High-energy Emissions from Neutron Star Mergers

Penn State (JSPS oversea research Fellow; IGC Fellow)

Shigeo S. Kimura

References
1) SSK, Murase, Bartos et al. 2018, PRD, 98, 043020
2) SSK, Murase, Meszaros, Kiuchi, 2017, ApJL, 848, L4
3) SSK, Murase, Meszaros, ApJ accepted (arXiv:1807.03290)

Collaborators
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PennState

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- Introduction
- HE Neutrinos from SGRBs
- HE Neutrinos from Choked Jets
- CR production at NS Merger Remnants
- Summary

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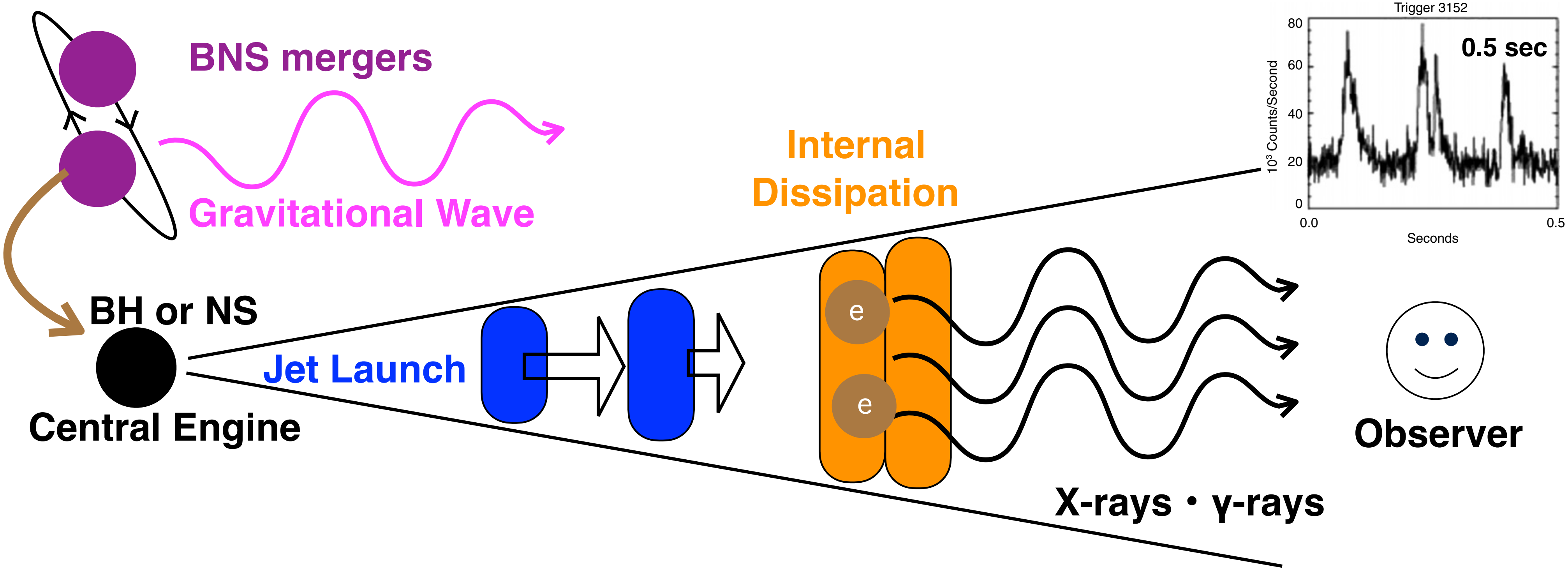
Short Gamma-ray Bursts

see e.g. Berger 2014
Troja's talk in Monday

- Binary neutron star mergers
  —> sources of **gravitational waves & γ-rays**
- Remnant black hole (or magnetar) launches a relativistic jet
  —> internal dissipation produces **high-energy particles**


