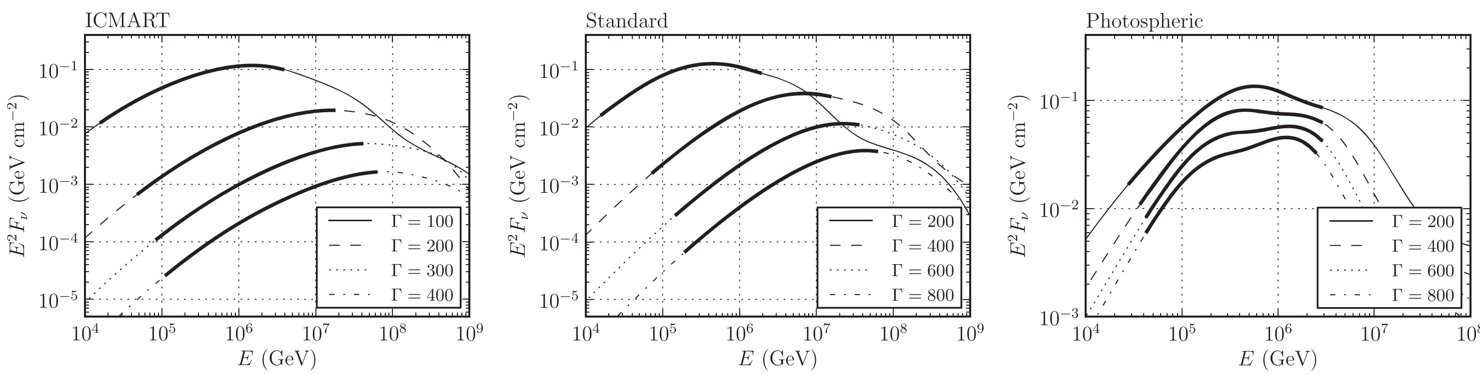


Figure 2. Total predicted neutrino fluence for various values of the bulk Lorentz factor Γ under different model assumptions. Bold lines reflect the energy region in which 90% of events are expected based on simulation. Normalization scales linearly with the assumed baryonic loading f_p, which is set here to 10. Models are arranged from left to right in order of increasing predicted fluence for given values of f_p and Γ.

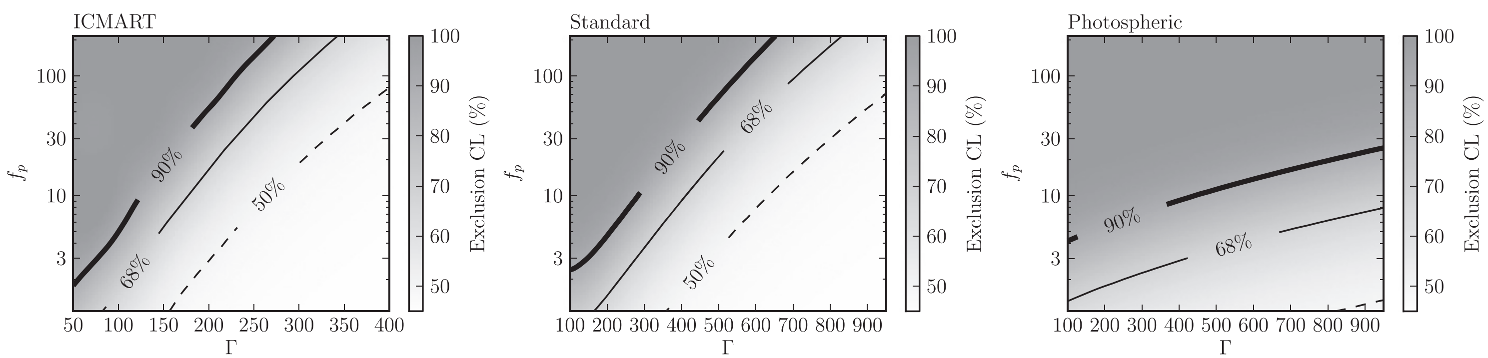


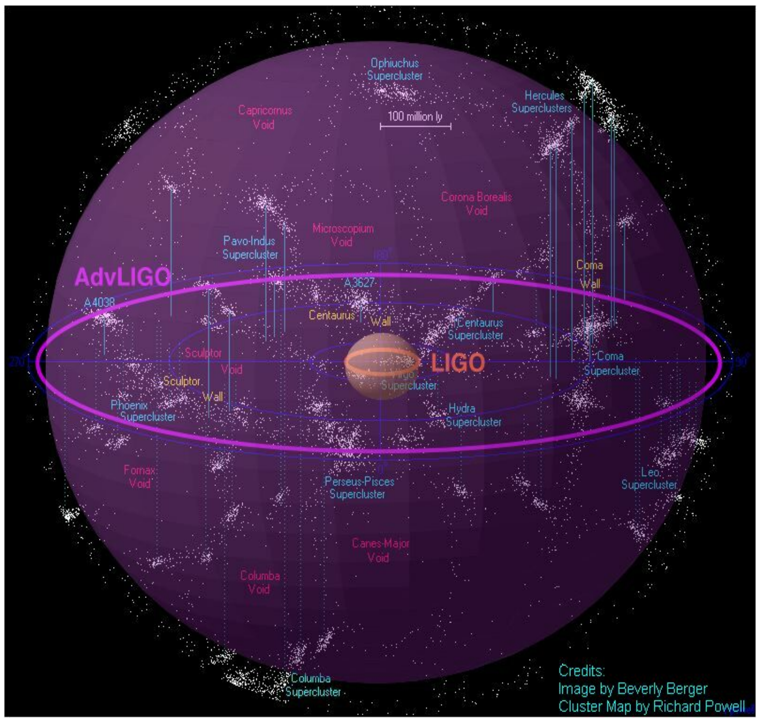
Figure 3. Allowed region for the baryonic loading f_p and bulk Lorentz factor Γ under different model assumptions.

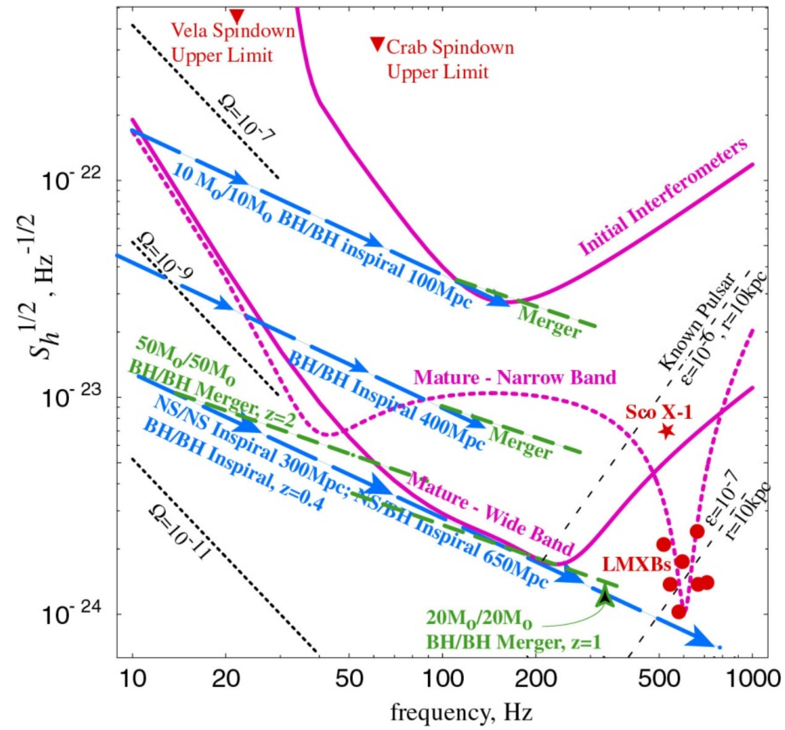
Aartsen et al. 2015, ApJL, 805, L5

Topic 2:

Electromagnetic counterparts of kHz gravitational wave sources

Detection of gravitational wave is around the corner

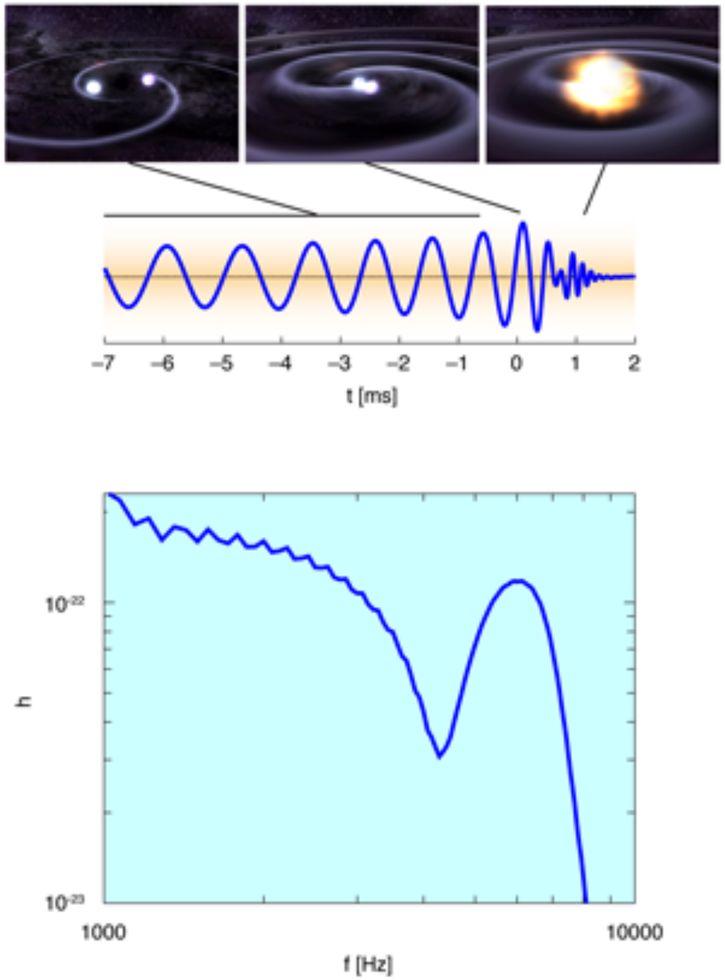




NS+NS $\sim 300 Mpc \, (z \approx 0.1)$

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

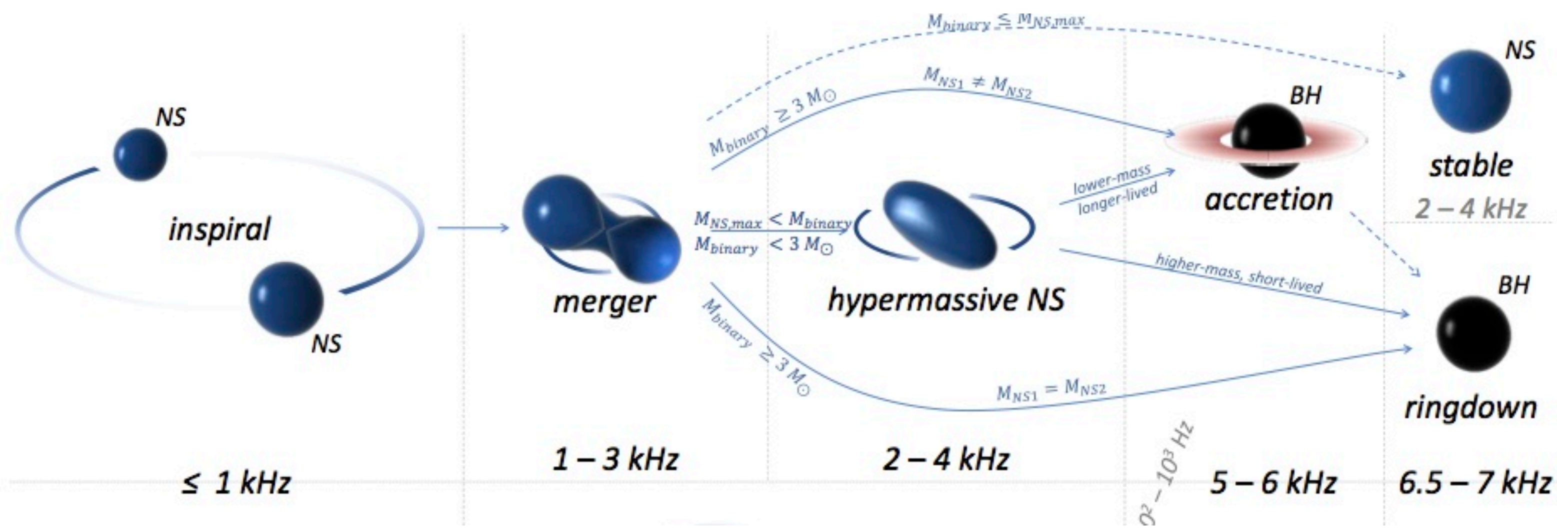
Top candidate of GW sources: NS-NS mergers



- Known systems in the Galaxy
- Indirect evidence of GW emission from PSR 1913+16 system
- Well studied "chirp" signals (short duration of detected signal – GW bursts or GWBs)
- What EM signals accompany with these events?

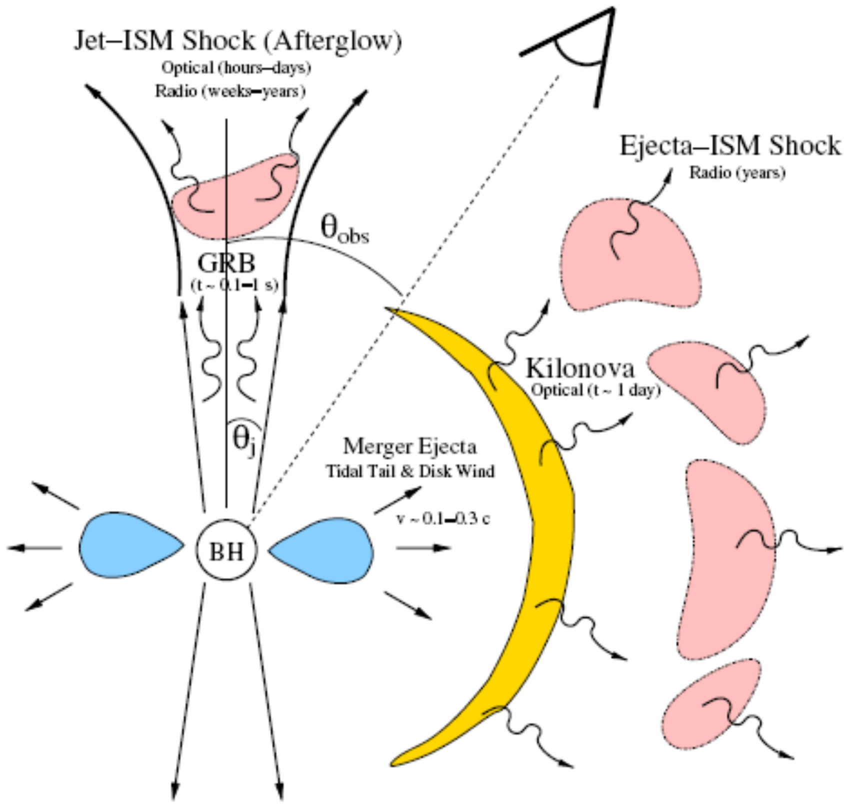
http://physics.aps.org/articles/v3/29 (adapted from Kiuchi et al. 2010, PRL, 104, 141101)

