# Neutrinos from NS-NS Mergers


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References


1) SSK, Murase, Meszaros, Kiuchi, 2017, ApJL, 848, L4
2) SSK, Murase, Bartos et al. 2018, PRD, 98, 043020



Collaborators

Peter Meszaros, Kohta Murase (Pennsylvania State University)
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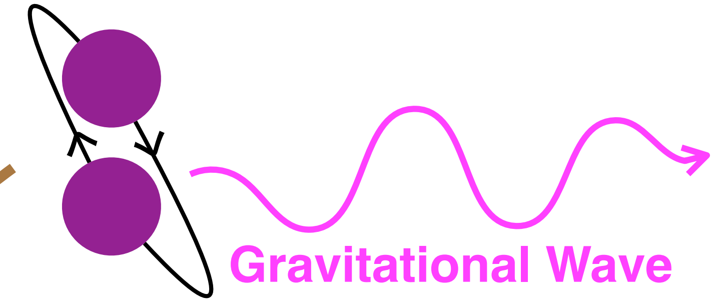
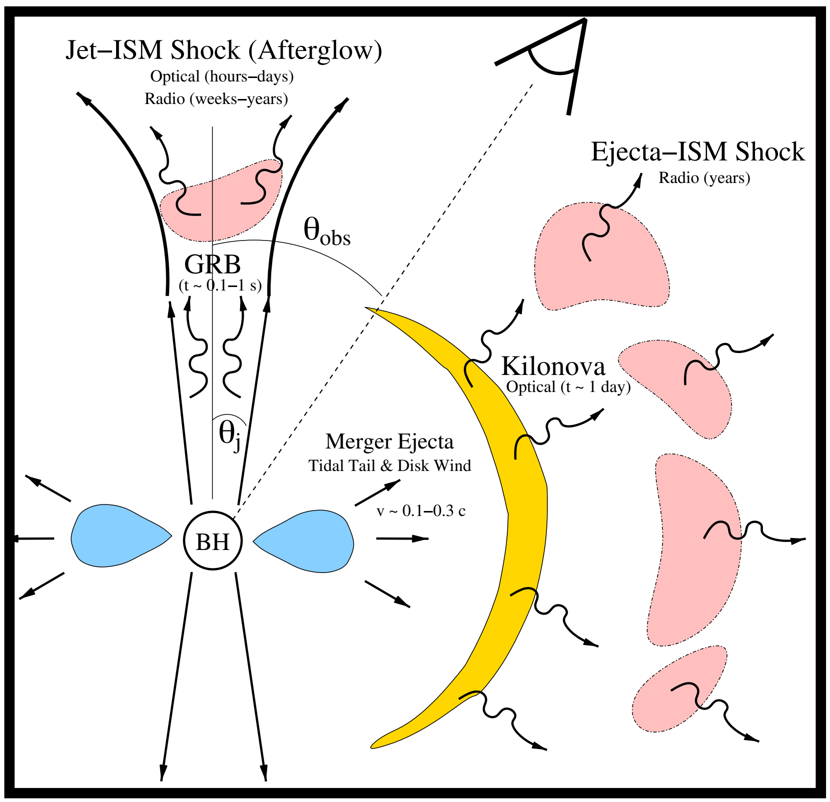
Theoretical Astrophysics
Tohoku University

# NS-NS mergers: Multi-messenger Source



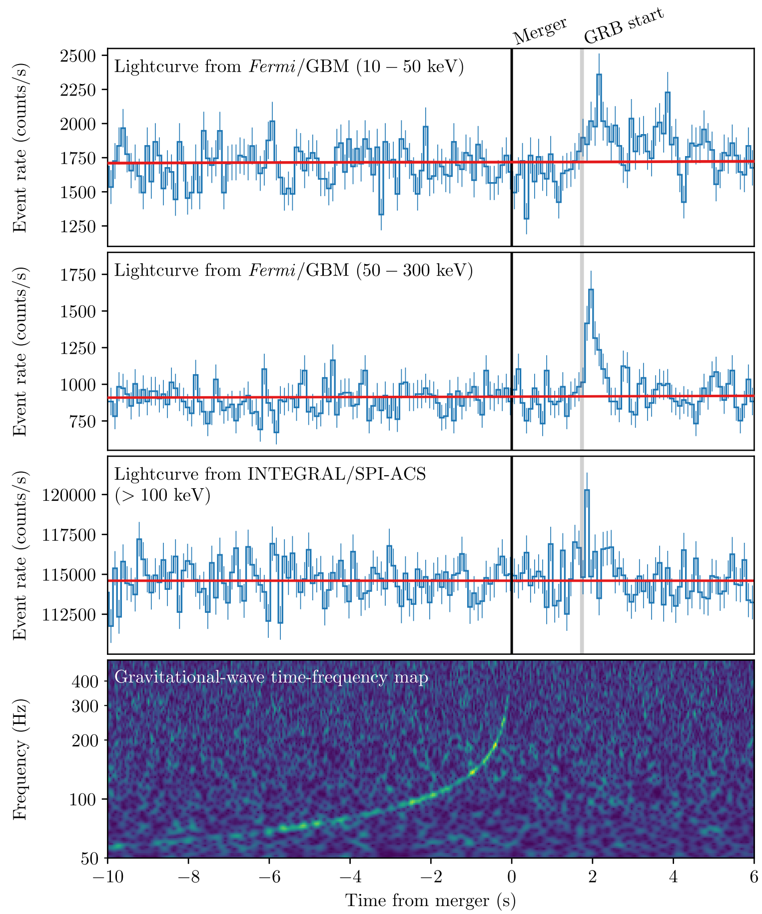

e.g.) Metzger & Berger 2012



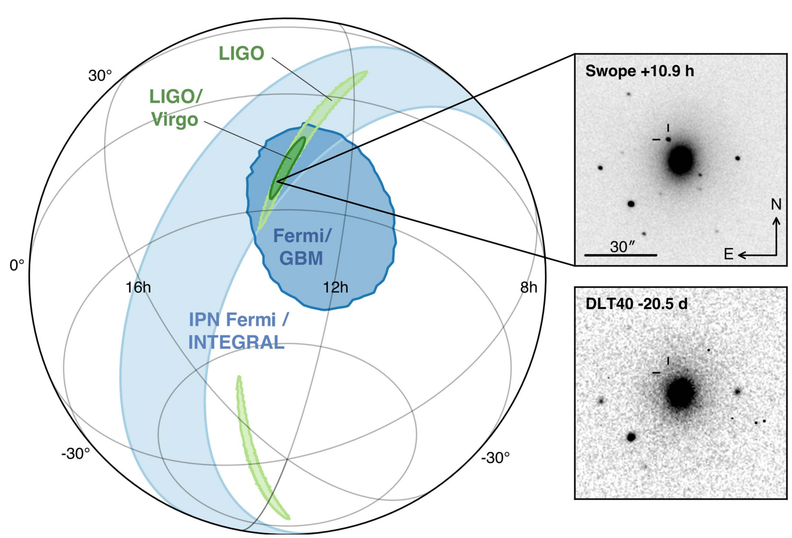

- Inspiral to merger: GW emission
- Progenitor of SGRBs: —> γ-ray, X-ray, Neutrino
- Kilonova/Macronova —> Infrared, Opt
- Afterglow —> Radio, X-ray, Cosmic-rays

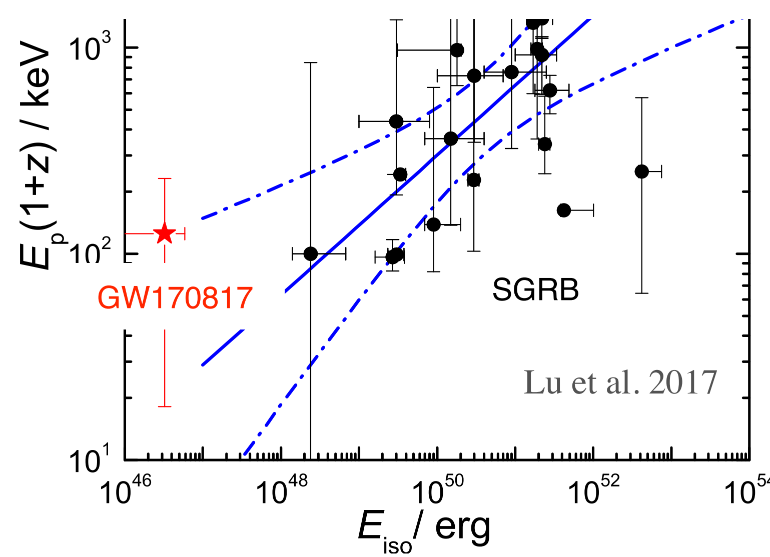
# GW170817

- The first detection of NS-NS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray
- Prompt γ-rays are faint → **low-luminosity SGRB**
- UV/Optical/IR counterpart → identify host galaxy & ejecta production