BNS mergers

Gravitational Wave

BH or NS

Central Engine

Jet Launch

Internal Dissipation

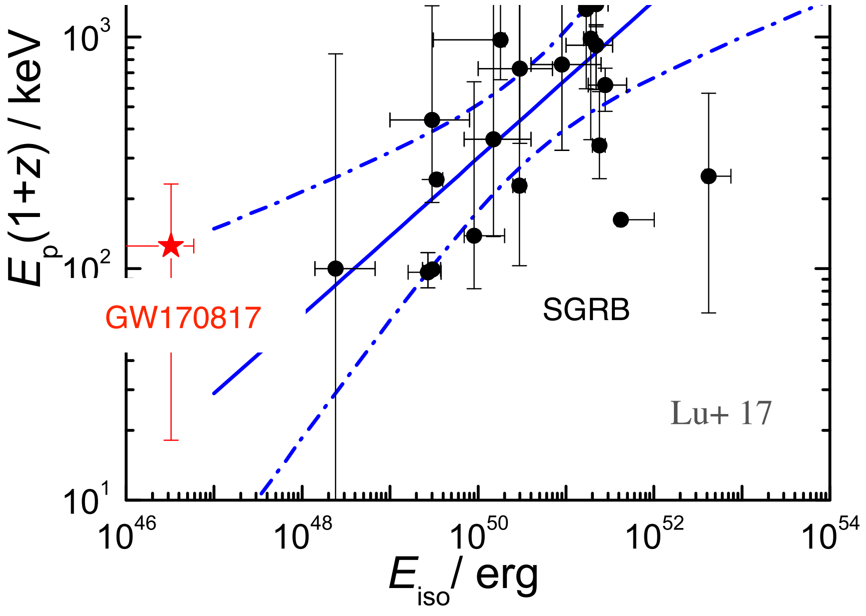
X-rays • γ-rays

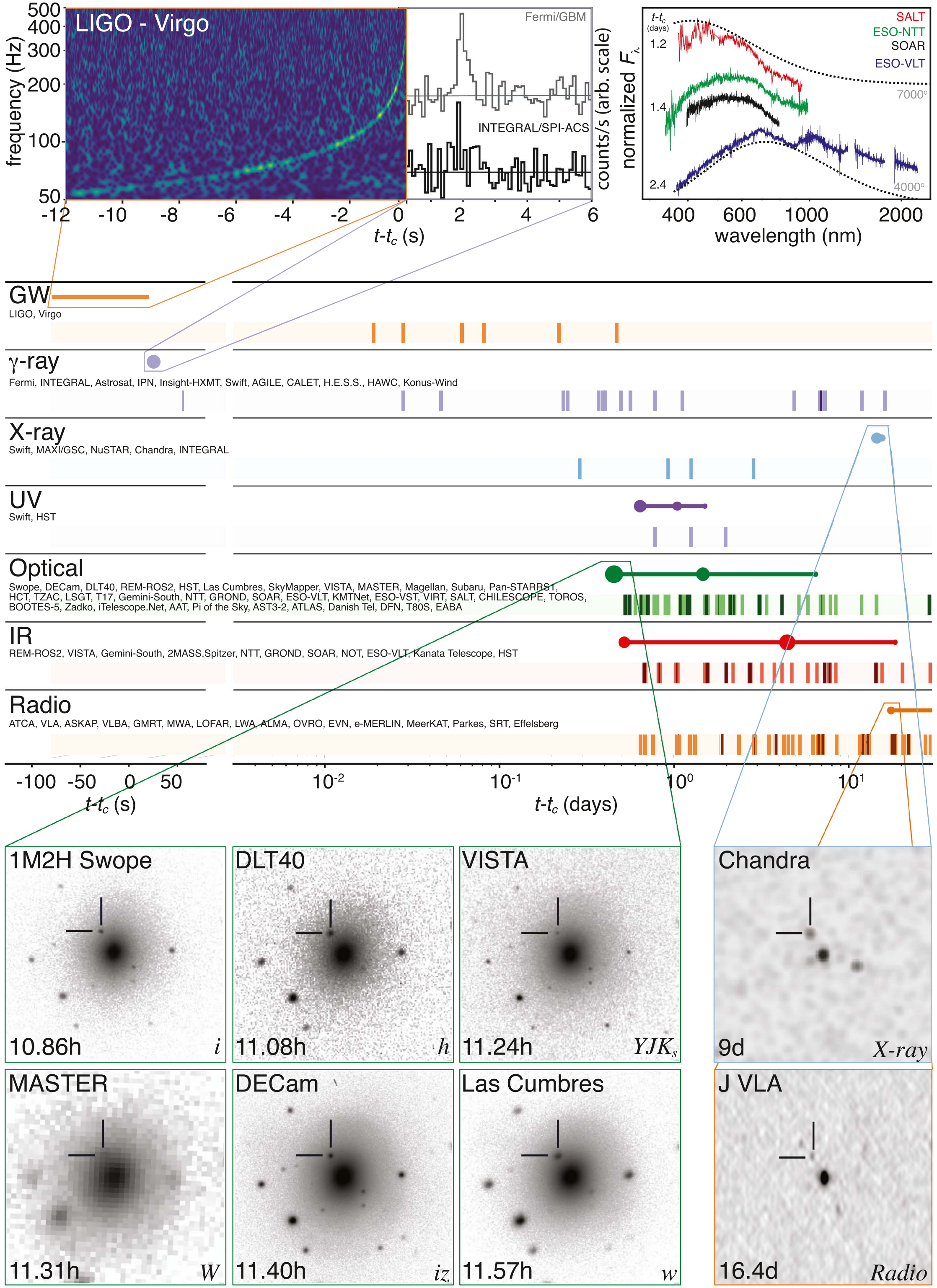
Observer

GW170817

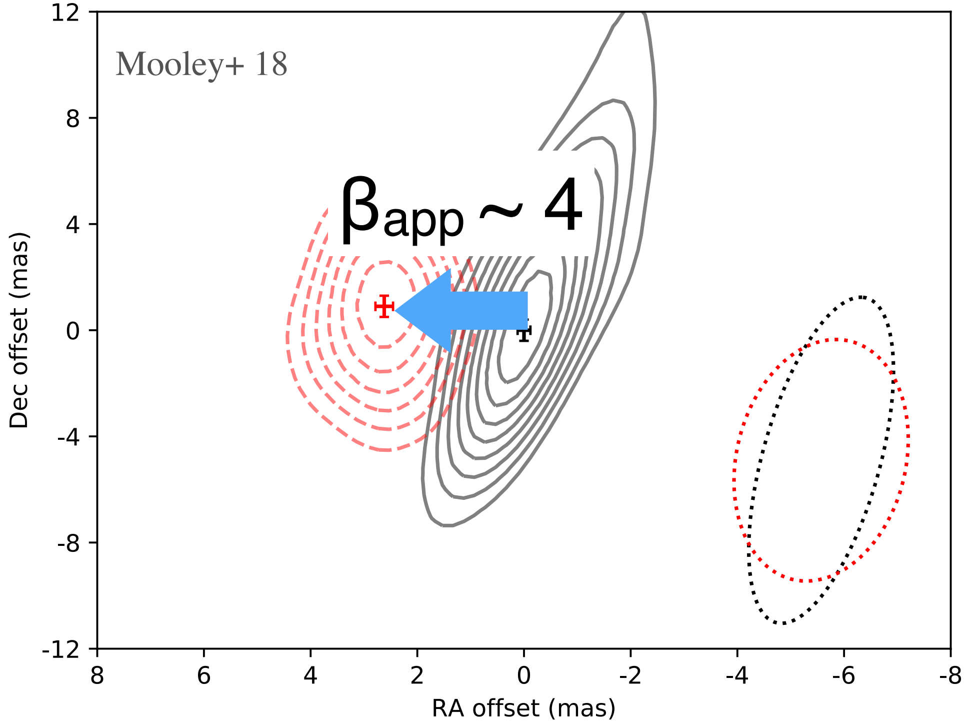
LIGO+ 17; Talks in Monday morning

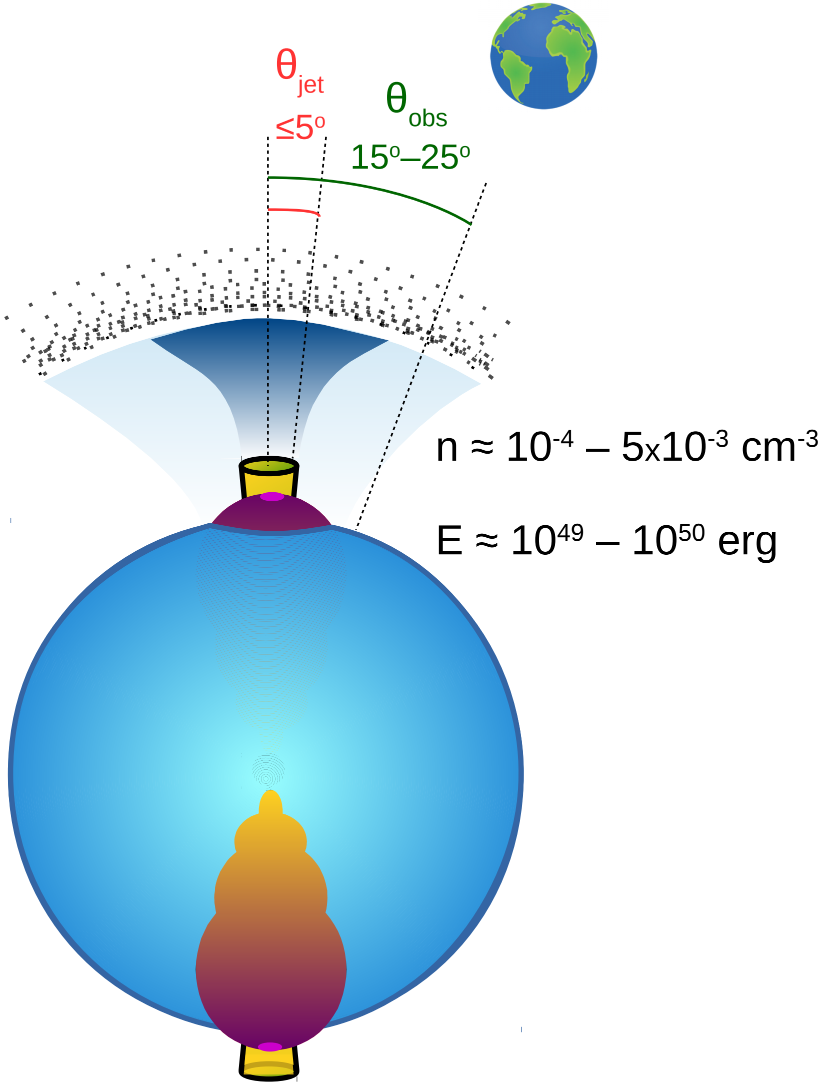
- The first detection of NS-NS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray
- Faint prompt gamma **—> unusual SGRBs**