Possible NS-NS merger products: BH vs. millisecond magnetar



Bartos, I., Brady, P., Marka, S. 2012, arXiv:1212.2289

EM signals
for a BH post-merger product



Metzger & Berger (2012)

SGRB

Multi-wavelength afterglow
~hours, days

Li-Paczyński Nova
(Macronova, Kilonova)

Li & Paczyński, 1998

Opical flare
~ 1 day

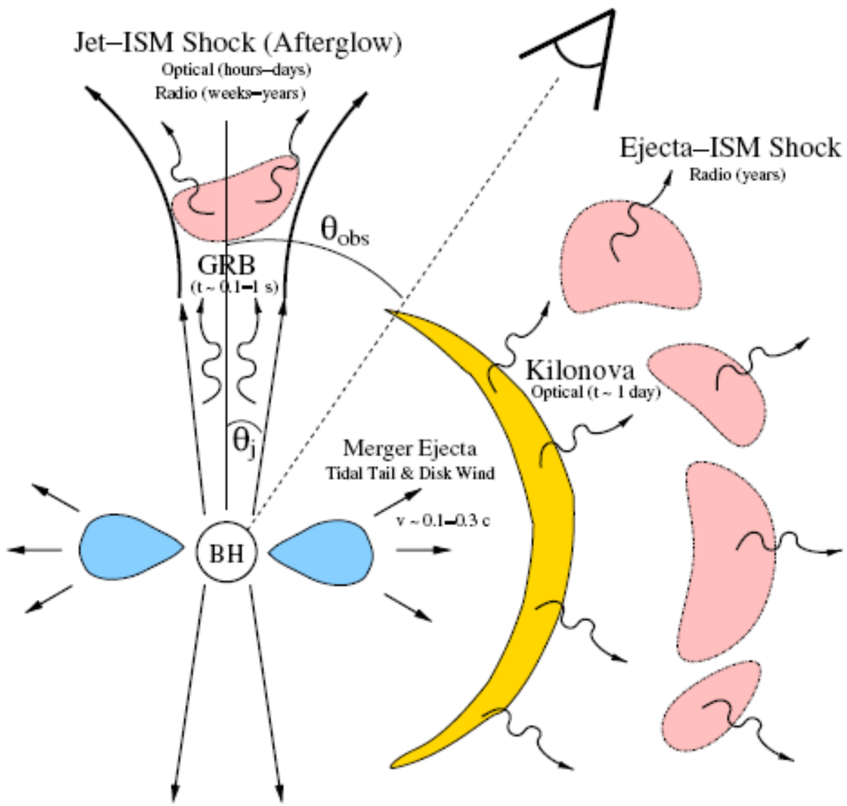
Ejecta-ISM interaction shock

Nakar& Piran, 2011

Radio
~years

Talks by Li & Ioka

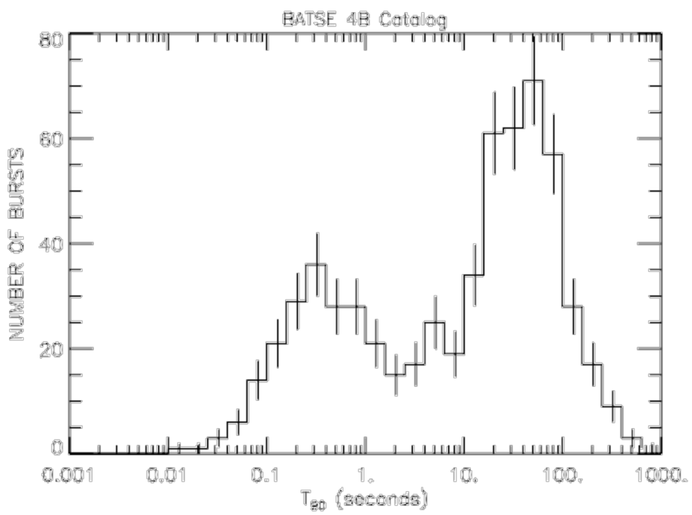
Short GRBs as GWB EM counterpart: issues

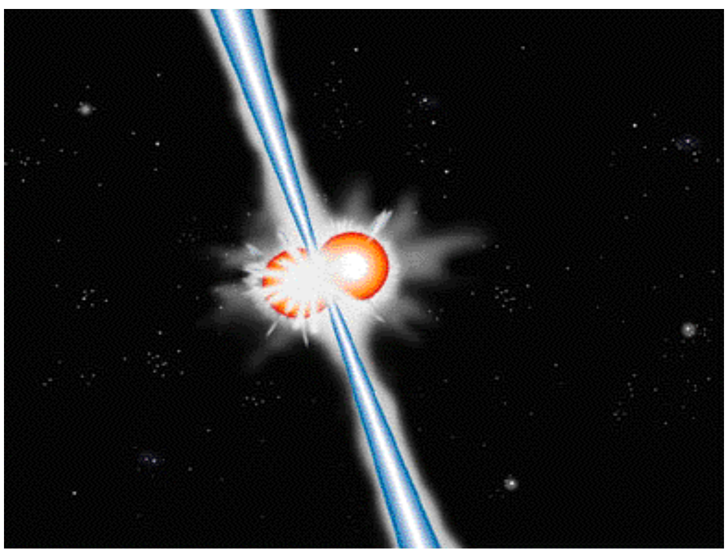


- Observationally, NS-NS origin of short GRBs is not firmly established: the NS-NS model cannot simultaneously interpret the BATSE and Swift short GRB data (Virgili et al. 2012)