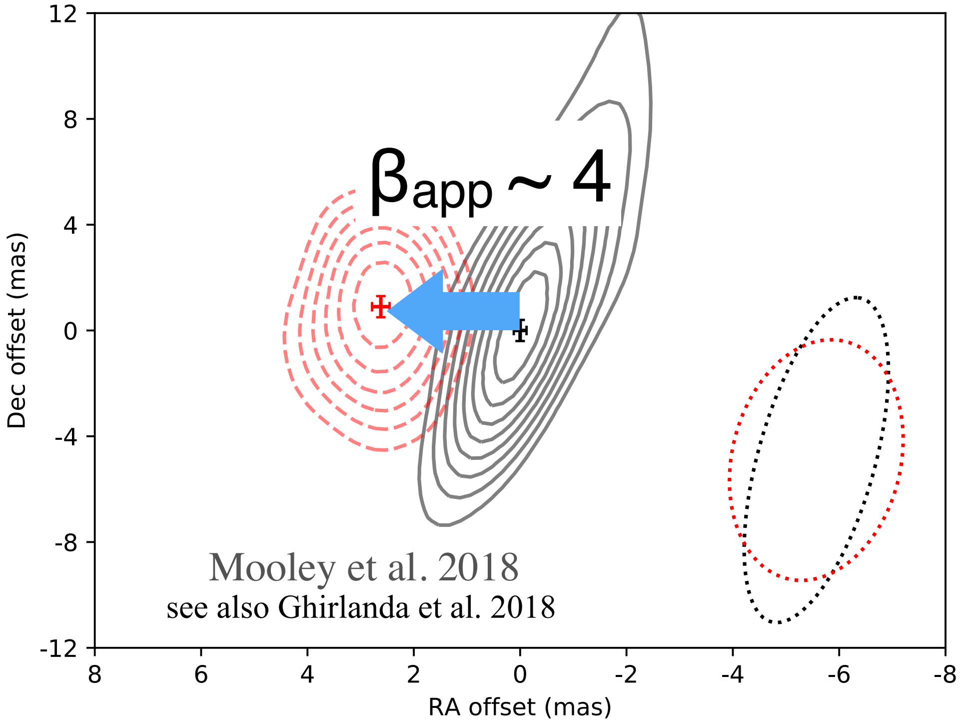

LIGO 2017 (Multi-messenger paper)

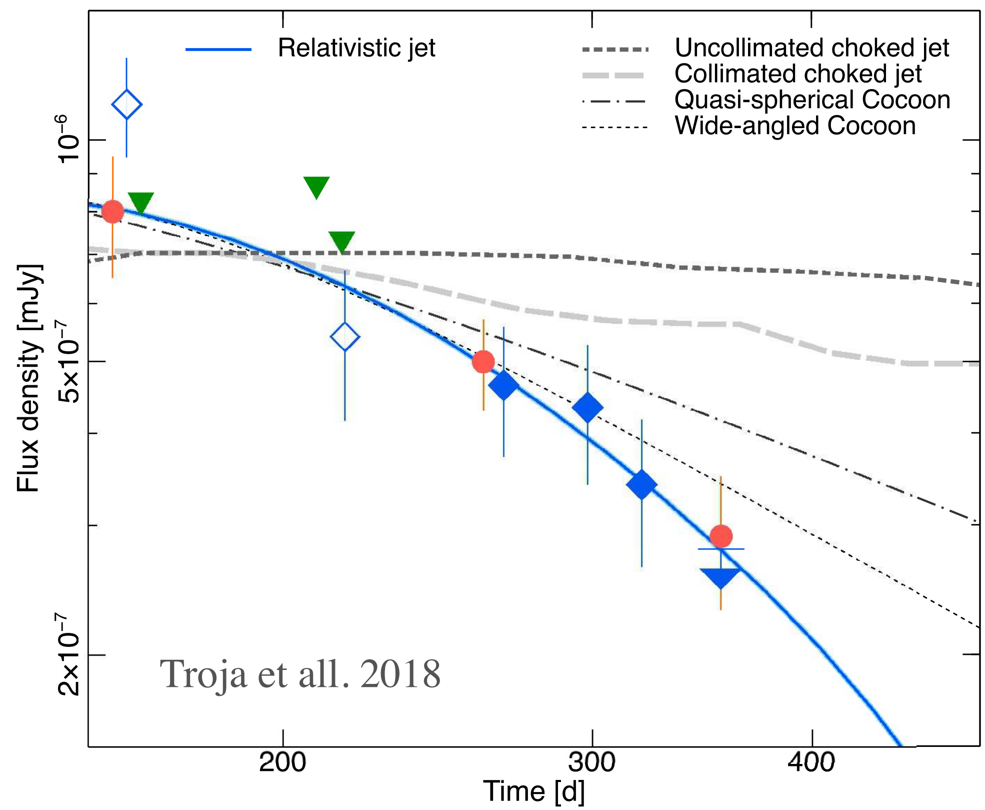


# Existence of Jet

## Superluminal motion & rapidly fading afterglow




- Superluminal motion & Rapidly declining light curve after 200 days
  —> **collimated relativistic jet**
- $E_{iso} \sim 10^{52}$ erg, $\Theta_j \sim 0.1$ rad
  —> **canonical SGRBs seen from off-axis**

# Summary of GW170817

- **First NS-NS merger seen by GWs and EMs**
- Optical/UV/IR counterparts
  —> **r-process element production**
- Radio & X-ray afterglows
  —> **NS-NS mergers create relativistic jets**