GW170817: Off-axis SGRBs





θ_{jet} ≤5°

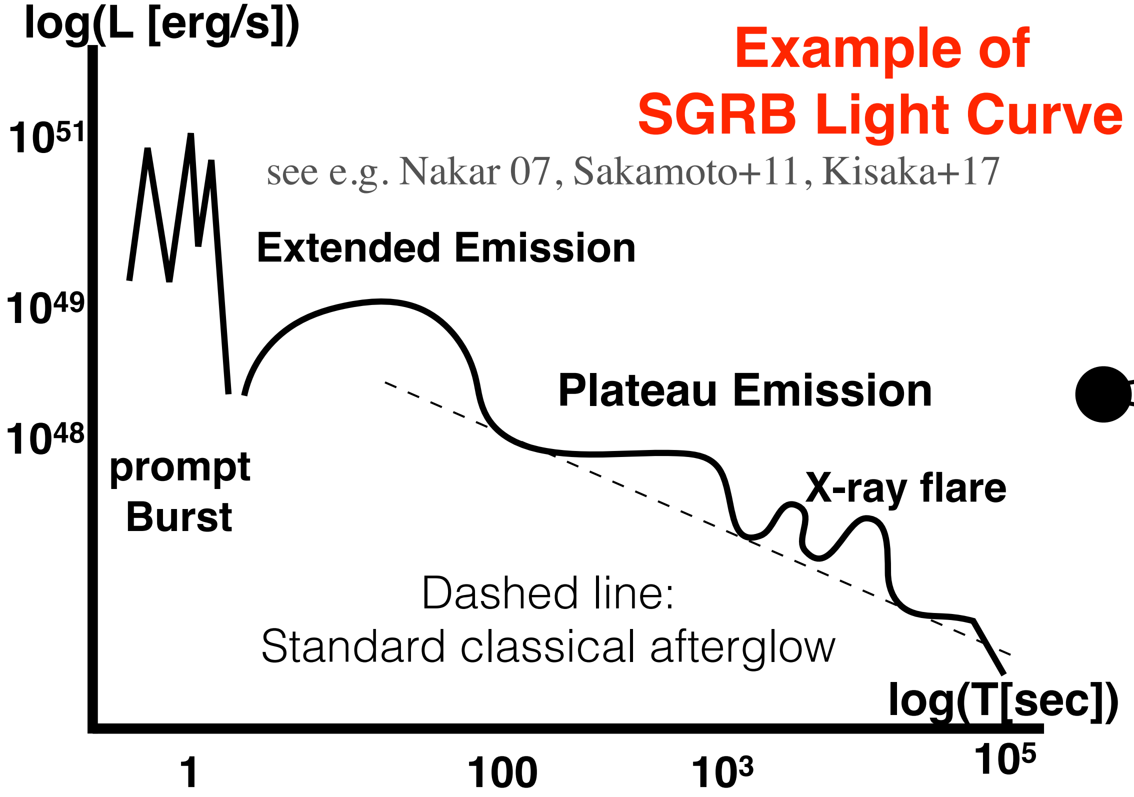
θ_{obs} 15°–25°

$n \approx 10^{-4} - 5\times10^{-3}$ cm^{-3}

$E \approx 10^{49} - 10^{50}$ erg

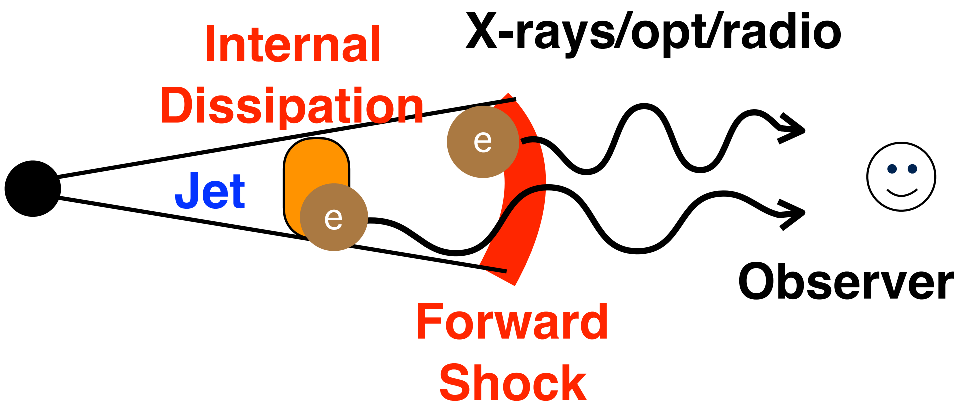
- Superluminal motion
  —> existence of relativistic jet
- Powerful-jet from off-axis
  —> faint prompt emission

Afterglows of SGRBs



Example of SGRB Light Curve

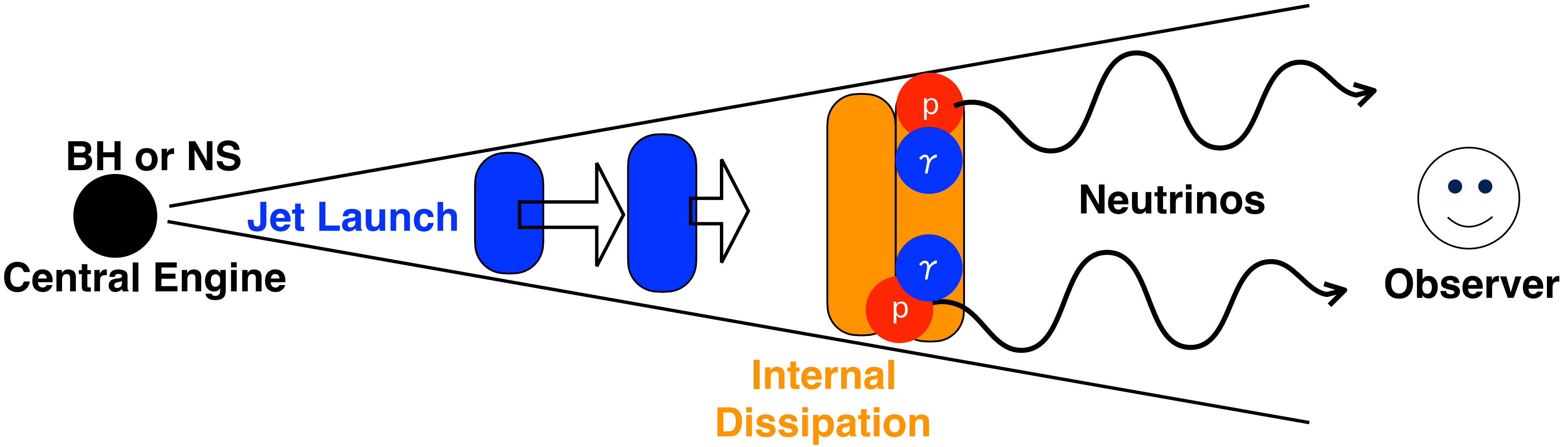
see e.g. Nakar 07, Sakamoto+11, Kisaka+17



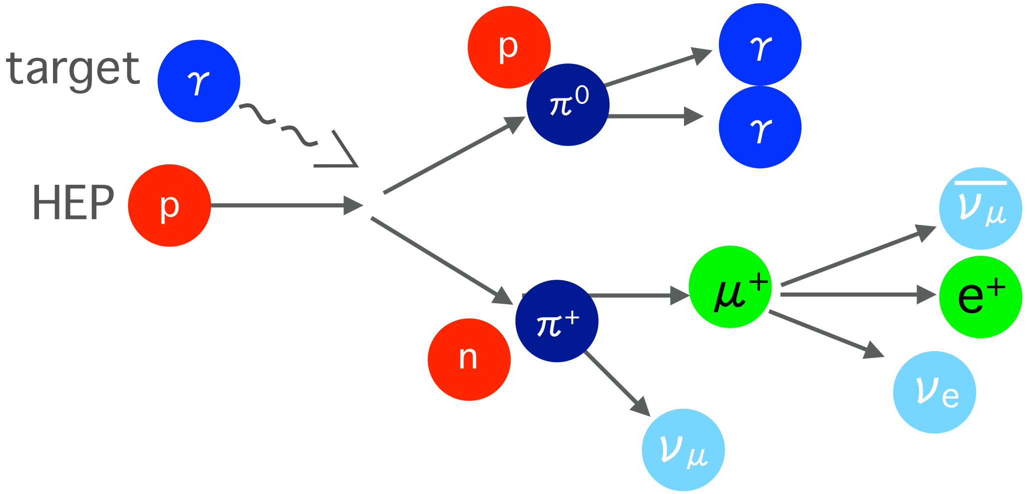
- Long-lasting non-power law X-ray emissions
  —> **Late-time engine activity?**
- **E_{iso} for late time activities ~ E_{iso} for prompt burst**

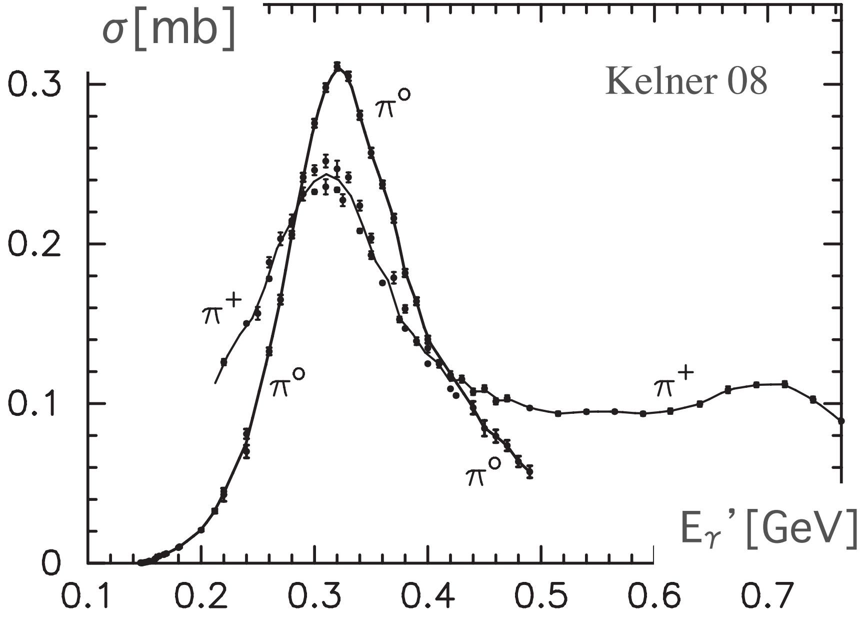
Waxman & Bahcall 1997

GRB Neutrinos



- Photomeson production (pγ)





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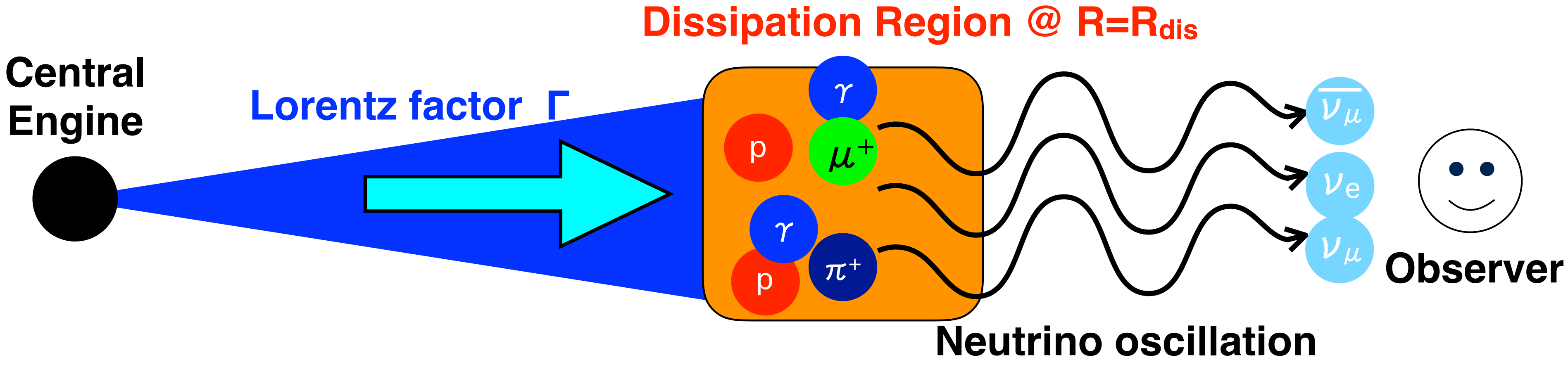
Multi-component One-zone Model