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

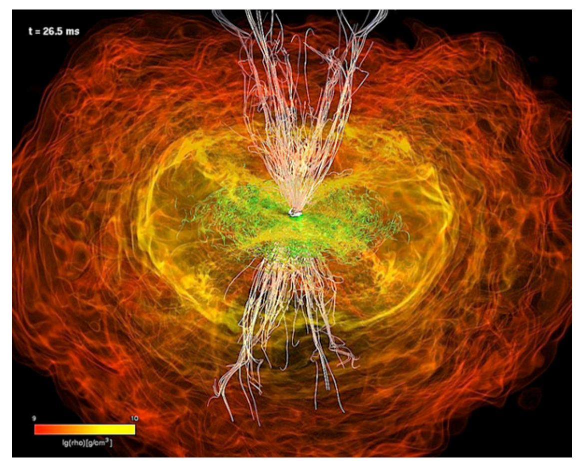
Short GRBs
Issue: Beamed





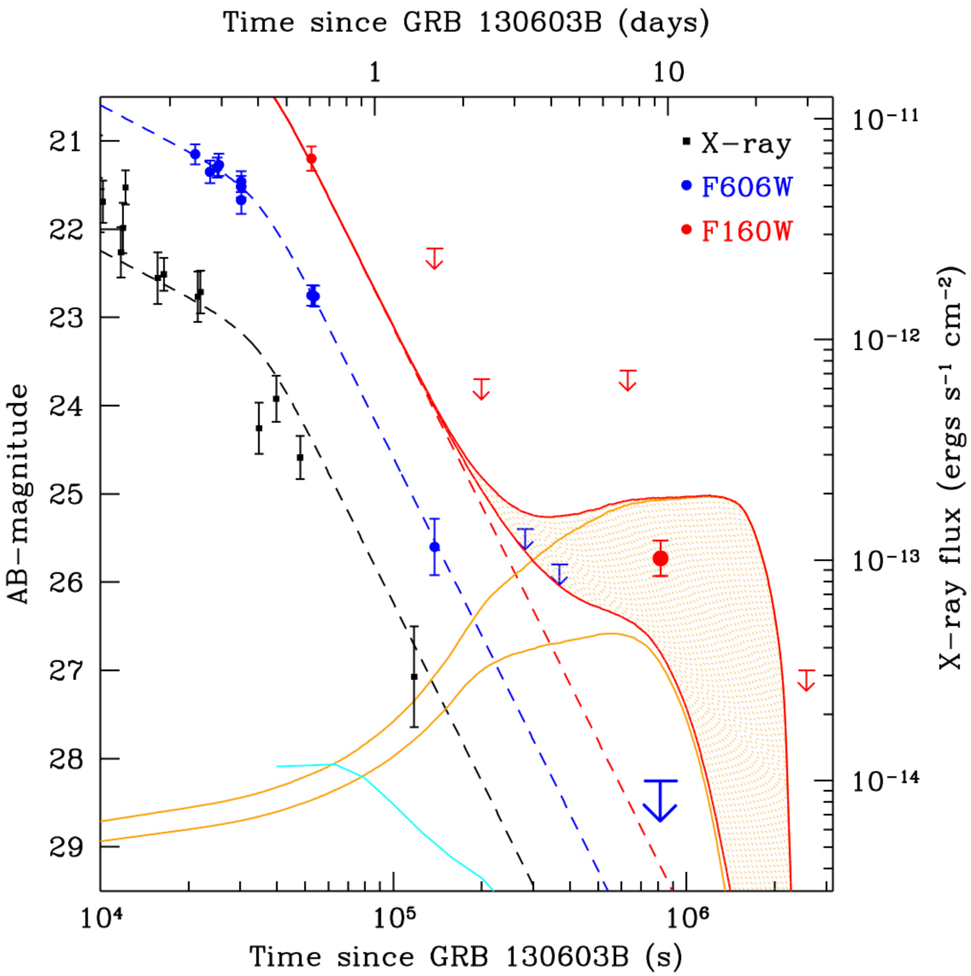
- In different types of host galaxies, including a few in elliptical/early-type galaxies, but most in star-forming galaxies
- Large offsets, in regions of low star formation rate in the host galaxy. Some are outside the galaxy.

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



Rezzolla et al. 2011

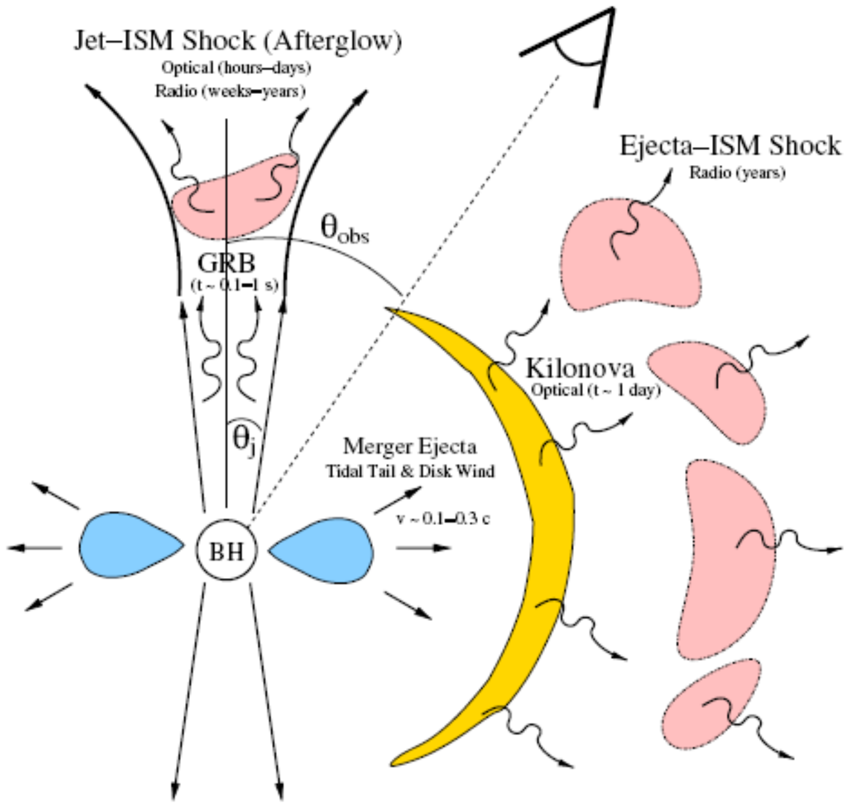
Kilo-novae: faint, in IR?



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?

Kilo-novae and radio afterglow: Too faint to detect



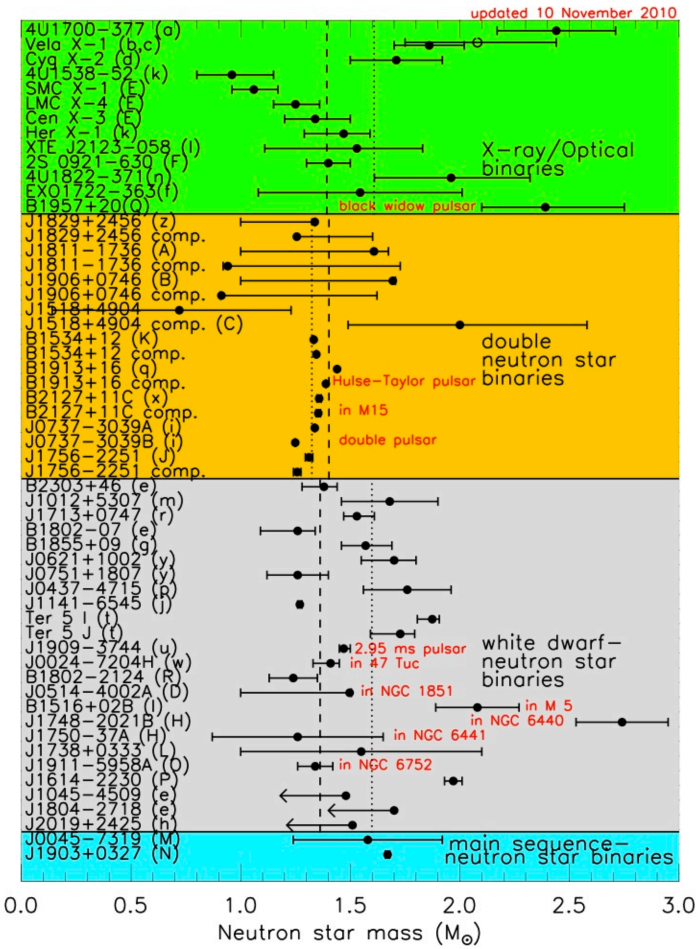
- Li-Paczynski novae: 1-day V-band luminosity: 3×10^{41} erg/s (Metzger et al. 2010): 3-5 orders of magnitude fainter than GRB afterglow
- Radio afterglow (Nakar & Piran): bright enough when n=1 cm^{-3}. For mergers, one expects n ~ 10^{-3} – 10^{-4} cm^{-3}, then radio afterglow not detectable

