# Potential Neutrino Sources associated to Gravitational Waves

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Reference:

SSK, Murase, Meszaros, Kiuchi 2017, ApJL, 848, L4 SSK, Murase, Bartos et al. 2018, PRD, 98, 043020 Matsui, SSK, Toma, Murase 2023, ApJ, 950, 190 Matsui, SSK, Hamidani 2024 in prep. (to appear on arXiv this week) Mukhopadhyay & SSK 2024 in prep.

Dialog at Dream Field 2024@Guiyang



### TOHOKU UNIVERSITY

### **Index**

- •Binary Neutron Star (BNS) Mergers & GW170817
- •Neutrinos from GRB jets
	- •Late-engine in Short Gamma-ray Bursts (sGRBs)
	- •Effect of cocoon photons
- •Choked jet systems
- •Remnant-powered scenario
- **•Summary**



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- Jet-ISM interaction o let-ISM interaction
- $\rightarrow$  radio, optical, X-ray ( $\sim$  hour day) independently identified) occur hours to months after coales-
- $\bullet$  Merger Ejecta
- $\rightarrow$  optical ( $\sim$  day) from this information is significantly reduced. For instance, if  $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$  $\to$  optical ( $\sim$  day)

### **BNS mergers as Multi-messenger sources** The Astrophysical Journal Journal, 746-48 (15pp), 746-48 (15pp), 2014 February 10 Metabolism and Berger & Berger

### **with specific stellar populations in the Stellar populations of the Wave**

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 $\lambda$  and the faint of  $\lambda$  spectroscopic redshift redshift

is challenging (cf. Rowlinson et al. 2010), in which case

- Binary inspiral nection Em and Gw events. One approximately the search for a property of a search for a positive search for a s Gw signal following an Emily String and Therman Emily String and Theorem in real time or at the set of the set o<br>The contract of the set of the s
- $\rightarrow$  GW ( $\sim$ min)
- GRB jets 2004). This is particularly promising for counterparts predicted to occur in temporal coincidence with the GW chirp, such as

spectroscopy of the host galaxy is the most promising means

It is important to distinguish two general strategies for con-

 $\rightarrow$  gamma-ray ( $\sim$  sec)



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- The first detection of BNS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray
- **• GW signal from BNS merger —> short GRB just 2 sec after the merger**

## **GW170817: Multi-messenger event**





### **GW170817: Multi-messenger event** reproduces the overall properties of the multicolor light construction and panel of  $\mathcal{L}_\text{in}$ . If the eigenvalue  $\mathcal{L}_\text{in}$ pletely finite of sight

- The first detection of BNS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray
- GW signal from BNS merger  $\rightarrow$  short GRB just 2 sec after the merger. red lines show the abundance patterns calculated with *Y*<sup>e</sup> = 0.30, 0.25,
- **• Optical signal from ejecta**  *A*e  $\overline{a}$



 $\rightarrow$  outflows with r-process elements line shows the solar abundances. Below show the arrows the lanthanide





- The first detection of BNS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray
- GW signal from BNS merger —> short GRB just 2 sec after the merger
- Optical signal from ejecta

—> outflows with r-process elements

**• Superluminal motion by VLBI observation —> existence of powerful relativistic jets**

## **GW170817: Multi-messenger event**

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Mooley et al. 2018





 $≤5<sup>o</sup>$ 

 $15^{\circ} - 25^{\circ}$ 

 $\frac{\theta_{\rm jet}}{\epsilon$ <sub>50</sub>  $\theta_{\rm obs}$ 





- Gamma-ray counterparts —> Some fraction of GRBs should be produced by BNS mergers
- UV/Optical/IR counterparts —> Existence of merger ejecta with r-process heavy elements
- Radio & X-ray afterglows —> BNS mergers create relativistic jets

# **Things confirmed by GW170817**

### **• Do BNS mergers produce detectable neutrino signals? • Do ν detection useful to probe GRB/BNS merger physics?**

# **High-energy neutrinos are not detected**



# High-energy neutrino production

• Photomeson production (pγ)





- $p + y \rightarrow p + \pi$
- $\bullet$   $\pi^{\pm} \rightarrow 3v + e$
- 
- 
- -
- 
- 