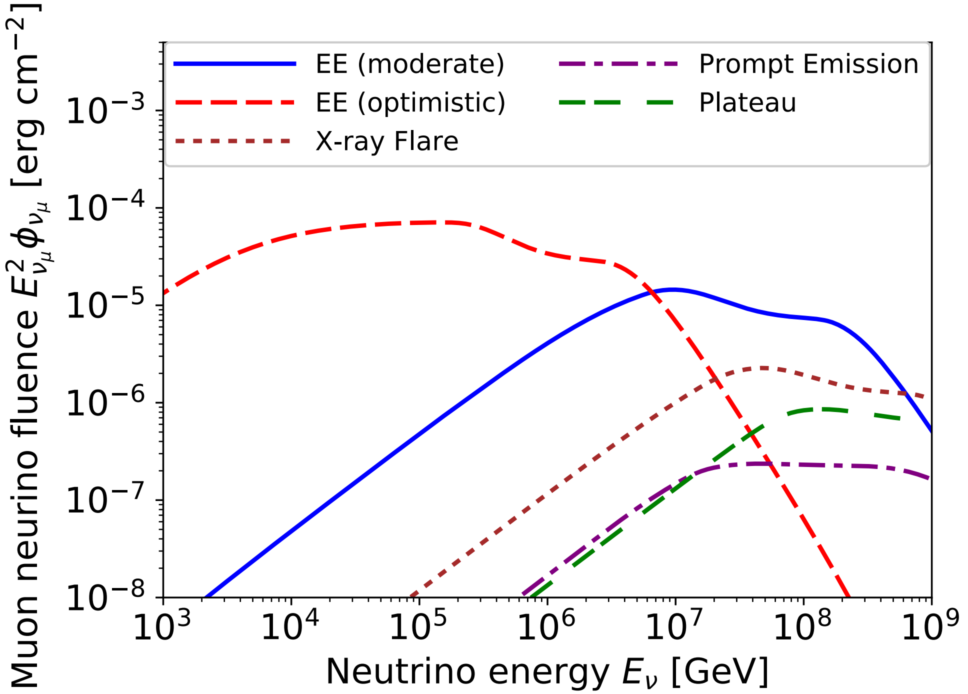


- Calculate ν fluence from each component by one-zone model
- Power-law proton injection: $E_p^2 dN_p/dE_p \sim \xi_p E_{\gamma,iso} / \ln(E_{p,max}/E_{p,min})$
- Proton cooling processes: synchrotron & adiabatic coolings
- μ and π also cool down by synchrotron & adiabatic coolings

$$E_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} \approx \frac{1}{8} f_{p\gamma} f_{\mathrm{sup}\,\pi} E_p^2 \frac{dN_p}{dE_p}$$

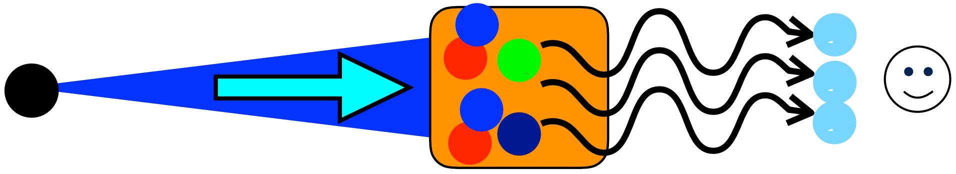
$$f_{p\gamma} = t_{p\gamma}^{-1} / t_{p,\mathrm{cl}}^{-1} \qquad f_{\mathrm{sup}\,\pi} = 1 - \exp(-t_{\pi,\mathrm{cool}}/t_{\pi,\mathrm{dec}})$$

Neutrino Fluence From SGRBs



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

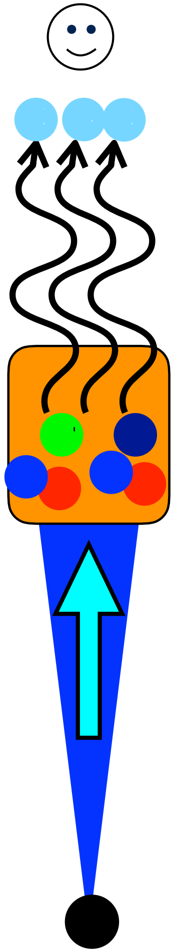
- Set d_L = 300 Mpc (GW horizon for design sensitivity)
- Extended emission (EE) can produce neutrinos efficiently
- Γ ↓ or R_{dis}↓ —> photon density ↑ —> fluence ϕ↑



Detection Probability Coincident with GWs

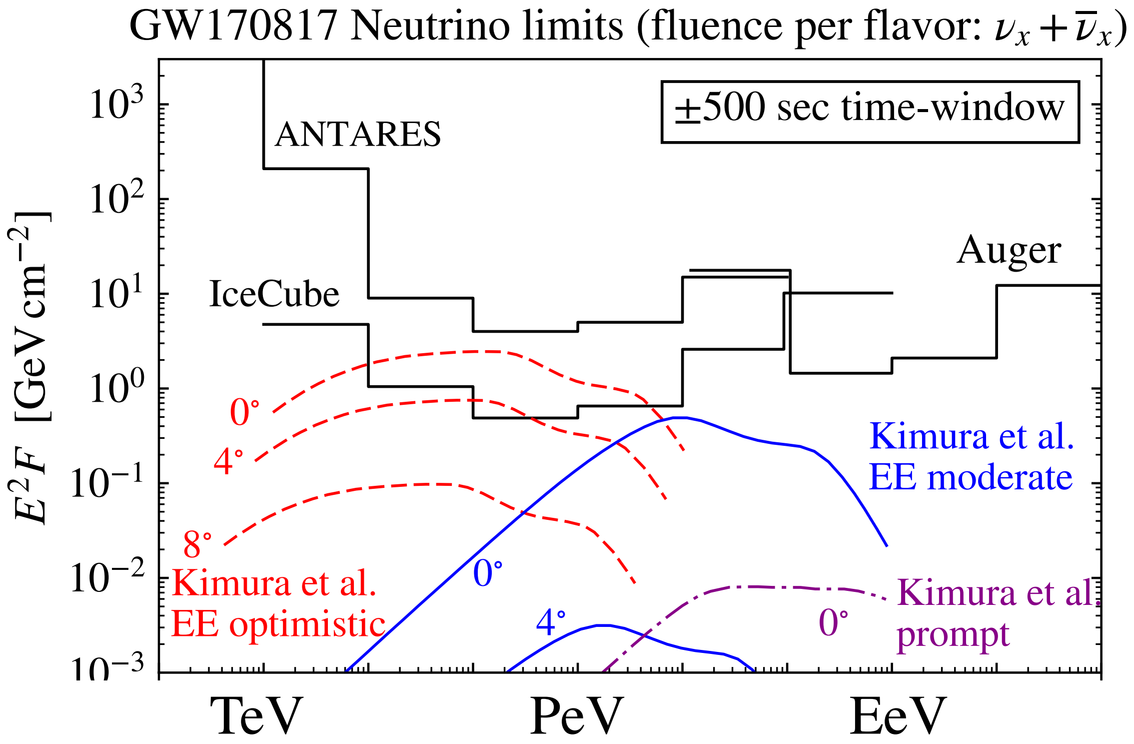
NS–NS ($\Delta T = 10$ years)	IC (all)	Gen2 (all)
EE-mod-dist-A	0.11–0.25	0.37–0.69
EE-mod-dist-B	0.16–0.35	0.44–0.77
EE-opt-dist-A	0.76–0.97	0.98–1.00
EE-opt-dist-B	0.65–0.93	0.93–1.00