Observational hints of a magnetar as the post-merger product (I)

- NS with mass > 2 $M_{\odot}$ has been discovered
- NS-NS systems: total mass can be below ~ 2.6 $M_{\odot}$

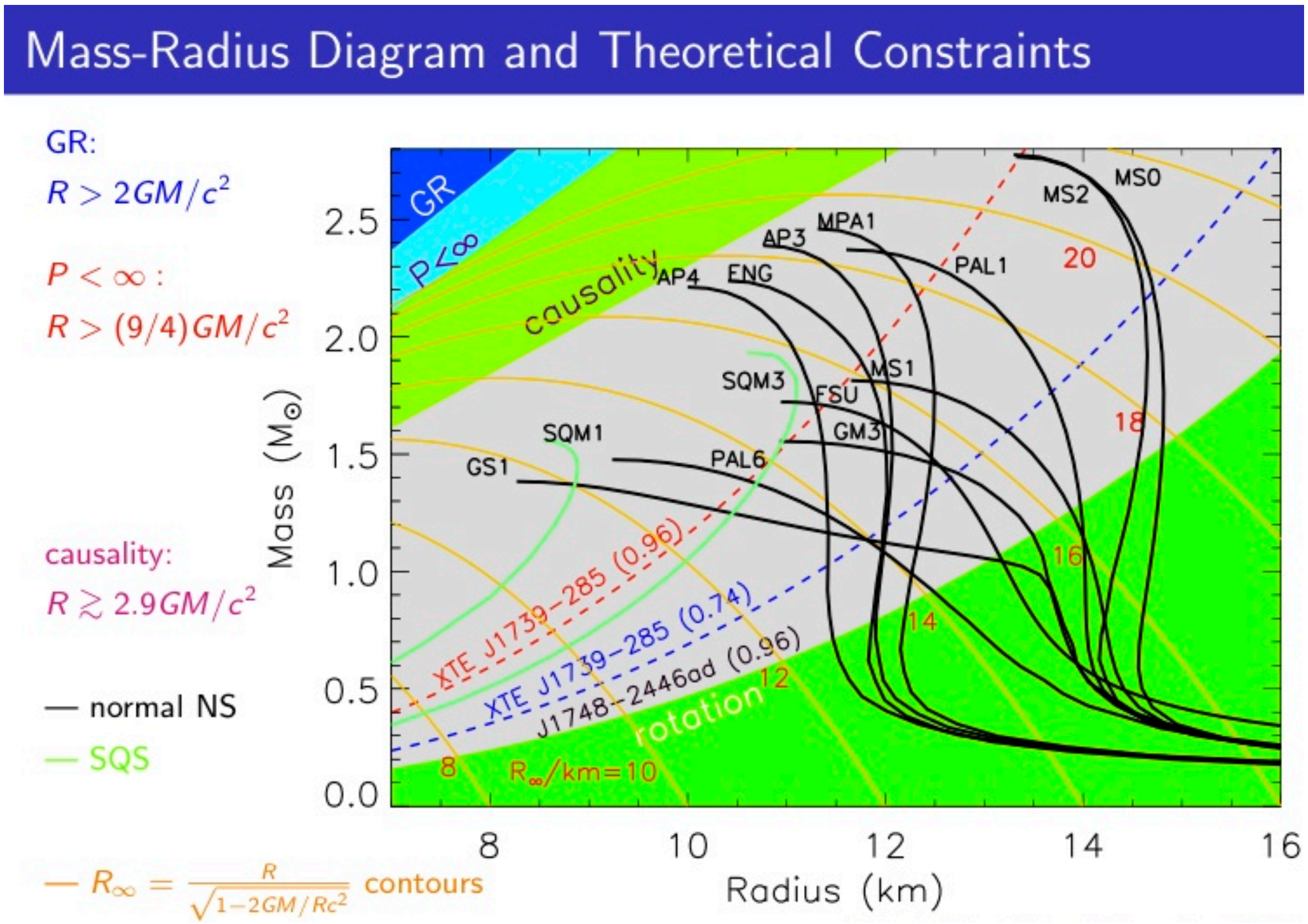
Neutron Star – Neutron Star Binaries (mean = 1.325 $M_{\odot}$, weighted mean = 1.403 $M_{\odot}$)

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 magnetar as the post-merger product (I)

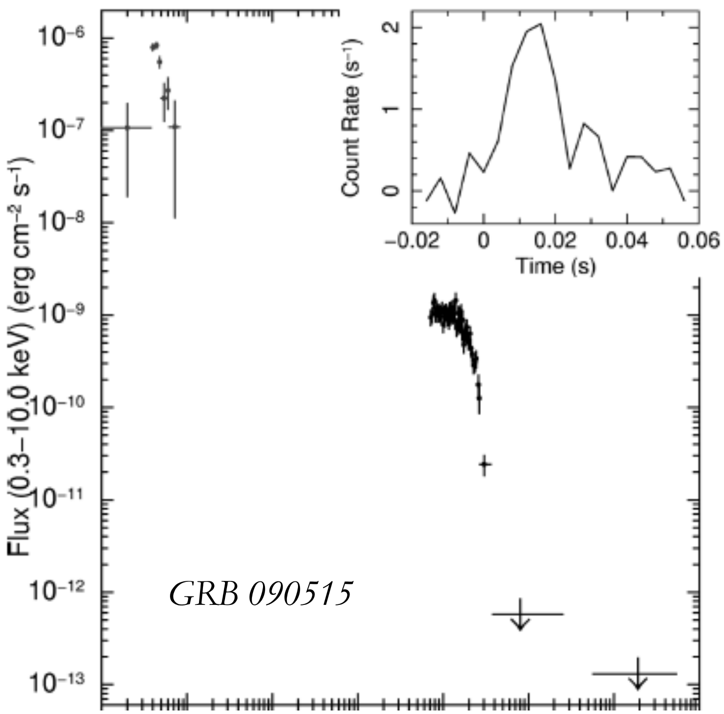


Lattimer (2012)

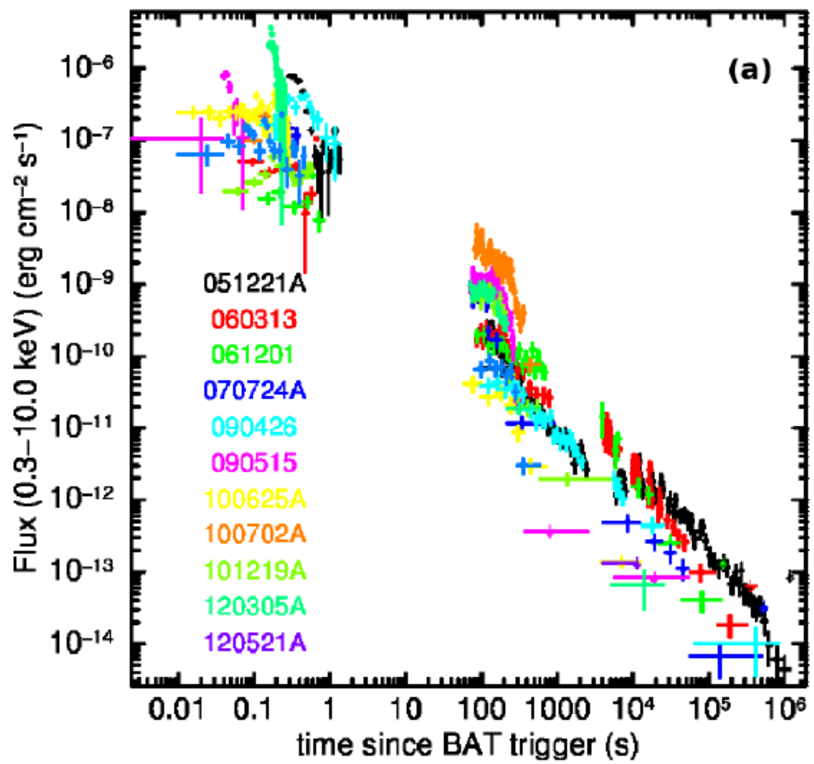
Stiff equation-of-state: maximum NS mass close to 2.5 $M_\odot$