# •  $\pi^0 \rightarrow 2\gamma$

Interaction between CRs & photons/nuclei  $\rightarrow$  Neutrino production **Gamma-rays inevitably accompanied with neutrinos**

### **Neutrino Emission Sites for BNS mergers** material during the propagation, forming a cocoon surrounding the jet  $\sim$  30,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–79 IS merners used in e.g., Refs. [76,77,79] is Lk;jet=2). At the down-

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tem involves studying the evolution of the spin-down the spin-down the spin-down the spin-down the spin-down t<br>The spin-down the spin-dow

### **Neutrino Emission Sites for BNS mergers** material during the propagation, forming a cocoon surrounding the jet  $\sim$  30,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–79 IS merners used in e.g., Refs. [76,77,79] is Lk;jet=2). At the down-





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### NS-NS merger





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• Short GRB afterglow: Extended & plateau emissions —> Late-time engine activity —> **Origin of late-engine is mystery** 

• **Neutrinos can be useful to probe late-engine**

# **short GRB afterglow**

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### • Calculate ν fluence from each component by one-zone model *dN dE* = *ξpEγ*,iso ln(*Ep*,max/*Ep*,min) **Multi-component One-zone Model Neutrino oscillation Observer Central Engine Lorentz factor Γ Dissipation Region @ rdis** p γ νe  $\overline{\nu}_\mu$  $\overline{\nu}_\mu$ p γ  $\pi^+$  $\mu^+$ fitting formulae based on GeANT4 (see Murase  $\sum_{i=1}^n \frac{1}{i} \sum_{j=1}^n \frac{1}{j} \sum_{j=1}^n \frac{1}{j$ Pions generated through the photomeson production decay of the photomeson producti into muons and muons  $\mathbf{r}$ • Calculate v fluence from each component by one-zone m<br> $\frac{1}{2}$  *p F* Power low protop injoction:  $\mathbb{E}^2 dN = \frac{\xi_p E_{\gamma\text{,iso}}}{\xi_p E_{\gamma\text{,iso}}}$  $\frac{\partial}{\partial \nu_{\mu}} \frac{\partial}{\partial \mathbf{r}} \frac{\partial \mathbf{r}}{\partial \mathbf{r}} \approx 0$  $\nu$  $\nu$  $\nu_{\mu}$   $\frac{1}{\Delta E}$   $\sim$   $\frac{1}{2}$   $p\gamma$  J sup  $\pi$  $\mu$  $\mu$  $E_{\nu_\mu}^2 \frac{\partial F}{\partial P} \approx \frac{1}{2} f_{p\gamma} f_{\text{sup}} \pi E_p^2 \frac{\partial F}{\partial P}$ *dN*  $\frac{dE_{\nu_\mu}}{dE_{\nu_\mu}} \approx \frac{1}{8} f_{p\gamma} f_{\sup\pi} E_{\mu}$ *dN dE* 1  $\frac{1}{8} f_{p\gamma} f_{\sup \pi} E_p^2 \frac{dr \gamma_p}{dE_p}$   $f_{\sup \pi} = 1 - \exp(-\frac{1}{2}$ *p p* 2 sup 2 The Astrophysical Journal Lorentz factor  $\Gamma$  and  $\Gamma$   $\Gamma$  $14$ we are the threater that a fraction  $\boldsymbol{e}$ ton energy, **U**γ ειδιαστηματικό της βρασιαστικής στις προσειλείς της διαφορείας της δ ken power-law spectrum, diameter<br>Example and the spectrum, diameter<br>of the spectrum, diameter<br>of the spectrum, diameter and the spectrum, diameter and the spectrum, diameter and the<br>of the spectrum, diameter and the spectr **Lorentz factor** ε<sup>γ</sup> *<* εγ*,*pk (ε<sup>γ</sup> *>* εγ*,*pk). The magnetic field at the internal shock is estimated to be *B* = !8πξ*BU*γ. In the bottom panel of Figure 2, we plot the inverse of timescales for model A whose parameters are tabulated • Calculate y fluence from each component by one-zone model  $\Box$ than the property provided by provided the property of the property of the property of the set of the  $\blacksquare$ PROPERTY PROVIDED **Example − 1**<br>Experience Region *®* ation Region @ r<sub>di</sub> <sup>−</sup> *<sup>E</sup><sup>p</sup>* where *E*iso ≈ *L*iso*t*dur is the isotropic equivalent kinetic energy, *Ep,*max and *Ep,*min are the maximum and mini- $\sim$  mum energy of the non-the non-the observer  $\sim$ **f**<sub>*π*</sub>, γ<sub>*μ*</sub> and *π*<sup>2</sup> and *π*<sup>2</sup> and *Γγ*<sup>*ν*<sub>μ</sub></sup> and *Diserver* **E**<br>**Ep E**<br>**E** These protons produce pions that decay to muons and decay is expressed as  $\epsilon$  is  $\mathbf{r}$ *E*<sup>2</sup> π−ν*<sup>µ</sup>*  $\frac{P}{\sqrt{I}}$  $\mathcal{L}_{p,\text{max}}$  $\bm E$ "1  $\dot{\mathbf{u}}$ *f*<sub>*p*</sub> $\left($ *p*<sub>2</sub>  $\right)$ *dN<sup>p</sup> dE<sup>p</sup> .,* (14)  $f_{p\gamma} = t_{p\gamma}^{-1}/t_{p,{\rm cl}}^{-1}$ *p,*cl are the neutrino production efficiency through photomeson production efficiency through photomeson produces  $\mathcal{L}_\text{max}$ fitting formulae based on  $\mathcal{I}^{t+1}$  (see Murase  $\mathcal{I}^{t+1}$ efficiency, *ftt <sup>p</sup><sup>g</sup>* º *p p* ,cool *<sup>g</sup>* (which always satisfies *f <sup>g</sup>* < 1 *<sup>p</sup>* in  $\xi_p E_{\gamma, \text{iso}}$ ijection:  $E_p^2 \frac{m}{\sqrt{D}} = \frac{1}{2}$ *n n f*  $f_{\infty} = t^{-1}$  $f_{p\gamma} = t_{p\gamma}^{-1}/t_{p,{\rm cl}}^{-1}$  $\ddot{t}$  $dE_p$   $f_{\text{sup }\pi} = 1 - \exp(-t_{\pi,\text{cool}}/t_{\pi,\text{dec}})$ suppression factor due to the cooling of pions. Here, The Astrophysical Journal  $\mathcal{A}$  and  $\mathcal{A}$  and  $\mathcal{A}$  and  $\mathcal{A}$  and  $\mathcal{A}$   $\mathcal{A}$   $\mathcal{A}$ CR Spectrum γ Spectrum