Wanderman & Piran 15, Nakar + 06



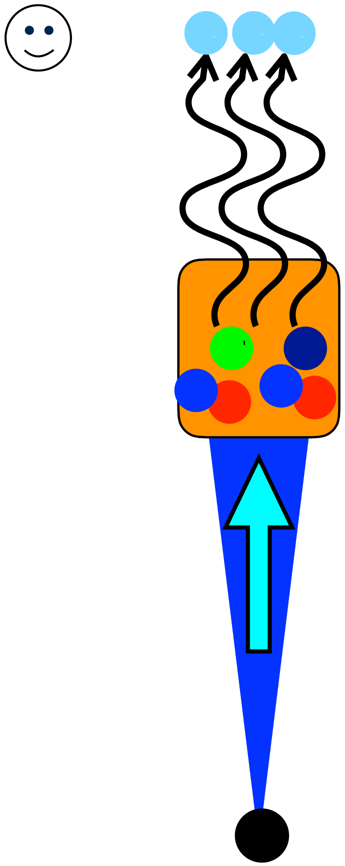
- R_{SGRB}~ 4 —10 Gpc^{-3} yr^{-3} & half of SGRBs have EE —> **~ 0.2-0.6 bursts/yr within 300 Mpc (GW horizon)**
- For optimistic case, simultaneous detection with GW is highly probable even with IceCube
- For moderate case, IceCube-Gen2 is likely to detect neutrinos

Implications for GW170817



ANTARES, LIGO-VIRGO, ICECUBE, AUGER 2017

Talk by DOBRIGKEIT



- The jet is seen from off-axis
  —> the flux is considerably lower
  —> consistent with our model

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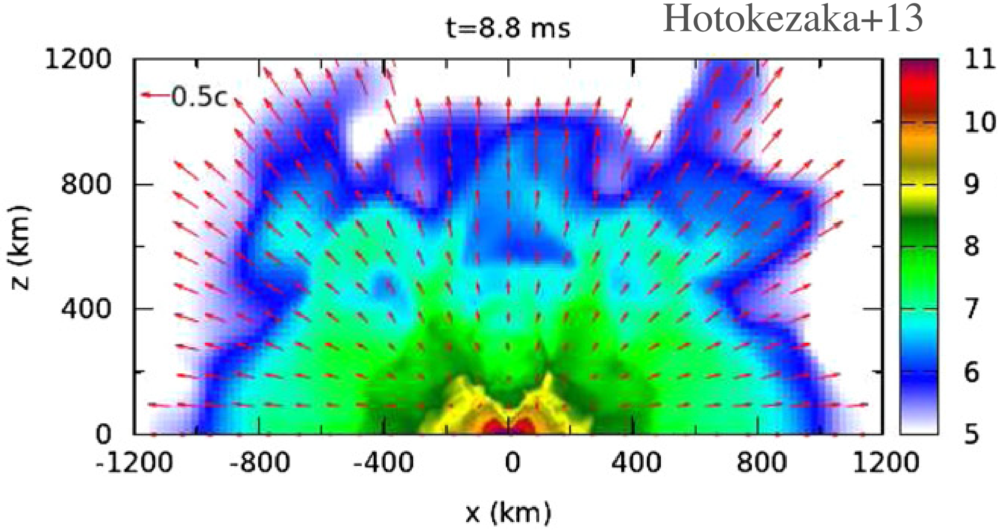
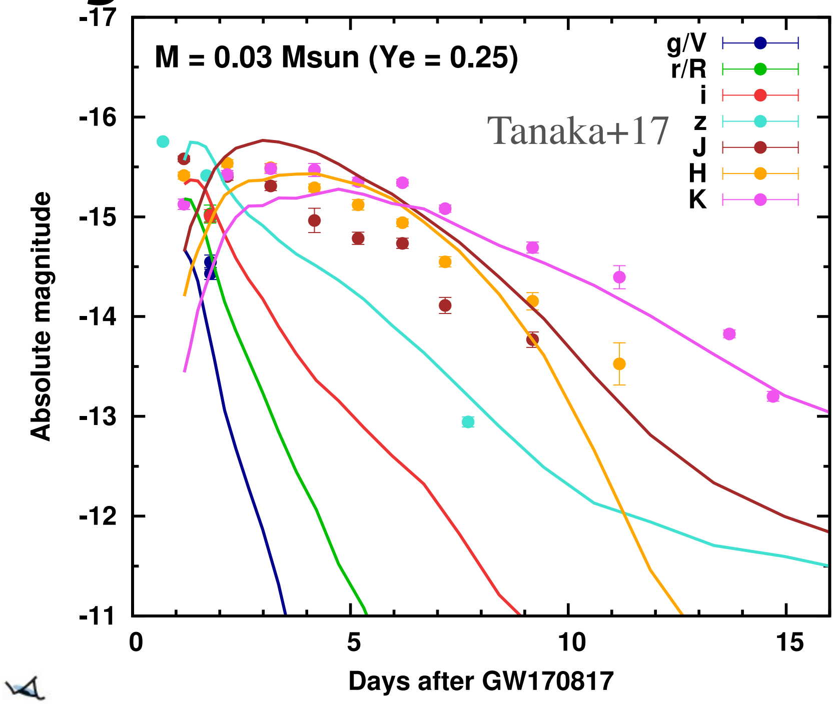
Choked jets?