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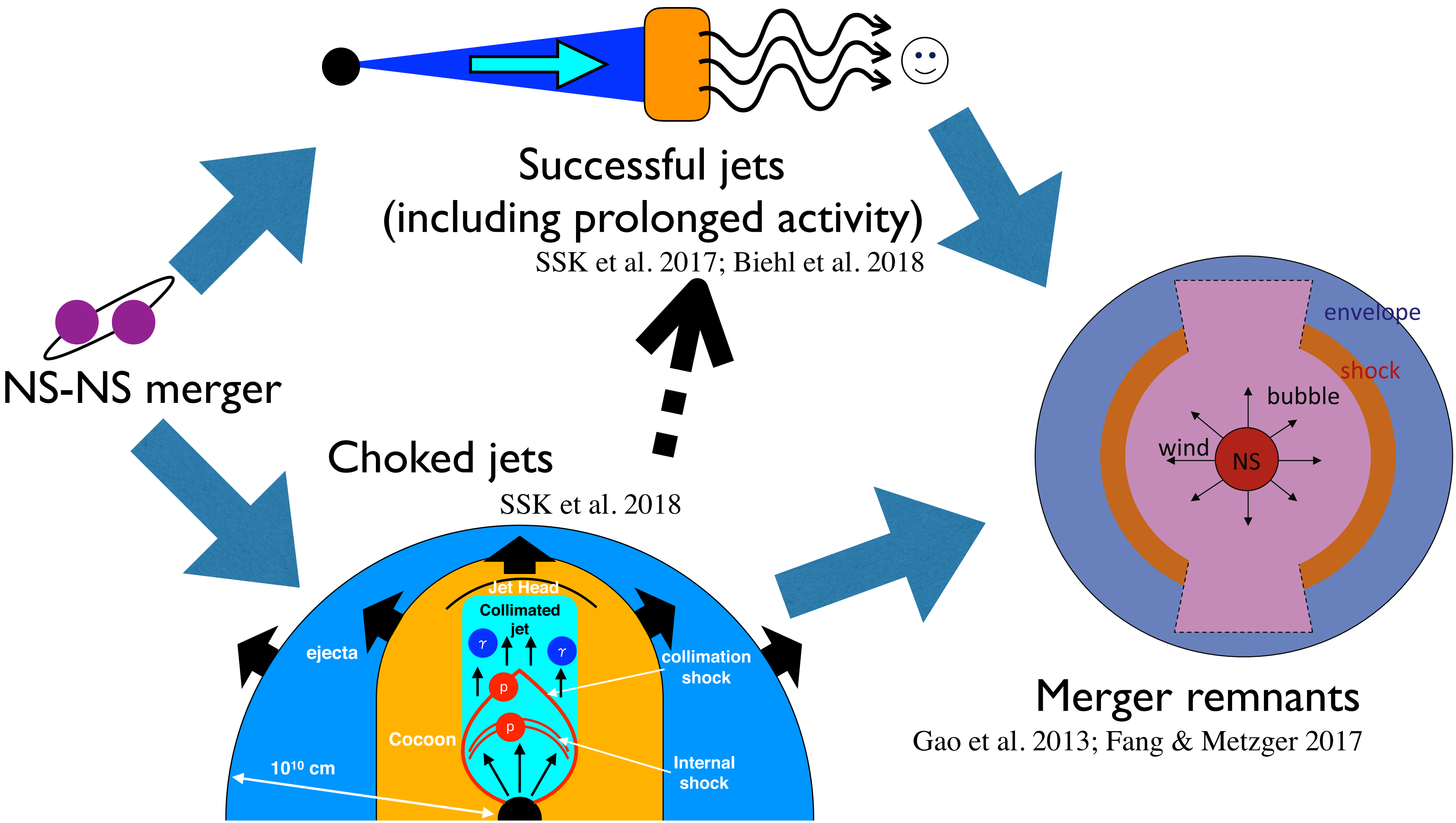
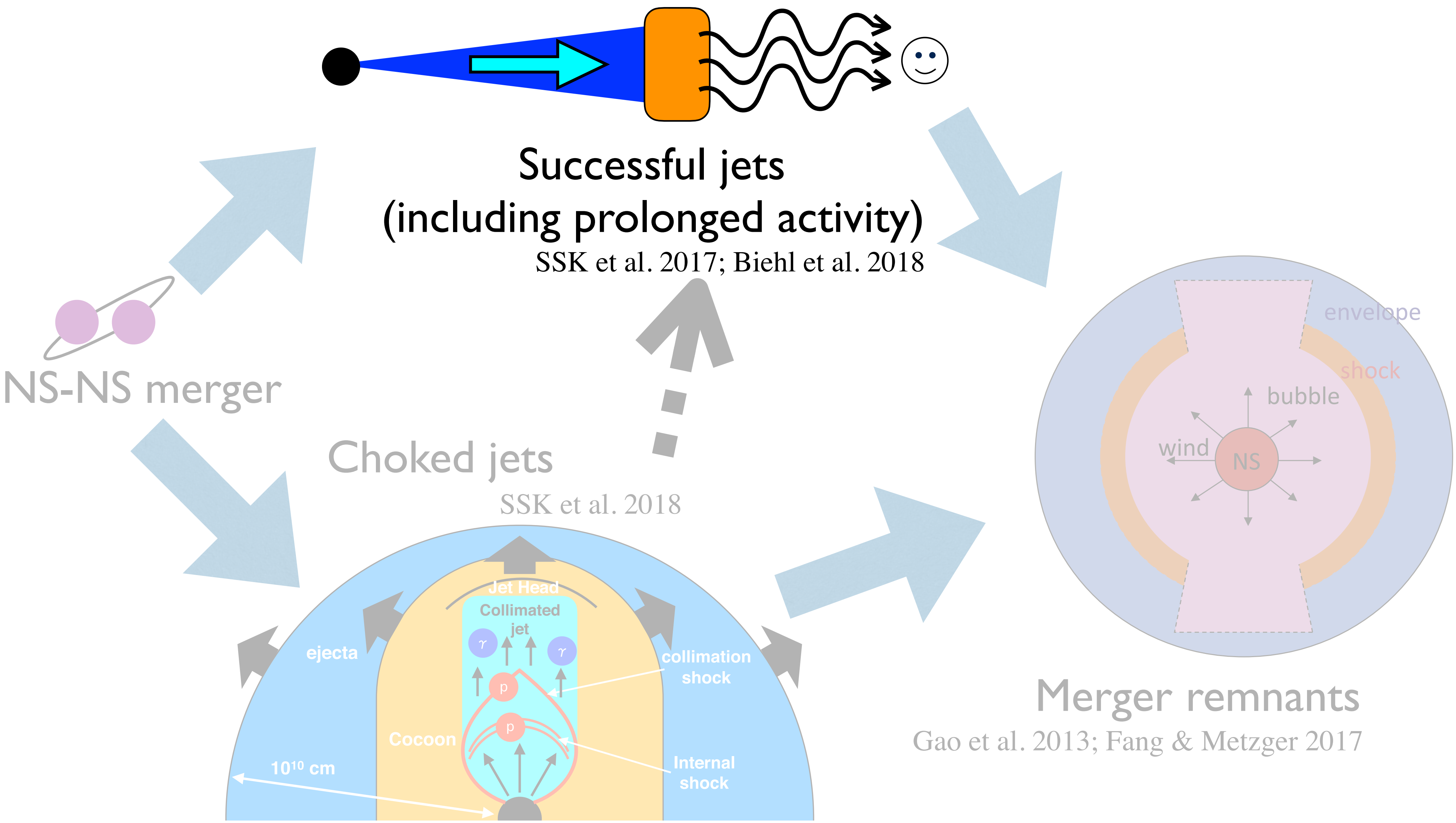
  —> **NS-NS mergers create relativistic jets**