Observational hints of a magnetar as the post-merger product (2)

- X-ray plateaus in some short GRB afterglows



Rowlinson et al. (2010)



Rowlinson et al. (2013)

Additional energy budget from the magnetar: the spin energy

$$E_{rot} = 2\times10^{52}\ erg\, I_{45} P_{0,-3}^{-2}$$

$$L_{sd,0} = 10^{49}\ erg\, s^{-1} B_{p,15}^{2} R_6^6 P_{0,-3}^{-4}$$

$$T_{sd} = \frac{E_{rot}}{L_{0,sd}} \sim 10^{3}\ s\, I_{45} B_{p,15}^{-2} R_6^{-6} P_{0,-3}^{2}$$

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

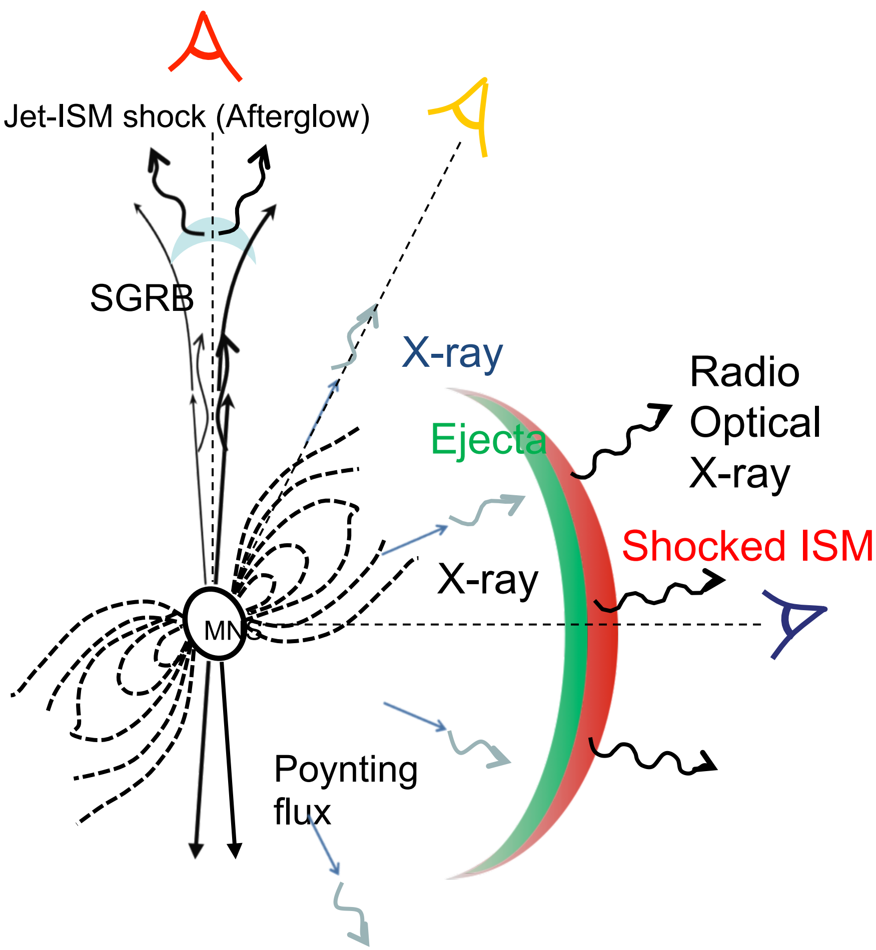
A huge energy budget: released in the EM form in different channels

Early EM signals from 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)

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

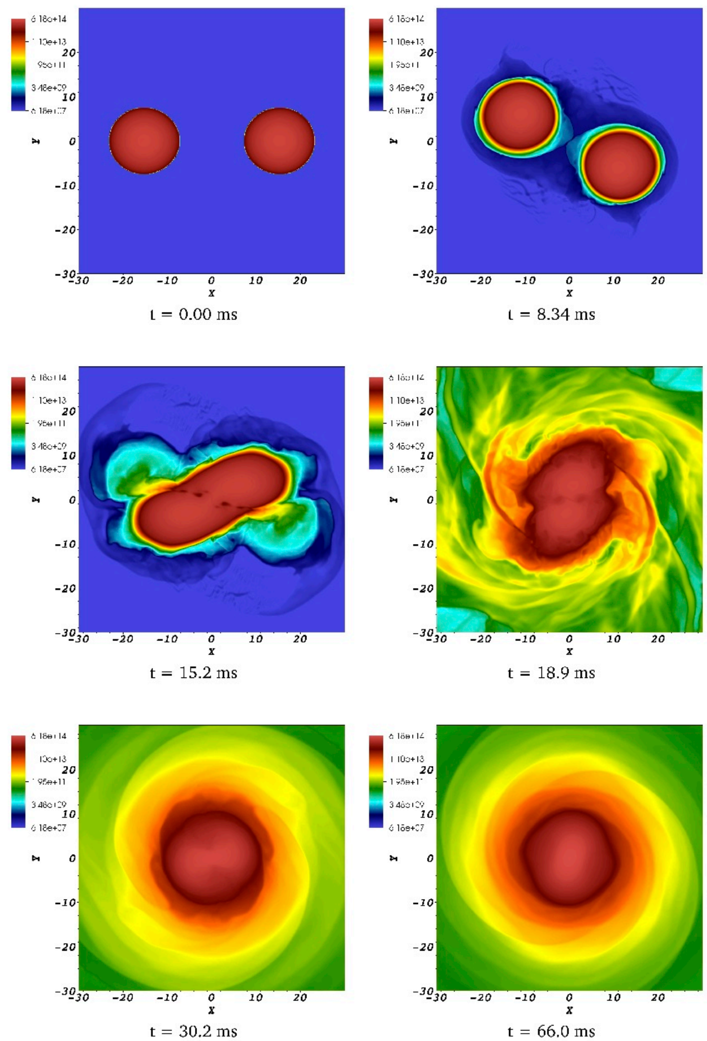
Ejecta-ISM interaction with continuous energy injection