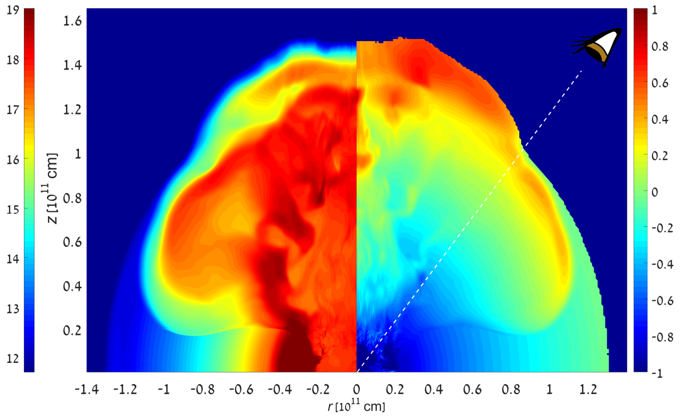


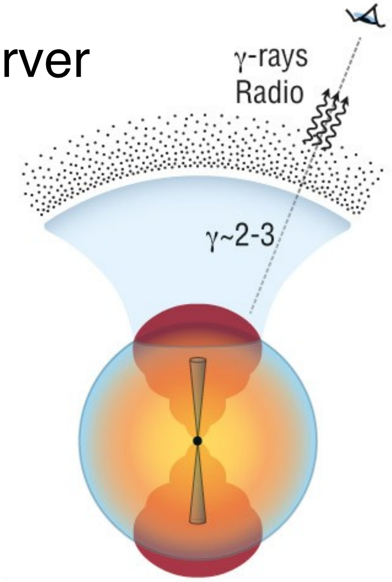


Choked Jet: Weak γ-rays

L_{iso}~10^{46} erg/s for on-axis observer

Gottlieb+18, talks in Tuesday

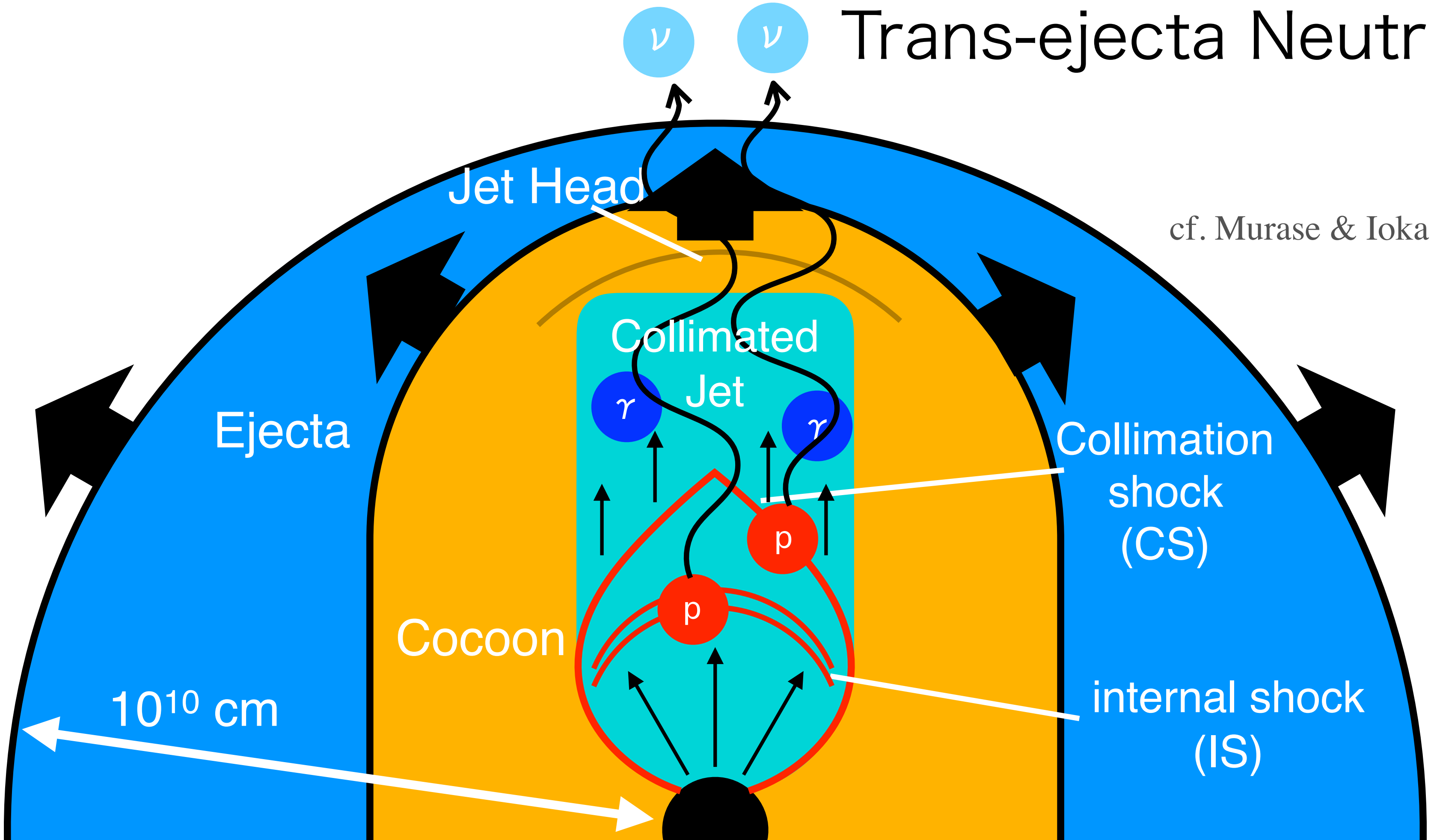




- weak prompt γ-ray and slowly rising afterglow
- **New subclass of SGRBs**
- **It would be observed in the future**

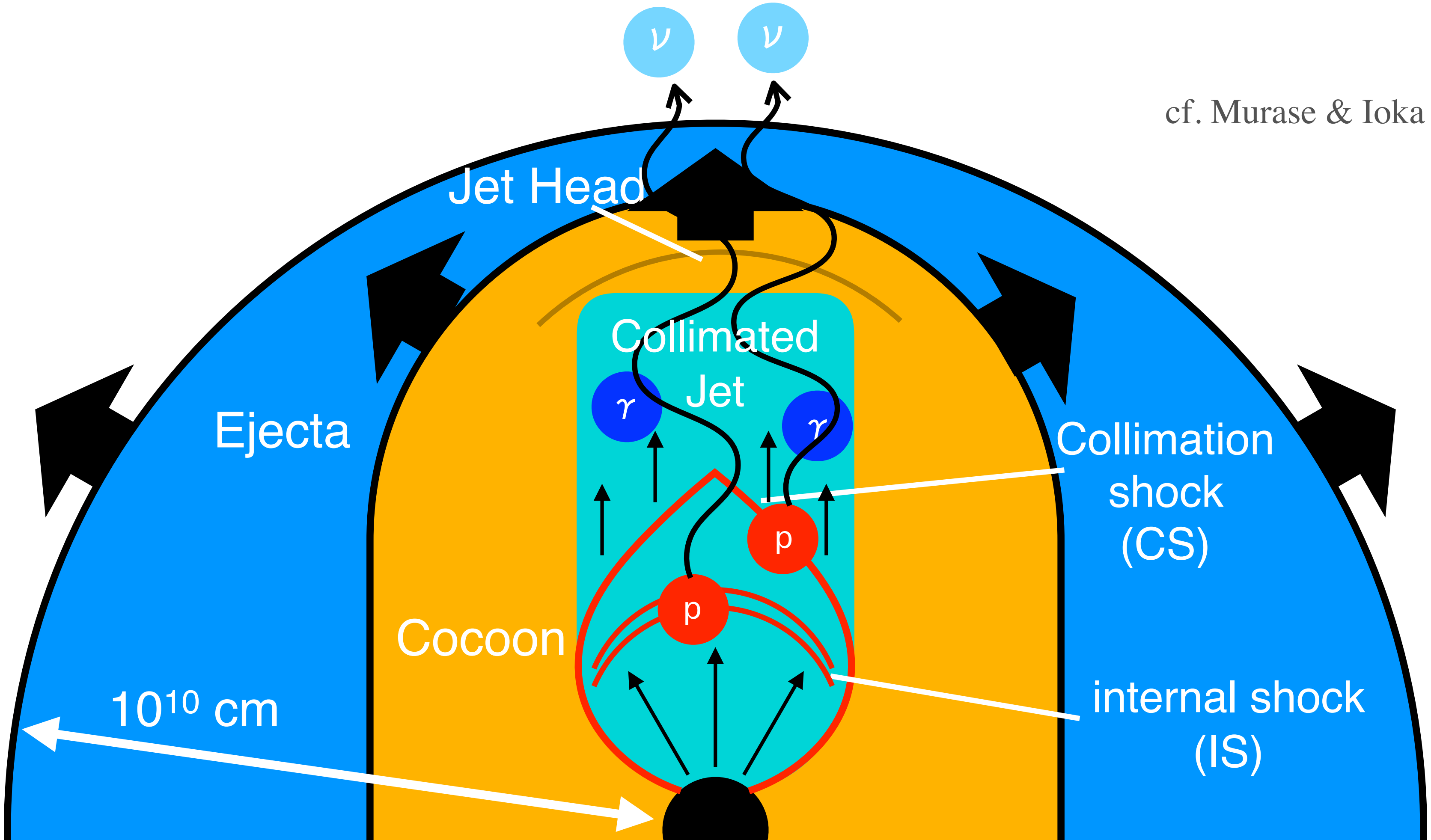
Schematic Picture

- swept-up ejecta forms cocoon surrounding the jet —> push the jet inward —> form **collimation shocks**
- Velocity fluctuations —> **internal shocks**



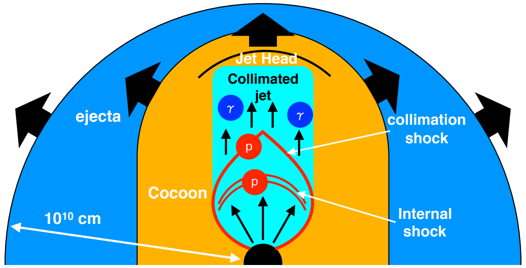
Schematic Picture

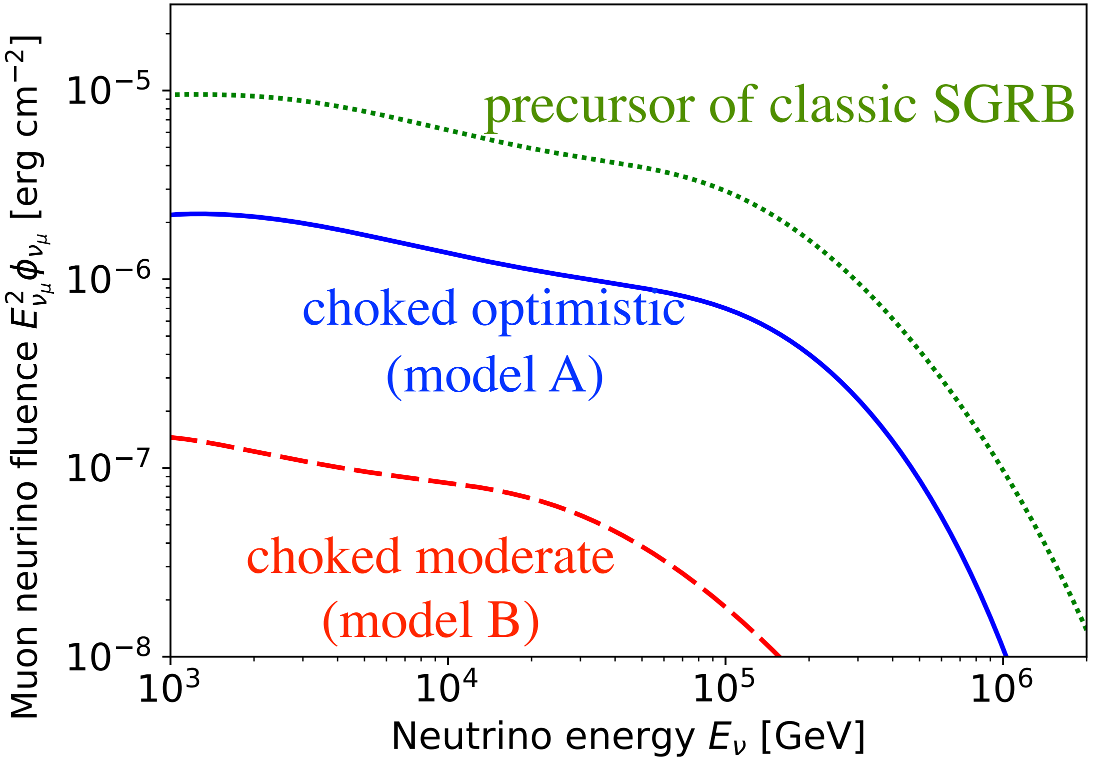
- Strong radiation density —> efficient pion coolings —> Suppression of neutrino fluency at higher energy
- **CS: Ev < 10 TeV <— low Γ ~ 3**
- **IS : Ev ~ 100 TeV <— high Γ ~ 300**



cf. Murase & Ioka 13

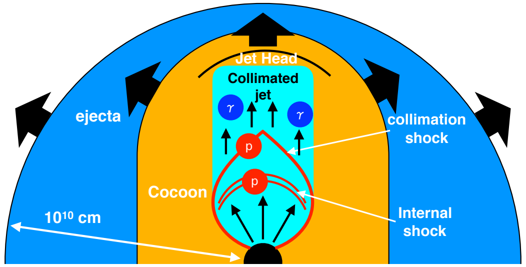
Neutrino Fluence from Choked Jets





- d_L=300 Mpc
- calorimetric system
  —> Neutrino spectrum is flat for ~1-100 TeV
- 1-100 TeV neutrinos for IS —> good for IceCube detection