Neutrinos were not detected
Need to discuss future prospects

# Neutrino Emission Sites

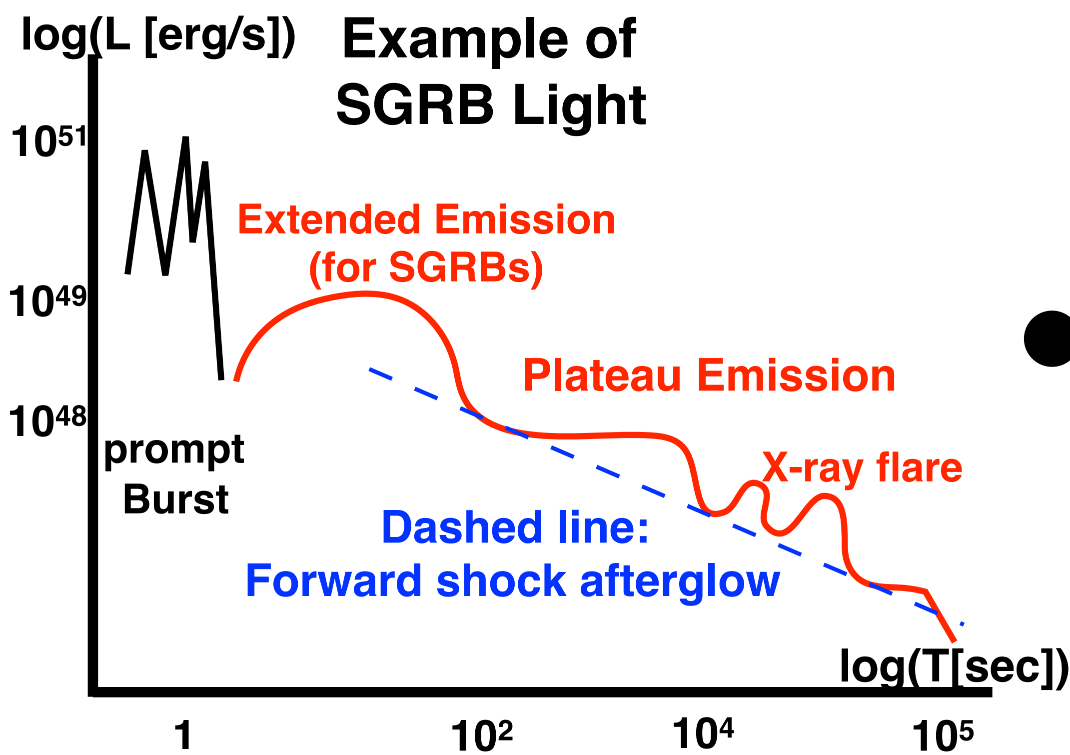


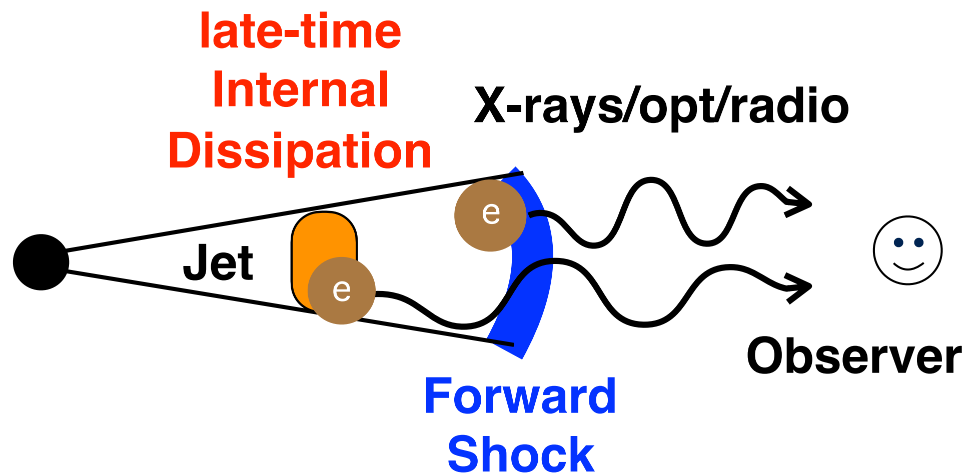
# Neutrino Emission Sites



# Successful Jets with Prolonged Activity

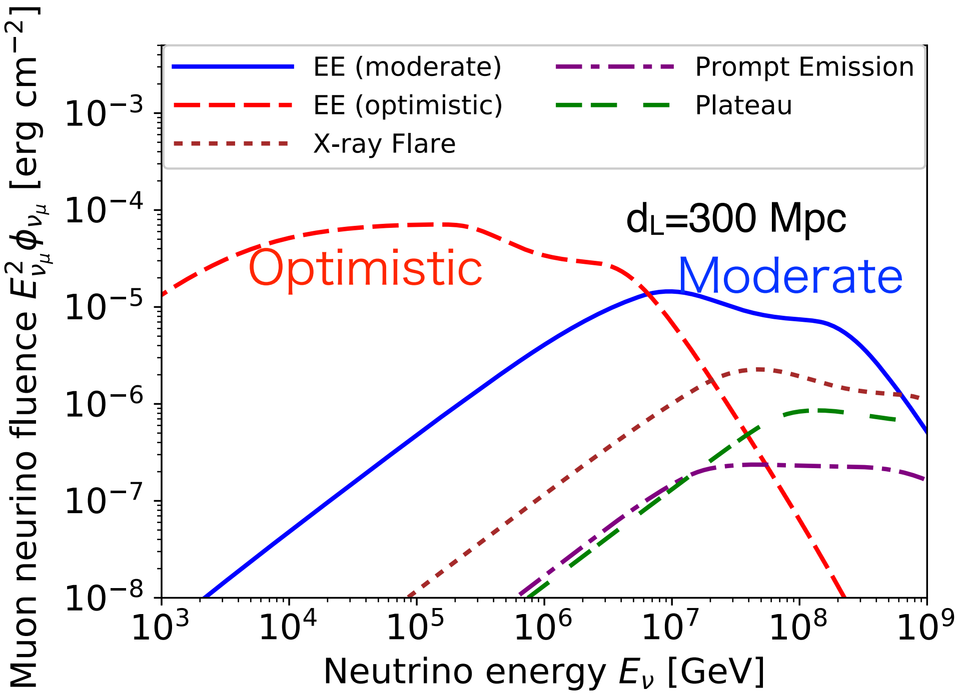
see e.g. Nakar 2007, Sakamoto et al. 2011, Kisaka et al. 2017




- Standard afterglow: Forward shock model, power-law decay
- Short-time variability, rapid decline —> **Late-time engine activity**
- Late time activities have comparable total energy to prompt burst
  **—> Short GRB is not short**

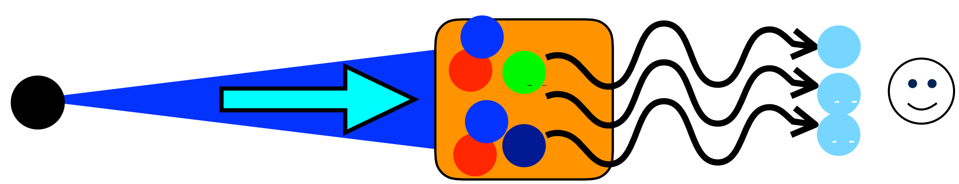
# Neutrino Fluences




| Model | EE | Plateau | Prompt | Flare |
|---|---|---|---|---|
| $\Gamma$ | 10–30 | 30 | 1000 | 30 |
| $R_{dis}$ [cm] | $10^{13}$–$10^{14}$ | $3\text{x}10^{14}$ | $3\text{x}10^{13}$ | $3\text{x}10^{14}$ |
| $E_{\gamma,pk}$ [keV] | 1—10 | 0.1 | 500 | 0.3 |
| $E_{\gamma iso}$ [erg] | $10^{51}$ | $3\text{x}10^{50}$ | $10^{51}$ | $3\text{x}10^{50}$ |

- Extended emission (EE) can produce neutrinos efficiently
- Low $\Gamma$ or low $R_{dis}$ → high photon density → high fluence $\varphi$
- Two breaks: seed photon spectrum & pion cooling

Waxman & Bahcall 1997



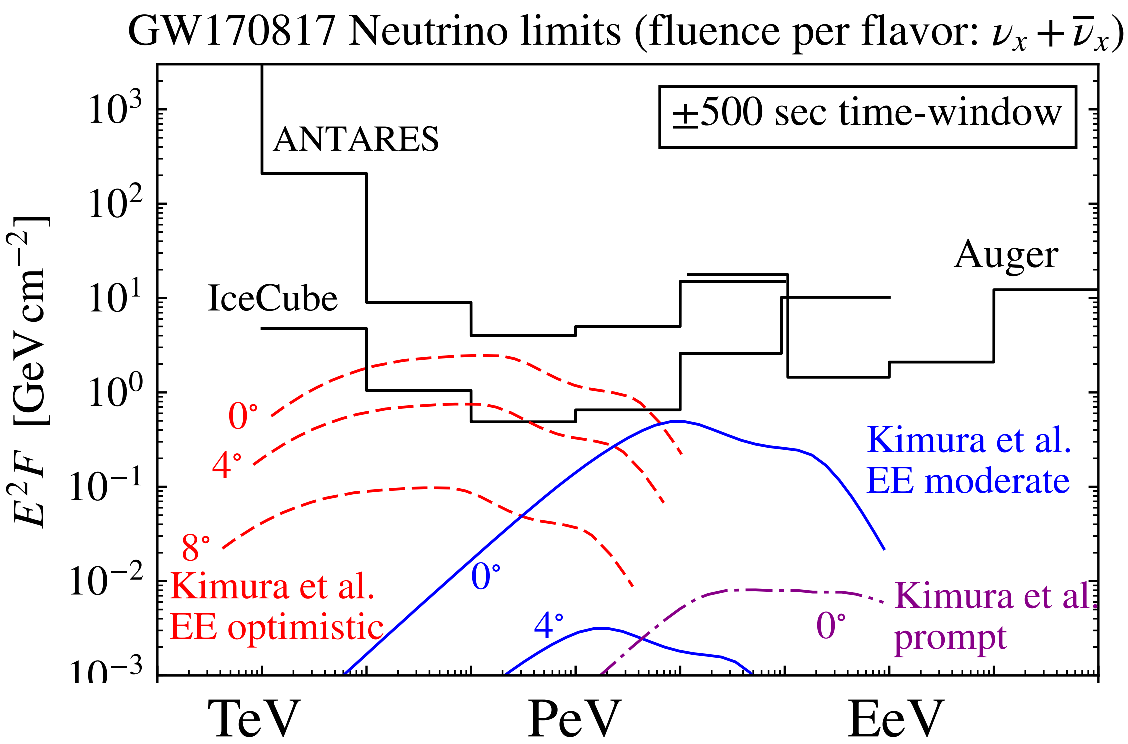
# Coincident Detection Probability with Gravitational Waves

| NS–NS ($\Delta T = 10$ years) | IC (all) | Gen2 (all) |
|---|---|---|
| EE-mod-dist-A | 0.11–0.25 | 0.37–0.69 |
| EE-mod-dist-B | 0.16–0.35 | 0.44–0.77 |
| EE-opt-dist-A | 0.76–0.97 | 0.98–1.00 |
| EE-opt-dist-B | 0.65–0.93 | 0.93–1.00 |