• Power-law proton injection:  $E_p^2$  $\bullet$  ruwer-law p photons have typically higher photons have photons higher photon energy, and the photon of  $\Gamma$ **Power-law proton injection:**  $E$ neutrino flux around 1–100 TeV range. The maximum flux around 1–100 TeV range. The maximum flux around 1–100 T<br>The maximum flux around 1–100 TeV range. The maximum flux around 1–100 TeV range. The maximum flux around 1–10  $n \, dN_{\nu}$  in the adiabatic cool- $E_{\nu}^2 \longrightarrow \omega - f_{\nu\alpha} f_{\text{sun}\pi} E_{\nu}^2$ 2. Power  $\overline{\mathbf{u}}$  $m_1$   $\partial_l$   $dN_{l\mu}$  $E_{\nu_\mu}^- \rightarrow \infty$ if  $a E_{\nu_\mu}$ 

### Multi-component One-zone Model  $\overline{15}$ PRIMIT 6.7 THE FROM FORD FOUND FOR THE RESPONSER TO THE RESPONSER TO A LIGITARY CONTACT

• v fluence from each component by one-zone

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SSK et al. 2017 SSK et al. 2017



- Extended emission (EE): highest neutrino production efficiency  $T$
- Low  $\Gamma_j$  or low  $r_{\text{diss}}$  $\rightarrow$  high photon density → high fluence φ  $\overline{\text{ow}}\Gamma_{i}$  or low  $\mathcal{U}$  is the probability of  $\mathcal{U}$ ability  $\frac{1}{\sqrt{2}}$  .  $\frac{1}{\sqrt{2}}$  .  $\frac{1}{\sqrt{2}}$  . 1 ,  $\frac{1}{\sqrt{2}}$  . 1 ,  $\frac{1}{\sqrt{2}}$  . 1 ,  $\frac{1}{\sqrt{2}}$  ,  $\frac{1}{$ orthologie and Icertificate and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice<br>For EE-option Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Ge  $\gamma$  mgn nuence  $\psi$