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	7.0×10^{-3}	0.46

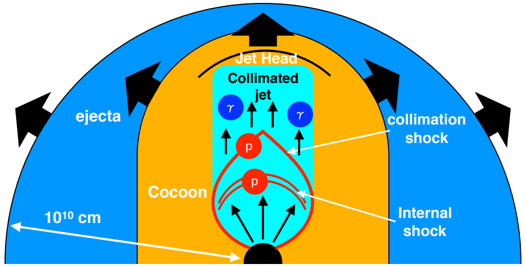
Number of detected neutrinos from single event at 300 Mpc

model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A (Optimistic)	0.035	2.9×10^{-3}	0.15
B (Moderate)	1.9×10^{-3}	1.3×10^{-4}	8.1×10^{-3}

- At 40 Mpc, detection is possible even with IceCube
- At 300 Mpc, detection is challenging even with Gen2

A	0.38	1.2
B	0.024	0.091

Detection Probability Coincident with GWs

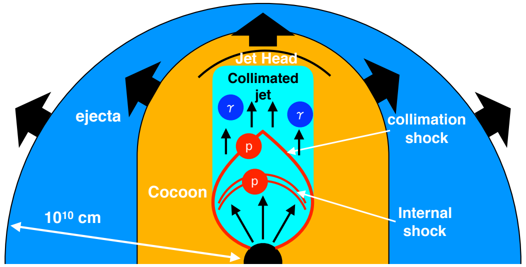


- Merger rate: R~1500 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Beaming factor: f_b~ 0.045
  —> on axis event rate: R_{on}~ 4 yr^{-1} (d < 300 Mpc)
- IceCube can detect neutrinos with a few years of operation with the optimistic model
- Gen2 can detect a coincident neutrino with 10-year operation even for the moderate model

GW+neutrino detection rate [yr^{-1}]

model	IceCube (up+hor+down)	Gen2 (up+hor)
A (Optimistic)	0.38	1.2
B (Moderate)	0.024	0.091

Detection Probability Coincident with GWs



- Merger rate: R~1500 Gpc^{-3} yr^{-1}
- Beaming factor: f_b~ 0.045
  —> on axis event rate R$_{on}$~ 4 yr^{-1}
- IceCube can detect neutrinos with a few years of
-

Choked system
—> faint prompt γ-rays
—> multi-messenger with ν & GW

GW+neutrino detection rate [yr^{-1}]

model	IceCube (up+hor+down)	Gen2 (up+hor)
A (Optimistic)	0.38	1.2
B (Moderate)	0.024	0.091

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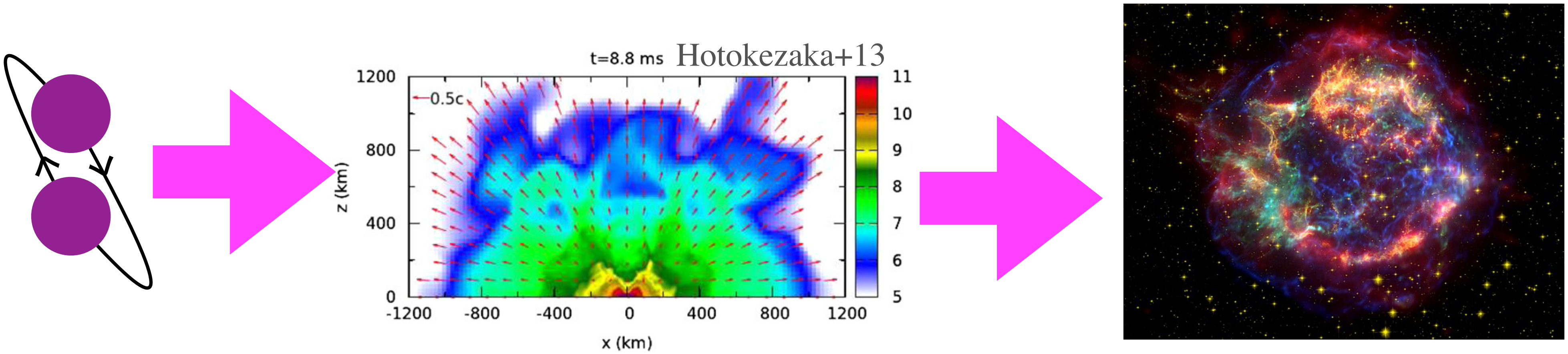
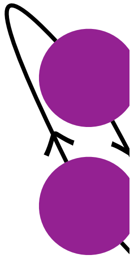
CR production at NS Merger Remnants