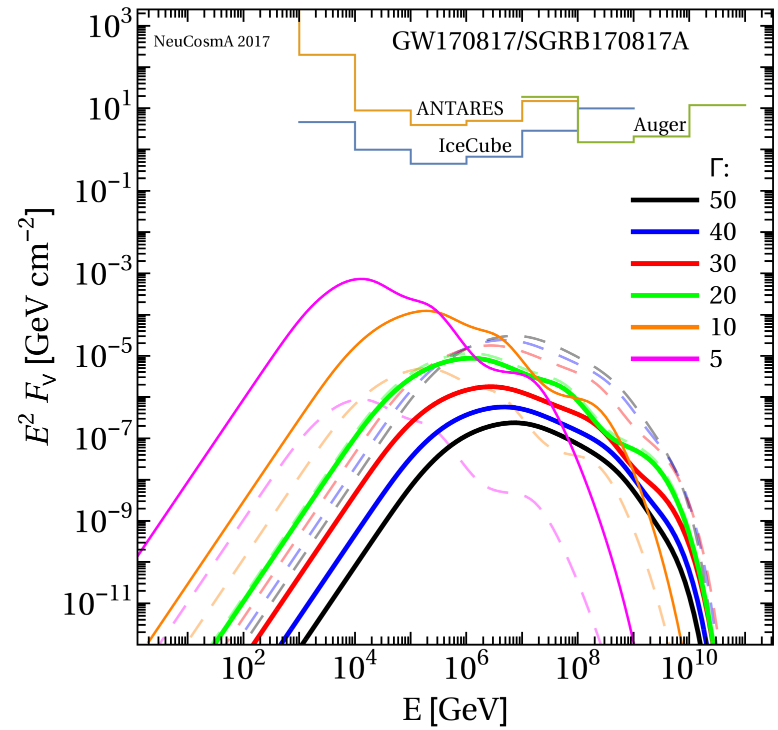
Wanderman & Piran 15, Nakar + 06

- Based on the observed SGRB rate, we estimate ν detection probability coincident with GWs
- For optimistic case, simultaneous detection of GWs and νs is highly probable even with IceCube
- Fore moderate case, IceCube-Gen2 is likely to detect neutrinos