 $10<sup>9</sup>$ 





- Assume that all the NS mergers within 300 Mpc are detected by GW  $E = \frac{1}{2}$ Expositive ende direction incigato within 500 imported detected by Own
- $\dot{\rho}_{sGRB} \sim 4 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$  & half of SGRBs have EE  $\rightarrow$  2-5 EEs (10 yr) within GW horizon (300 Mpc) •  $\dot{\rho}_{sGRB} \sim 4 - 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$  & half of SGRBs have EE Wanderman & Piran 15, Nakar + 06
- For optimistic case, **simultaneous detection of GWs and νs**  is highly probable even with IceCube
- Even fore moderate cases, IceCube-Gen2 is likely to detect neutrinos

### **Prospects for GW-Neutrino association**   $L_2$ ,  $L_1$ The Parties of Probabilities with Probabilities with  $\sigma$

**SSK** et al. 2017 SSK et al. 2017



• Optimistic model was consistent with IceCube upper limit for GW170817

 $-3$ 

# **IceCube Constraint on GW170817**

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• GW170817 is slightly off-axis event  $\rightarrow$   $F \propto (\Gamma \theta)$ 

### **IceCube Constraints on late-time emission** The Astrophysical July 2022, 939:116 (17pp), 2022 November 10 Abbasic et al. 1939:11

![](_page_17_Figure_1.jpeg)

● For EX, stacked fluence should be 0.03 - 0. 2 GeV/cm<sup>2</sup> for 200 sGRB 2091 GR, Stacked hached Shound be 0.00% of 200 years to 200 Sond

• Tvnical distance (d=3 Gnc; z=0.5) —>  $\mathcal{L}^{\text{iso}}$  < 10<sup>50</sup> - 10<sup>51</sup> erg ner hurst

**•**  $\begin{bmatrix} 1.0 \\ \times 1 \end{bmatrix}$ 

IceCube 2023

![](_page_17_Picture_6.jpeg)

![](_page_17_Figure_9.jpeg)

### Multi-component One-zone Model  $19$ PRIMIT 6.7 THE FROM FORD FOUND FOR THE RESPONSER TO THE RESPONSER TO A LIGITARY CONTACT

• v fluence from each component by one-zone

19

SSK et al. 2017 SSK et al. 2017

![](_page_18_Picture_459.jpeg)

- Extended emission (EE): highest neutrino production efficiency  $T$
- Low  $\Gamma_j$  or low  $r_{\text{diss}}$  $\rightarrow$  high photon density → high fluence φ  $\overline{\text{ow}}\Gamma_{i}$  or low  $\mathcal{U}$  is the probability of  $\mathcal{U}$ ability  $\frac{1}{\sqrt{2}}$  .  $\frac{1}{\sqrt{2}}$  .  $\frac{1}{\sqrt{2}}$  . 1 ,  $\frac{1}{\sqrt{2}}$  . 1 ,  $\frac{1}{\sqrt{2}}$  . 1 ,  $\frac{1}{\sqrt{2}}$  ,  $\frac{1}{$ orthologie and Icertificate and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice<br>For EE-option Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Genzie and Ice-Ge  $\gamma$  mgn nuence  $\psi$

 $10<sup>9</sup>$ 

![](_page_18_Picture_7.jpeg)

![](_page_18_Figure_2.jpeg)

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![](_page_19_Picture_11.jpeg)

- Optical counterpart detection in GW170817 —> outflow/ejecta at BNS merger
- 2-sec delay time between GW & γ-ray —> jet is launched sometime after merger
- Jets need to propagate in ejecta
- —> Jet-ejecta interaction form shocks
- Shock heated material surrounds jets
- —> Formation of cocoon

## **Formation of Cocoon**

![](_page_20_Figure_9.jpeg)

Hamidani & Ioka 2023

 $log_{10}$   $\rho$  at t = 0.40 s

![](_page_21_Figure_1.jpeg)