Multi-band transient

~hours, days, weeks, or even years

Gao et al, 2013

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



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

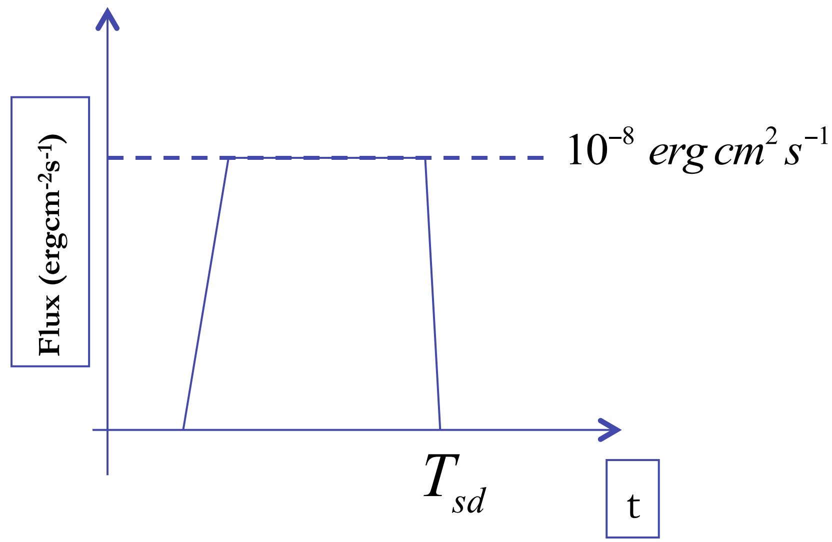
Giacomazzo & Perna (2013)

Bright early X-ray Afterglow from NS-NS mergers

Zhang, 2013, ApJ, 763, L22

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

$$E_p \sim 5\,{\rm keV}\, L_{w,49}^{1/4} (R/(3\times10^{10}\,{\rm cm}))^{-1/2}$$



The proto-magnetar would eject a wide-beam wind, whose dissipation would power an X-ray afterglow as bright as~ **$(10^{-8}$–$10^{-7})$ 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.*

Enhanced (Magnetar powered) Merger Novae

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

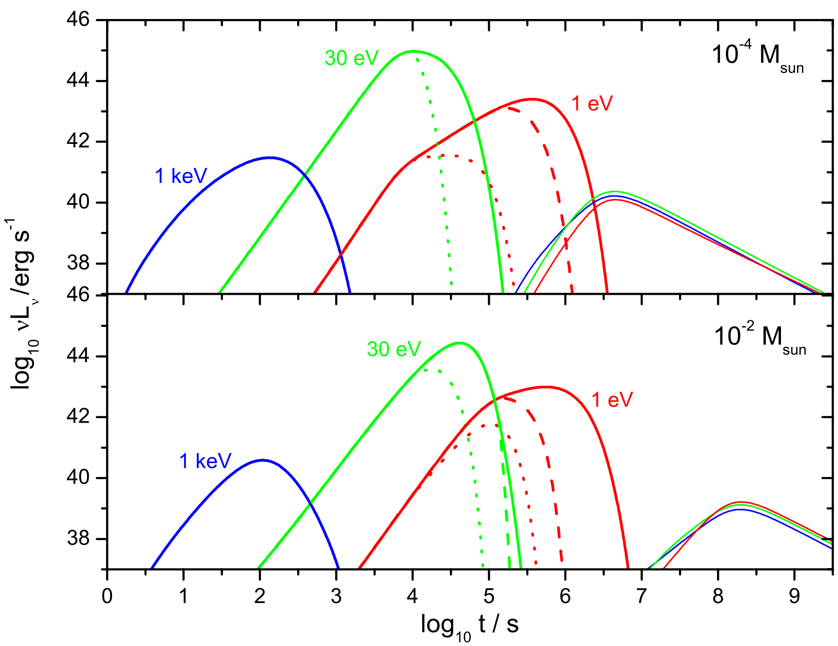


Figure 2. Light curves of the merger-nova (thick) and afterglow (thin) emissions at different observational frequencies as labeled. The dashed and dotted lines are obtained for an optionally taken magnetar collapsing time as $t_{col} = 2t_{md}$ and $t_{col} = 10^4$ s, respectively. The ambient density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