# Implications from GW170817



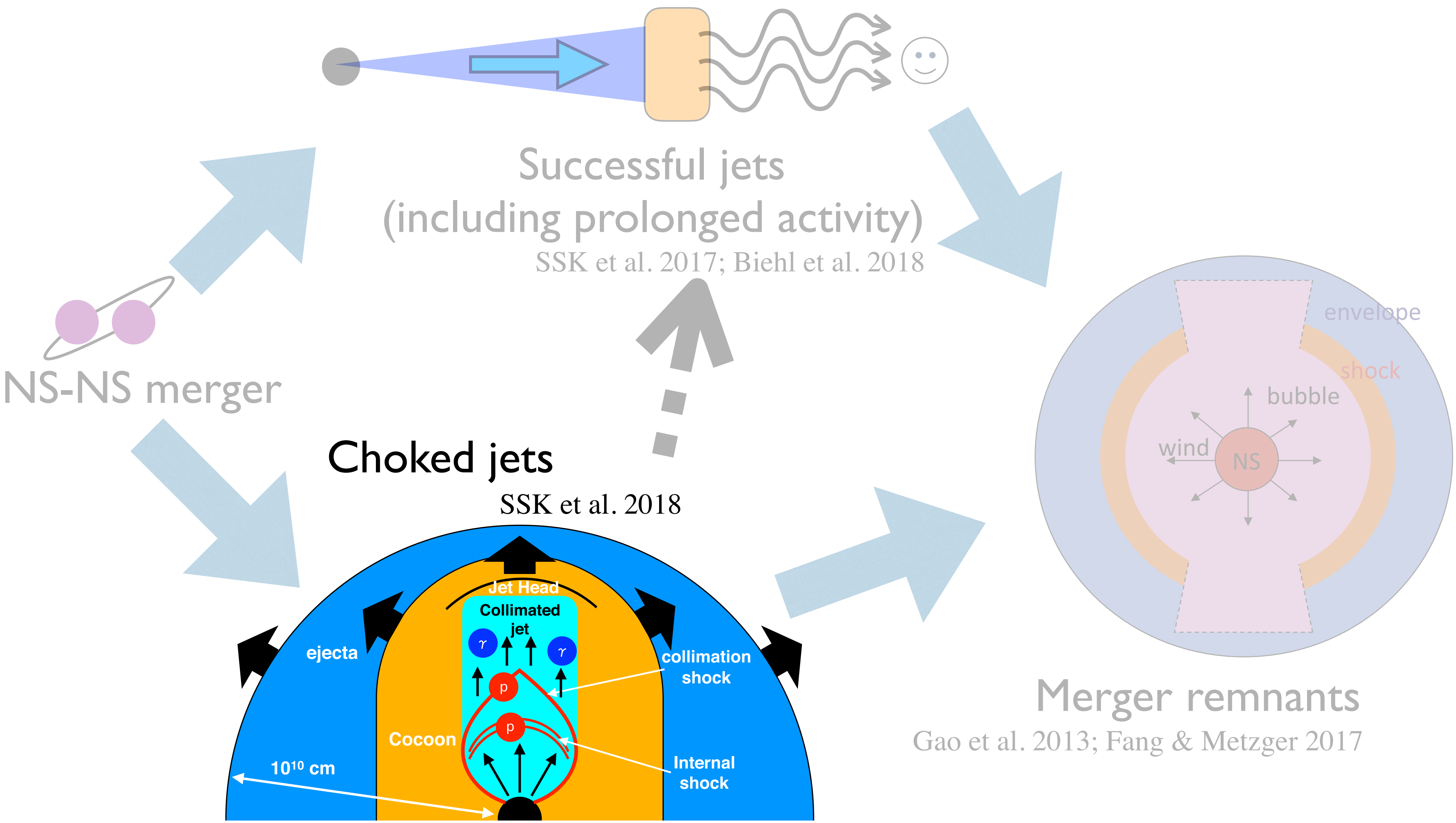

LIGO,VIRGO,IceCube,Auger,ANTARES 17



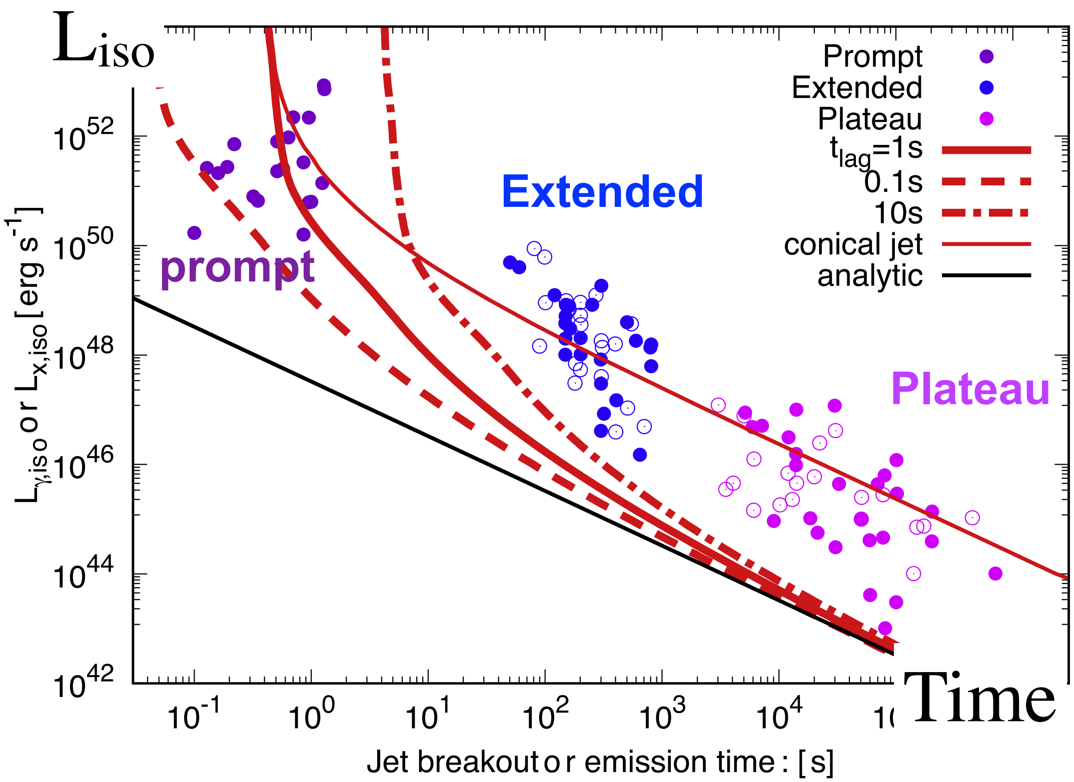

Biehl et al. 2018

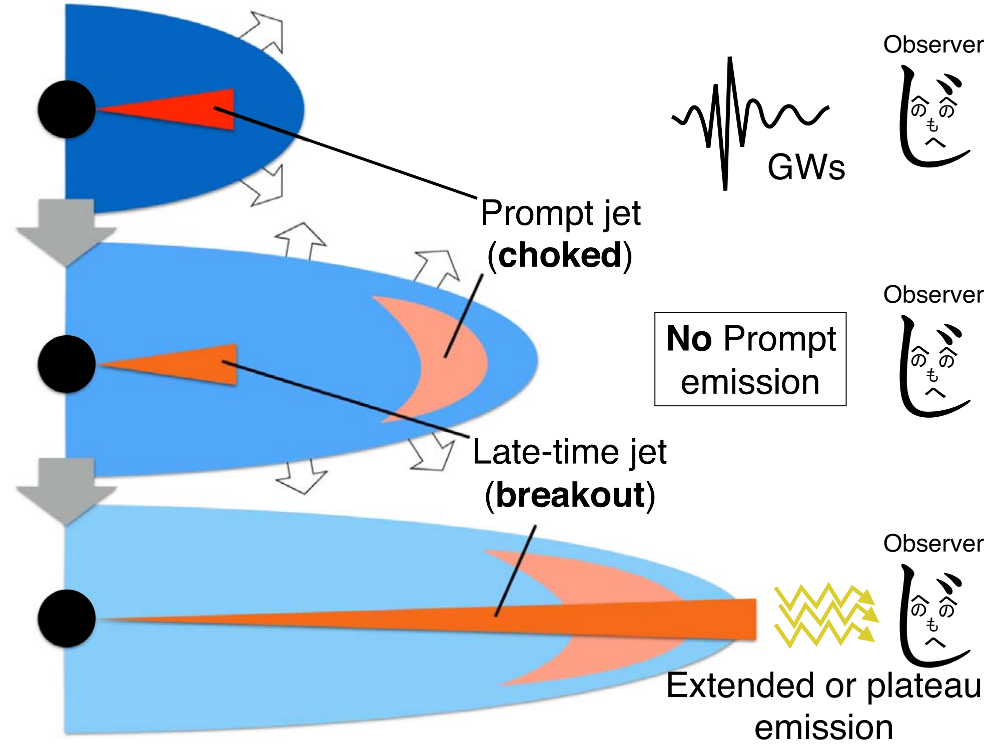
- Off-axis flux is lower than the on-axis flux
- Extended emission is not observed from this event
  —> neutrinos from EE may not be observed
- Prompt emission is too dim to detect by IceCube

# Neutrino Emission Sites



# Breakout Time




Matsumoto & SSK 2018

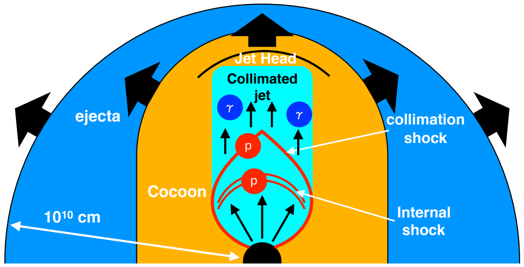
- Half of prompt jets will be choked
- Late-time jets can easily penetrate the ejecta

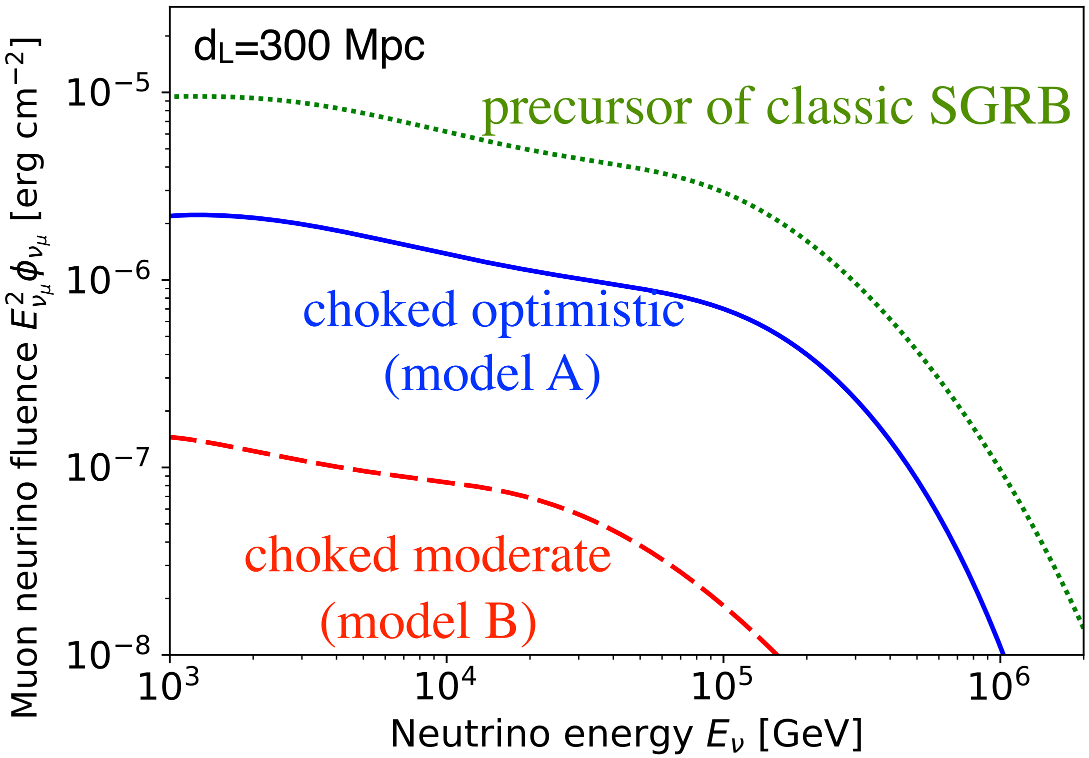
**Delayed breakout scenario**

Prompt jet : **choked** (short duration & dense ejecta)

Late-time jet : **breakout** (long duration & dilute ejecta)

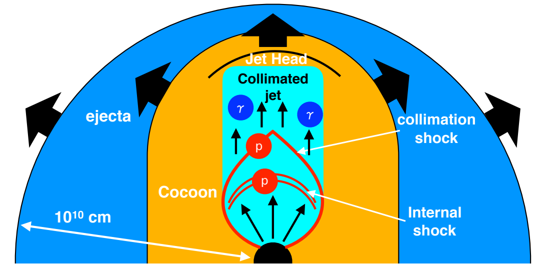
# Neutrino Fluence from Choked Jets




- Calorimetric system & flat injection spectrum
  → Neutrino spectrum is flat for ~1-100 TeV
- Bethe-Heitler process suppresses neutrinos for GeV-TeV

# Detection Probability Coincident with GWs




Number of detected neutrinos from single event at 40 Mpc

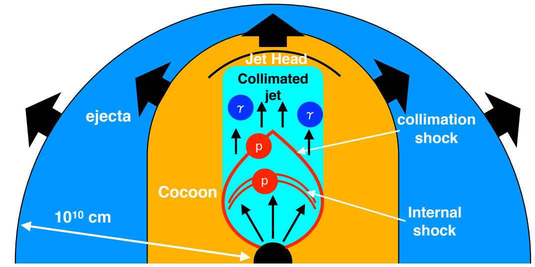
| model | IceCube (up+hor) | IceCube (down) | Gen2 (up+hor) |
|---|---|---|---|
| A (Optimistic) | 2.0 | 0.16 | 8.7 |
| B (Moderate) | 0.11 | $7.0\times10^{-3}$ | 0.46 |

Number of detected neutrinos from single event at 300 Mpc

| model | IceCube (up+hor) | IceCube (down) | Gen2 (up+hor) |
|---|---|---|---|
| A (Optimistic) | 0.035 | $2.9\times10^{-3}$ | 0.15 |
| B (Moderate) | $1.9\times10^{-3}$ | $1.3\times10^{-4}$ | $8.1\times10^{-3}$ |

- At 40 Mpc, detection is possible even with IceCube
  → **ν observation can put a limit on physical quantities**
- At 300 Mpc, detection is challenging even with Gen2
  → stacking technic is important