- **Cocoon breaks out from the ejecta with jets** kinetic energy within the cocoon radius. The cocoon supplies soft photons to
- Cocoon is dense & filled with photons (thermal distribution with  $T \sim 10^4 10^5$  K) **O** Coroon is dense & filled with photons (thermal distributed) EIC process. Higher-energy gamma-rays are attenuated and reprocessed to
- **Cocoon can provide photons to prolonged jets**
- **—> enhances pγ interaction & inverse Compton scattering** Canances by michaelion & miverse complon scaller

with  $T_c$ ,  $10^4 - 10^5$  K) contractive that the operation.  $\overline{a}$ l uistribution with  $\overline{I}$ 

 $\mathsf S$ 

scattering analytic experiment and  $\mathbf s$ and intelasticity are approximated to be  $\mathcal{A}$ 

![](_page_22_Figure_1.jpeg)

- 
- 

- e Drotons interact with sesson photons • Protons interact with cocoon photons  $\rightarrow$  neutrinos @  $E \sim 10^5-10^7$  GeV  $\overline{\nu}$ —> neutrinos @  $E_{\nu} \sim 10^5 - 10^7$  GeV
- case is a calculate the spectrum of GeV constructions of the spectrum of GeV-Tev gammae Dotoctable with 10 w aporation with 10 km3 d • **Detectable with 10-yr operation with 10-km3 detector**  —> Non-detection will put constraint

![](_page_23_Figure_10.jpeg)

Matsui, SSK, Toma, Murase 2023 Matsui, SSK, Hamidani in prep.

![](_page_23_Picture_8.jpeg)

### **Neutrino Counterparts to GWs** The Internet Counterbarts, 887:2014 Internet Strongwish and Letters, 887:2019 Internet al., 2019 December 10 Ki

![](_page_23_Figure_1.jpeg)

**observed gamma-ray flux**  0  $J$ ld del cannot

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# **GeV gamma-rays from GRB 211211A Article**

![](_page_24_Figure_3.jpeg)

![](_page_24_Figure_1.jpeg)

# **GeV gamma-rays from GRB 211211A**

 $\blacksquare$ 

- 
- (but, see Liu et al. 2022 ApJL)
- 

![](_page_25_Figure_4.jpeg)

# **GeV gamma-rays from GRB 211211A**

![](_page_26_Picture_6.jpeg)

- 
- (but, see Liu et al. 2022 ApJL)
- —> **Evidence of late-time engine?**

![](_page_26_Figure_4.jpeg)

### **Neutrino Emission Sites for BNS mergers** material during the propagation, forming a cocoon surrounding the jet  $\sim$  30,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–79 IS merners used in e.g., Refs. [76,77,79] is Lk;jet=2). At the down-

![](_page_27_Figure_1.jpeg)

![](_page_27_Picture_3.jpeg)

## **Choked short GRBs?** 7

![](_page_28_Figure_5.jpeg)

- BNS merger produce ejecta -> Jet needs to propagate inside the ejecta —> some prompt jet fails to penetrate the ejecta **•** Jets can dissipate energy inside the ejecta  $F = F \cup F$  $\bullet$  bivs merger produce ejecta we are the same is the fails to monotent the area that and the same is a strong the second strong and radiation is a strong and radiation of the second strong strong strong and radiation of the second strong strong strong  $\rightarrow$  some prompt jet rails to penetrate the ejecta
- —> sub-photosperic neutrino production  $\overline{C}$  $\rightarrow$  sub-photosperic neutrino production

Gottlieb et al. 2018

![](_page_28_Figure_2.jpeg)

![](_page_28_Figure_3.jpeg)

- jet sweeps up ejecta  $\rightarrow$  shocks at jet head
- cocoon surrounding the jet  $\rightarrow$  push the jet inward  $\rightarrow$  collimation shocks
- Velocity fluctuations in jet-> internal shocks

![](_page_29_Figure_4.jpeg)

![](_page_29_Picture_6.jpeg)

- jet sweeps up ejecta  $\rightarrow$  shocks at jet head
- cocoon surrounding the jet  $\rightarrow$  push the jet inward  $\rightarrow$  collimation shocks
- Velocity fluctuations in jet-> internal shocks
- Jet head: too dense to accelerate CR protons
- Collimation shocks: too dense for pions to decay before  $pπ$  collisions
- **• HE neutrinos are emitted only from internal Shock**