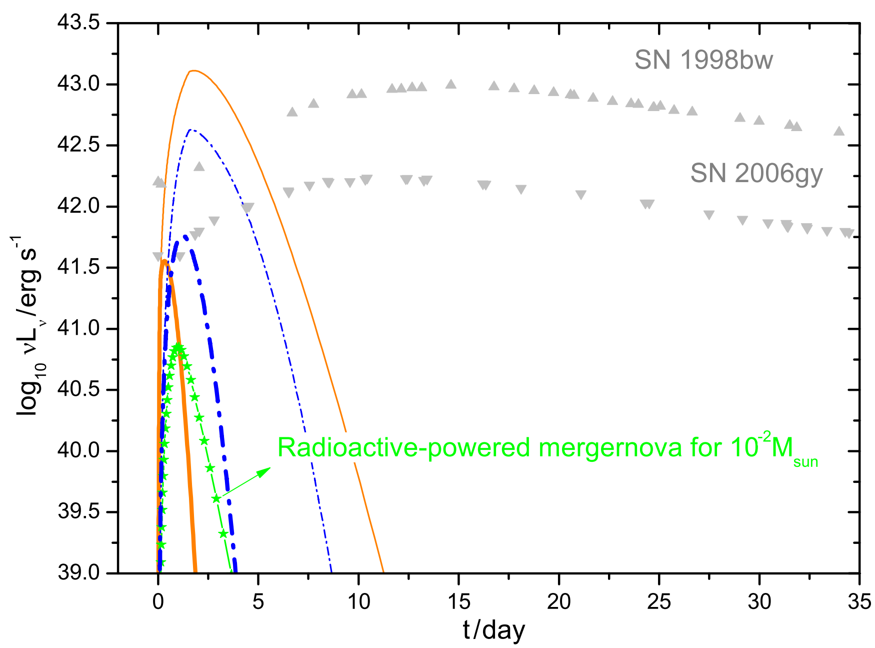


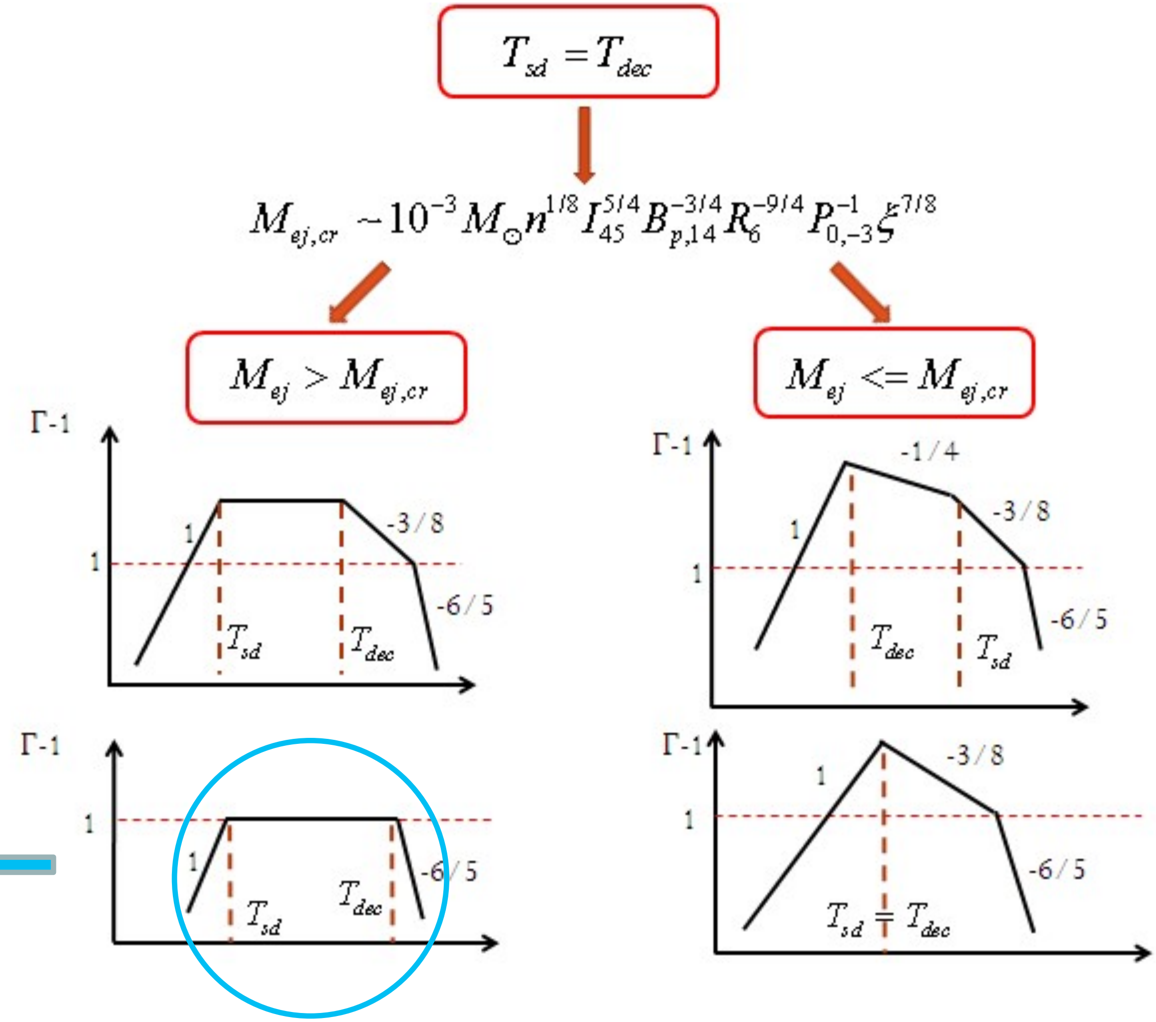
Figure 3. Optical (∼1 eV) light curves of the millisecond-magnetar-powered merger-nova, in comparison with the light curves of two supernovae (bolometric) and one radioactive-powered merger-nova (as labeled). The dash-dotted (blue) and solid (orange) lines represent $M_{ej} = 10^{-2}\ M_\odot$ and $10^{-4}\ M_\odot$, 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.

See also Metzger & Piro (2014)

Ejecta-ISM shock with Energy Injection

Gao et al. 2013, ApJ, 771, 86

Different M_{ej} leads to different dynamics cases.



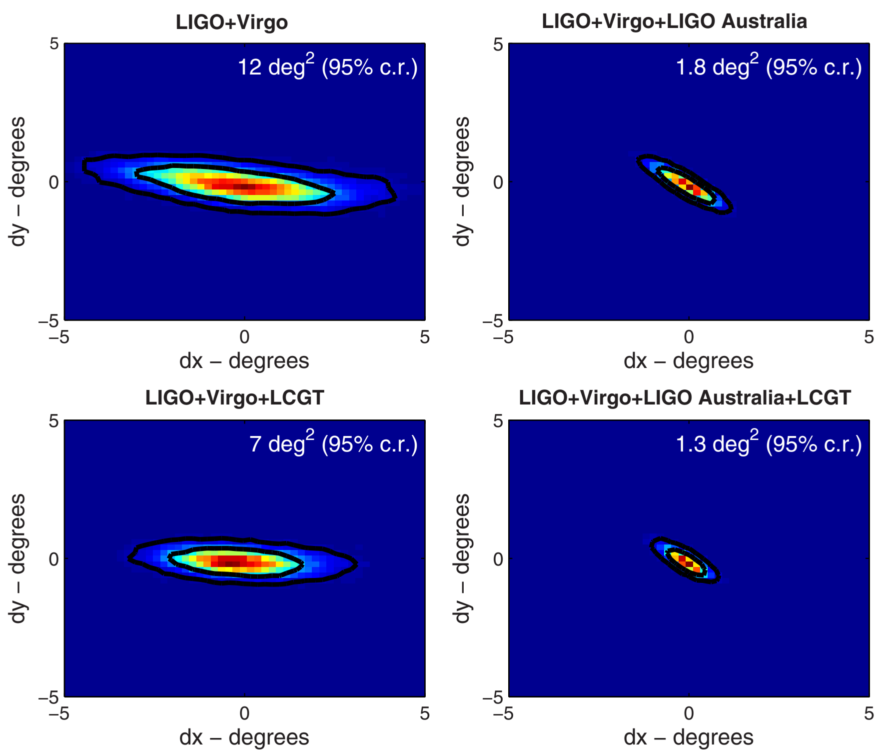
$$M_{ej,cr,2} \sim 6\times10^{-3} M_e I_{45} P_{0,-3}^{-2} \xi$$

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

Non-relativistic

Observational strategy

GWB Localization Error Box



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**

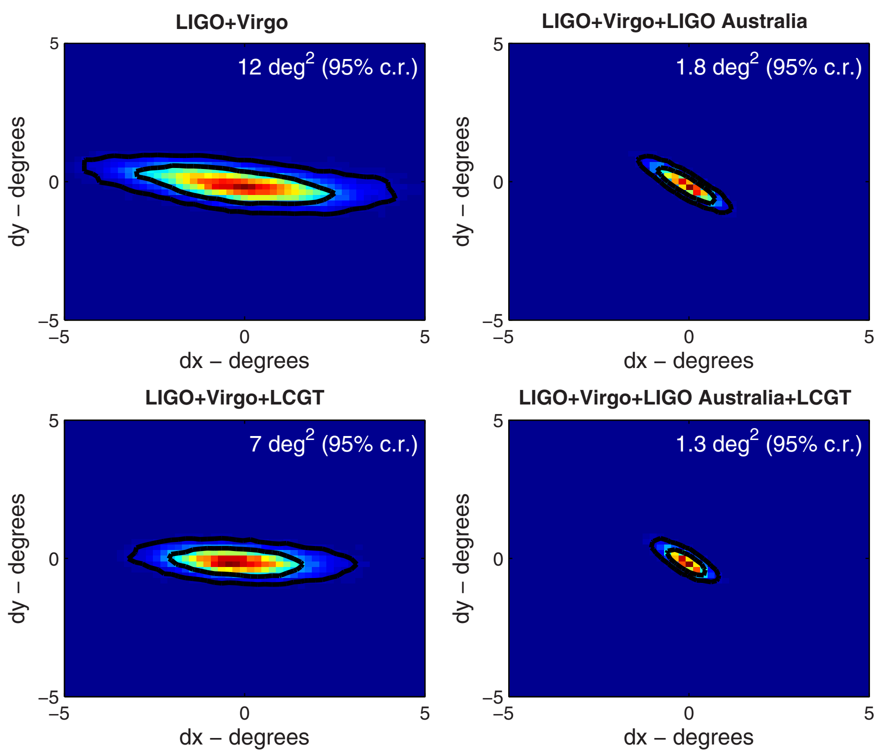
   Not easy

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, so that we do not know what fraction of NS-NS mergers will leave behind a magnetar rather than a black hole
- If a magnetar forms, essentially every one will have 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 2015
- Advanced LIGO sends an alert to the EM community about a “chirp” GWB signal
- Einstein Probe / ISS-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
- Continuously processing the GWB signal revealed a “ring-down” phase – consistent with a BH as the post-merger product
- 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 2015
- Advanced LIGO sends an alert to the EM community about a "chirp" GWB signal
- Einstein Probe / ISS-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-model 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!