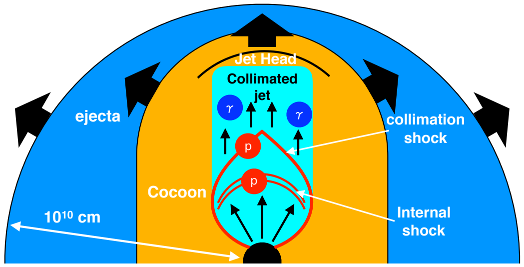
# Detection Probability Coincident with GWs




- IceCube can detect neutrinos with a few years of operation with the optimistic model
- Gen2 can detect a coincident neutrino with 10-year operation even for the moderate model

| GW+neutrino detection rate [$yr^{-1}$] | | |
|---|---|---|
| model | IceCube (up+hor+down) | Gen2 (up+hor) |
| A (Optimistic) | $\boxed{0.38}$ | 1.2 |
| B (Moderate) | 0.024 | $\boxed{0.091}$ |

# Detection Probability Coincident with GWs




- IceCube can detect neutrinos with a few years of

- **Choked system —> prompt γ-rays will not be detected**
- **Multi-messenger with ν & GW will provide information of choked jets without EM counterpart from jets**

| model | IceCube (up+hor+down) | Gen2 (up+hor) |
|---|---|---|
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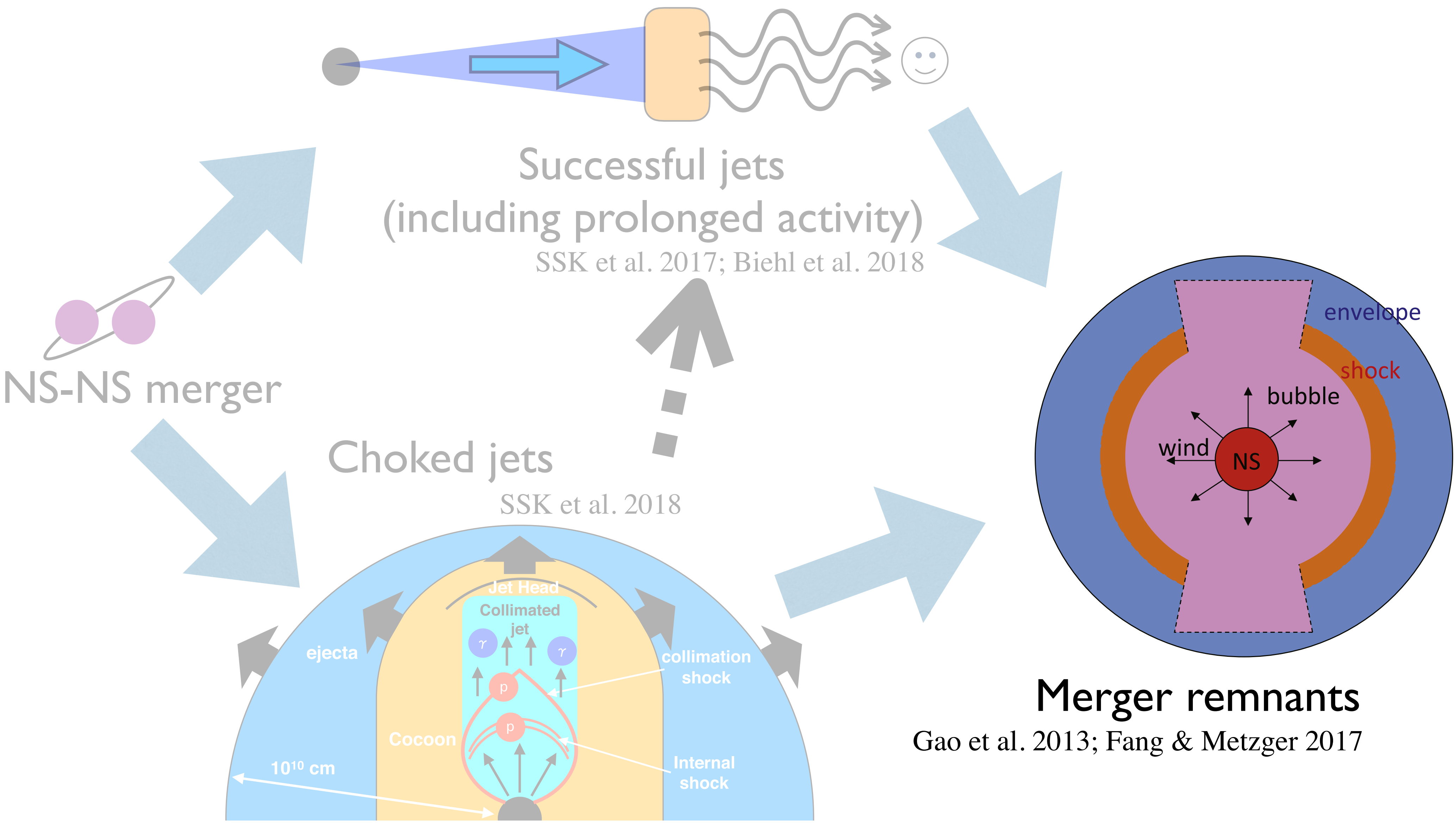
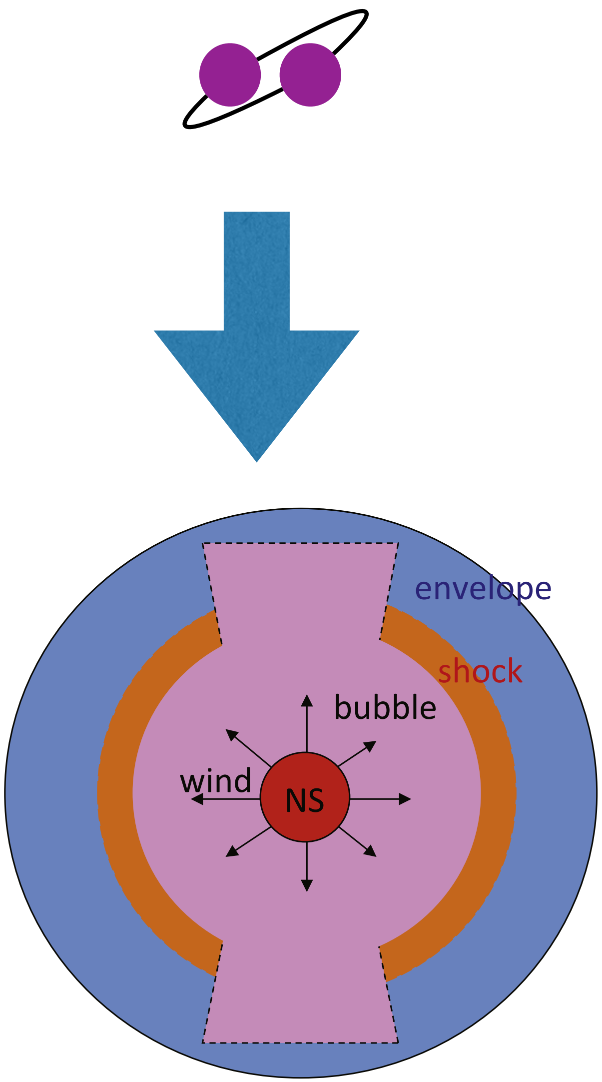
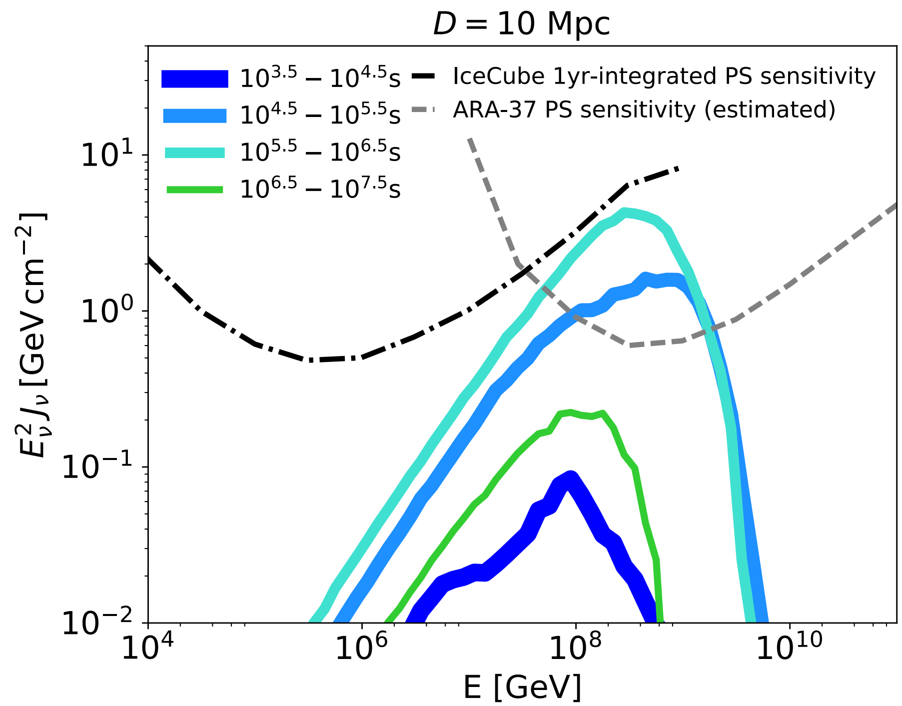