![](_page_30_Picture_7.jpeg)

![](_page_30_Picture_9.jpeg)

![](_page_31_Picture_7.jpeg)

### **Trans-ejecta neutrino spectrum** neutrino events, assuming that SGRBs happen within the design sensitivity range of current GW experiments (aLIGO/ γ (ε−α<sup>2</sup> ) **d** a let γ (ε−α2 ) **d** a let α<sup>1</sup> ns-electa neutrino spect ternal shock is estimated to be *B* = !8πξ*BU*γ. The Astrophysical Journal Letters, 848:L4 (6pp), 2017 October 10 Kimura et al.

![](_page_31_Figure_1.jpeg)

- 
- 

![](_page_31_Picture_6.jpeg)

### Pions generated through the photomeson production decay into muons and muon neutrinos. Using the meson production where *E*iso ≈ *L*iso*t*dur is the isotropic equivalent kinetic energy, *Ep,*max and *Ep,*min are the maximum and minito be produced  $\mathcal{P}$  ,  $\mathcal{P}$ material during the propagation, forming a cocoon sur-

### **Neutrino Emission Sites for BNS mergers** material during the propagation, forming a cocoon surrounding the jet  $\sim$  30,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–78,74–79 IS merners used in e.g., Refs. [76,77,79] is Lk;jet=2). At the down-

![](_page_32_Figure_1.jpeg)

![](_page_32_Picture_2.jpeg)

![](_page_32_Figure_6.jpeg)

### NS-NS merger

![](_page_32_Picture_3.jpeg)

![](_page_33_Figure_0.jpeg)

**•** Detectable by 30-yr operation with 10 km<sup>3</sup> detectors

Mukhopadhyay, SSK+ in prep. (see also Fang & Metzger 2017; Gao et al. 2013)

### Mainak Mukhopadhyay

![](_page_34_Picture_4.jpeg)

![](_page_34_Figure_0.jpeg)

E [GeV]<br>BNS Merger may leave a magnetar as a remnant • Magnetar spin-down energy will be deposited to ejecta • Protons are loaded into the nebula —> neutrino production • Efficient neutrino production  $(10 - 100 \text{ PeV})$  for T  $> 10^6 \text{ s}$ **• Detectable by 30-yr operation with 10 km3 detectors**

![](_page_34_Picture_6.jpeg)

### **EM counterpart powered by remnants**  $36$  $\mathbb{F} \times \mathbb{R}$  and  $\mathbb{R}$  and  $\mathbb{R}$  and  $\mathbb{R}$  $\blacksquare$  ivi  $\sim$ d bushes as a meta ed by remnants

![](_page_35_Figure_1.jpeg)

• Very bright X-rays & γ-rays unless B >1016 G for P < 10 ms • GW170817: B should be very high (> 1016 G) or lifetime of magnetar should be short Figure 7. X-ray light curves from a long-lived pulsar as a  $\bullet\,$  Very bright X-rays & γ-rays unless B >10 $^{16}$  G for P < 10 ms • GW170817∙ B should be very high (> 10<sup>16</sup> G) or lifetime of magnetar should be sho  $f<sub>1</sub>$  and  $f<sub>2</sub>$ B∗ = 1015 G and Pi = 3 ms, the sub-mission of the sub-mission of the sub-mission of the sub-mission of the sub-<br>Department of the sub-mission of spectrum (which cannot be harder than Formula be harder than Fund be harder than Fund be harder than  $\frac{1}{2}$  $P_1$  $P_2$   $P_3$  and  $P_4$  and pulsar p  $0^{16}$  G for  $P < 10$  ms  $(16C)$  or lifetime of mag

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![](_page_36_Picture_11.jpeg)

• Binary neutron star mergers have been discussed as multimessenger sources,

## **Summary**

- including GW, EM, & neutrinos.
- Short GRB jets with late-engine activities are the most likely neutrino emission site
- Cocoon photons might enhance neutrino production efficiency at late jets in sGRBs => meaningful constraints/probable v detection with future detectors
- Other possible sites for ν production: choked jets & magnetar wind nebulae => less promising, but still possible parameters to be detected with future detectors line is *t* ad , and brawn dotted line is *t* syn .

![](_page_37_Figure_5.jpeg)