# Neutrinos from Remnants

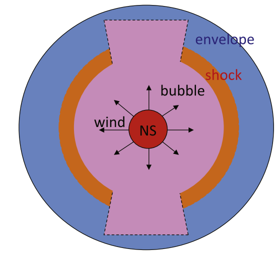



Fang & Metzger 2017
(see also Gao et al. 2013)

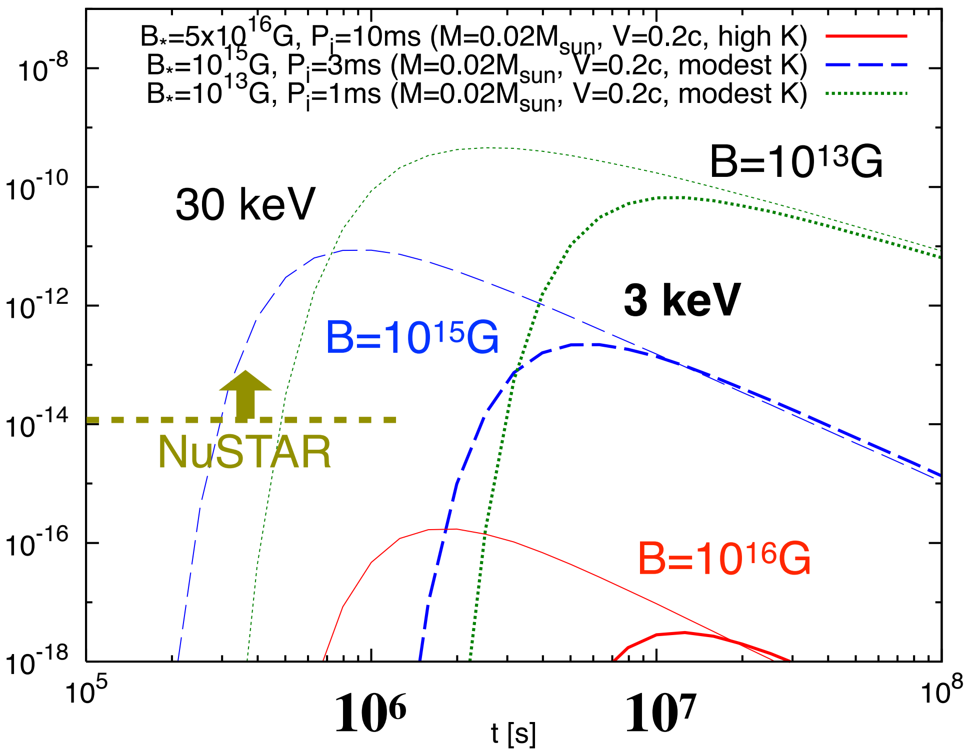
- Protons lose energy by synchrotron for $t<10^5$ s
- Pions are produced, but they lose energy by synchrotron for $10^5$ s < t < $4 \times 10^5$ s
- Efficient neutrino emission around $10^6$ s

# X & γ Rays from Remnants

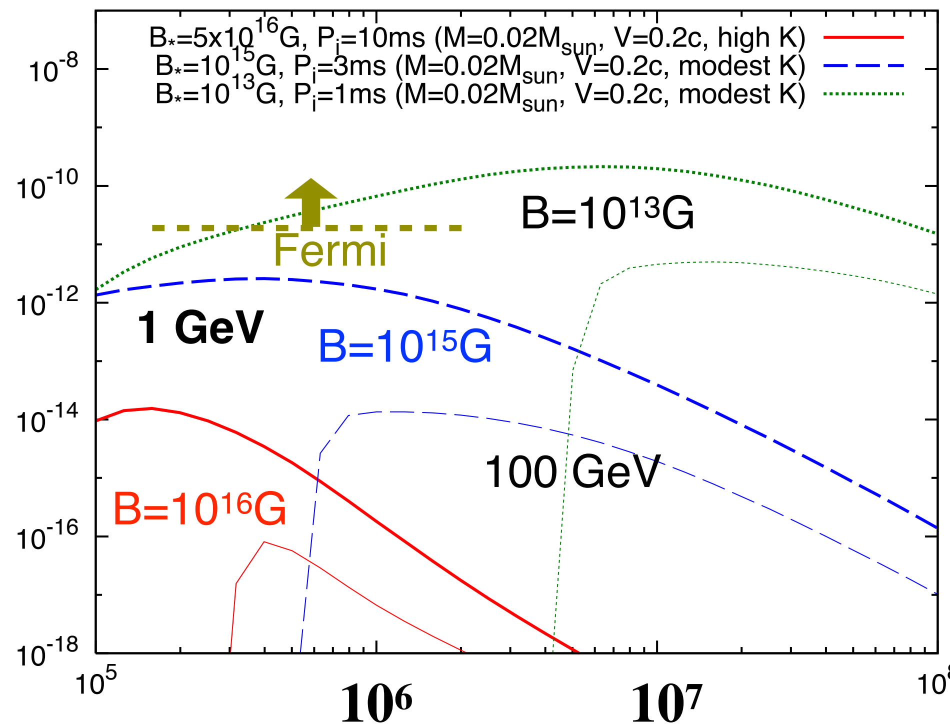



Murase et al. 2018

## X-ray Light Curve



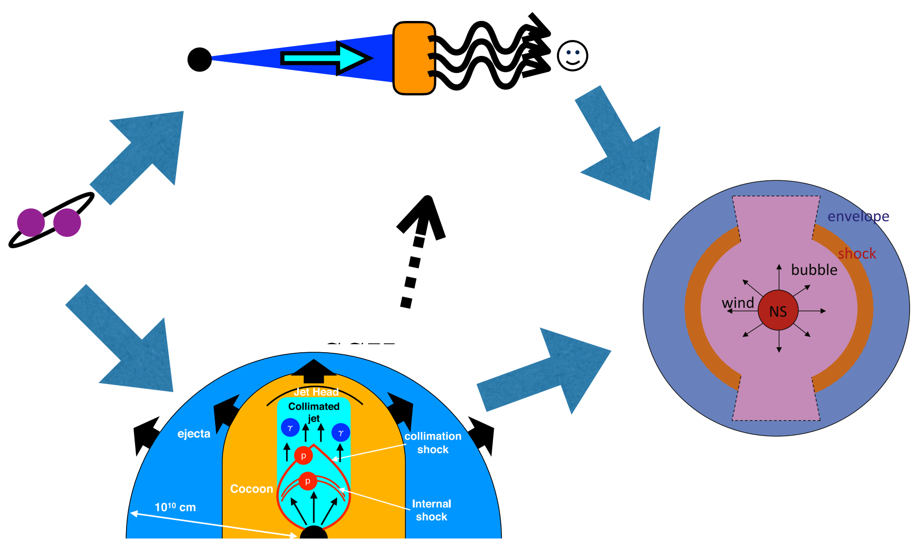

## γ-ray Light Curve




- Very bright X-rays & γ-rays unless $B > 10^{16}$ G for $P$ <~10 ms
- $B$ should be very high (~$10^{16}$ G) or lifetime of magnetar is short

# Summary

- NS mergers are interesting multi-messenger sources
- **Coincident detection of GWs & νs is possible**
- Neutrinos from SGRBs can be detected or put meaningful constraints with IceCube-Gen2
- Neutrino observation is useful to obtain physical quantities in choked jet without prompt γ rays
- Magnetar remnants may produce VHE neutrinos, but magnetar model is disfavored by GW 170817



# Thank you
# for your attention