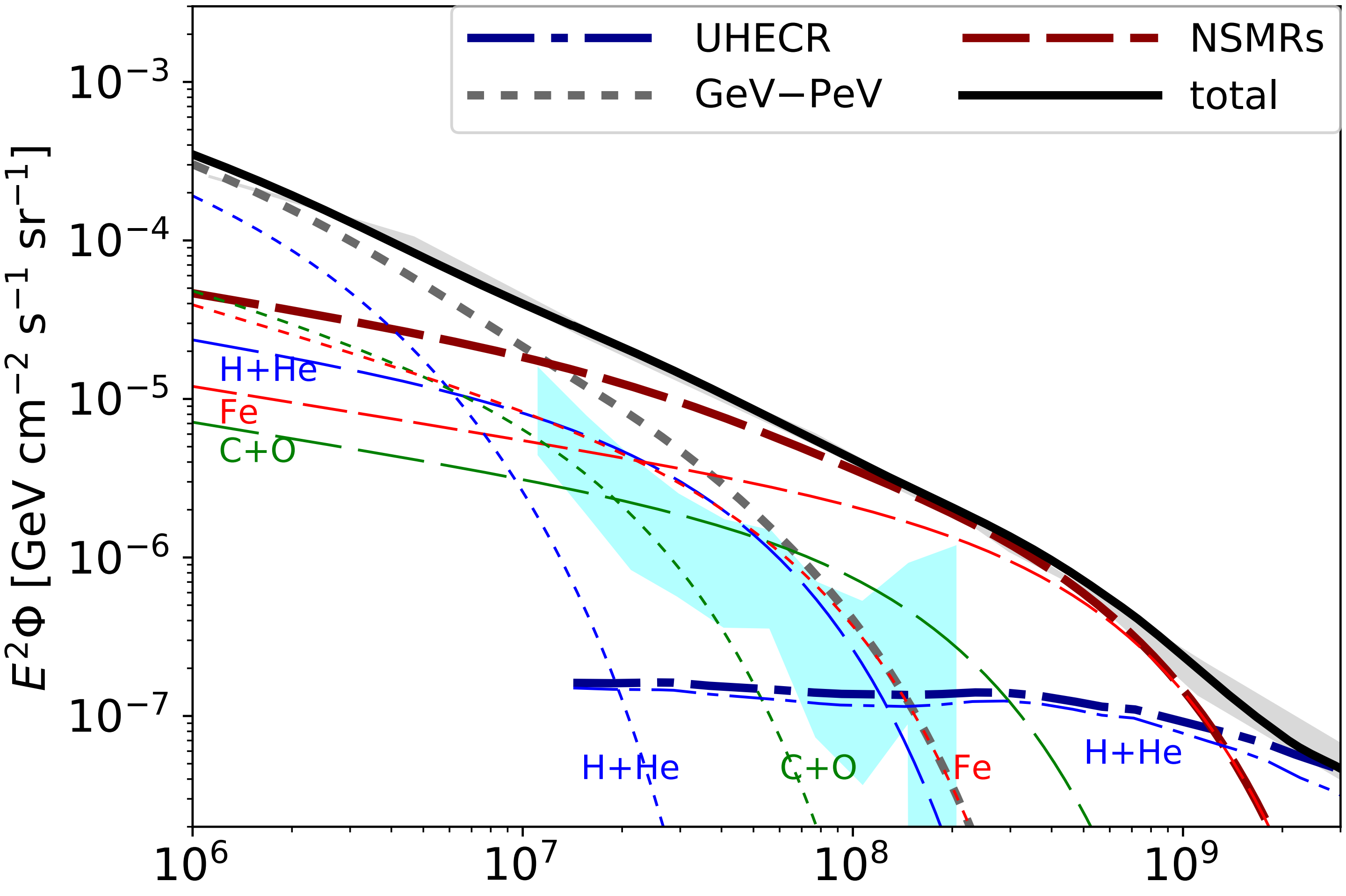


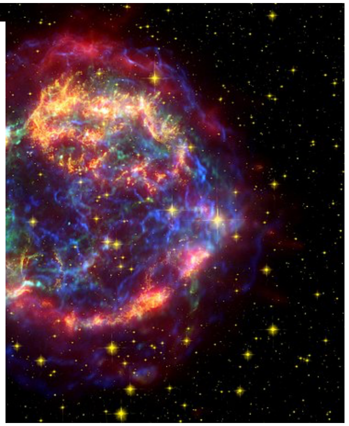
Hotokezaka+13

- Ejecta form forward shocks through interaction with ISM
  —> The forward shocks produce CRs analogous to SNRs
- Maximum energy: $t_{acc} \sim t_{age}$
  —> **20 PeV for protons, 500 PeV for iron nuclei**
  —> Between “knee” and “ankle”
- NS merger rate: R~1500 Gpc^{-3} yr^{-1} LIGO+17
  —> CR production rate in the Galaxy: ~ 1% of SNR
  —> **enough to explain CRs above “knee”**

CR production at NS Merger Remnants







- ISM
- SNRs
- R

—> **enough to explain CRs above “knee”**

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Summary

- NS mergers are interesting multi-messenger sources
- **Neutrinos associated with SGRBs are detectable with IceCube-Gen2** if SGRBs accompanies extended emissions
- Using trans-ejecta neutrinos, we can do **multi-messenger astrophysics with ν & GW** without photons
- NS merger remnants can produce **the observed CRs between knee and ankle**

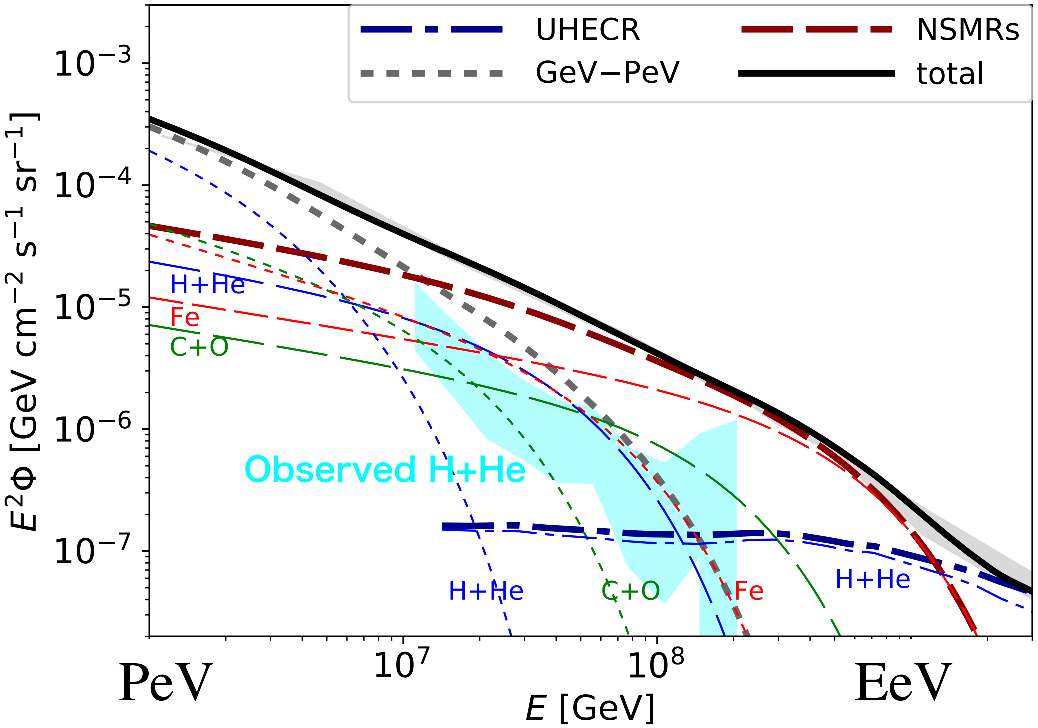
Thank you for your attention

Backup

Spectrum on Earth

- Spectrum:
  escape-limited model
  cf.) Ohira+10
- Composition:
  ISM +metal enhancement
  Caprioli +17
- One-zone ISM
  $Q_{\mathrm{inj}} \sim Q_{\mathrm{esc}}$
  cf.) Murase+18

$$(E^2\Phi)_i \approx \frac{(EQ_{E,\mathrm{inj}})_i X_{\mathrm{esc}}}{4\pi M_{\mathrm{gas}}} \propto E^{-\delta} \exp\left(-\frac{E}{E_{i,\mathrm{max}}}\right)$$



- **NSMRs can be dominant source of CRs for 10 PeV to 1 EeV**
  E < 10 PeV: GeV-PeV (SNR?), E>1EeV: UHECR (ANG?)
- Consistent with observational features:
  - Slight hardening of total spectrum at E~10 PeV
  - Light element spectrum at E~10 — 100 PeV

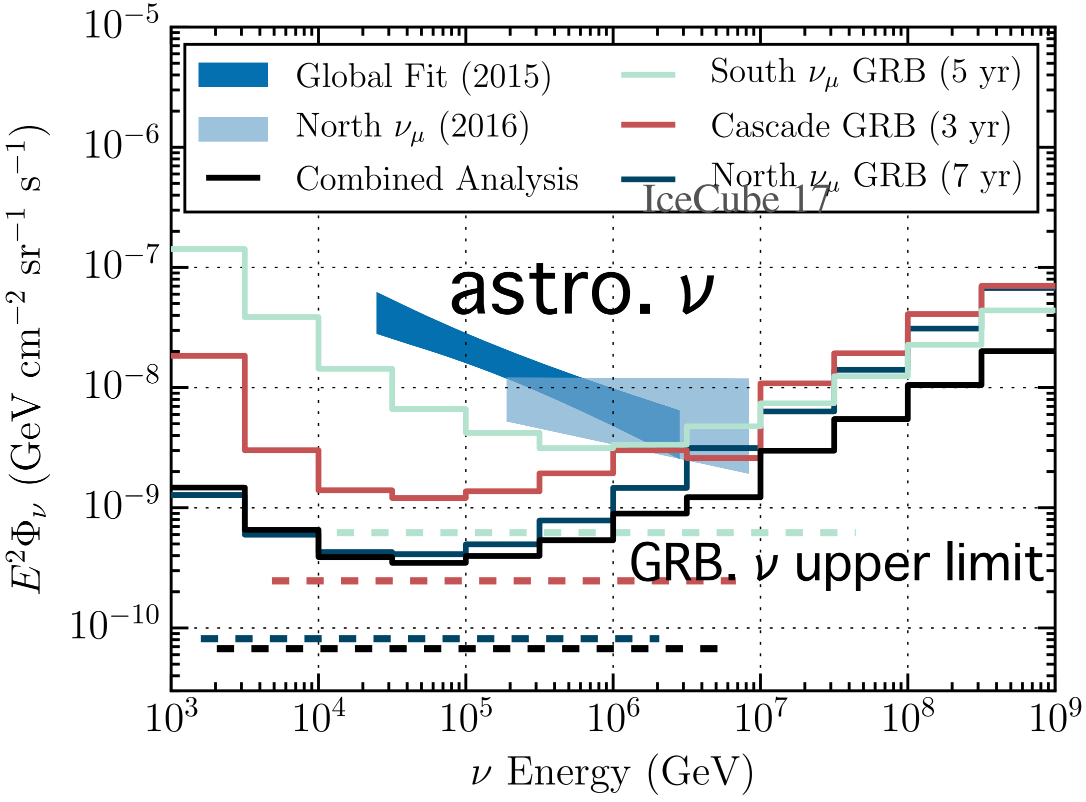
Why Neutrinos?

	Neutrino	**Photons**
Transparency	**Be able to see the inside deeply**	Only see the surface due to absorption
Probe for hadronic CRs	**Efficiently produced only from protons**	Produced from both electron and protons
Multi-messenger	**always observe all sky**	Limited field of view

Difficulty for Neutrino Astronomy

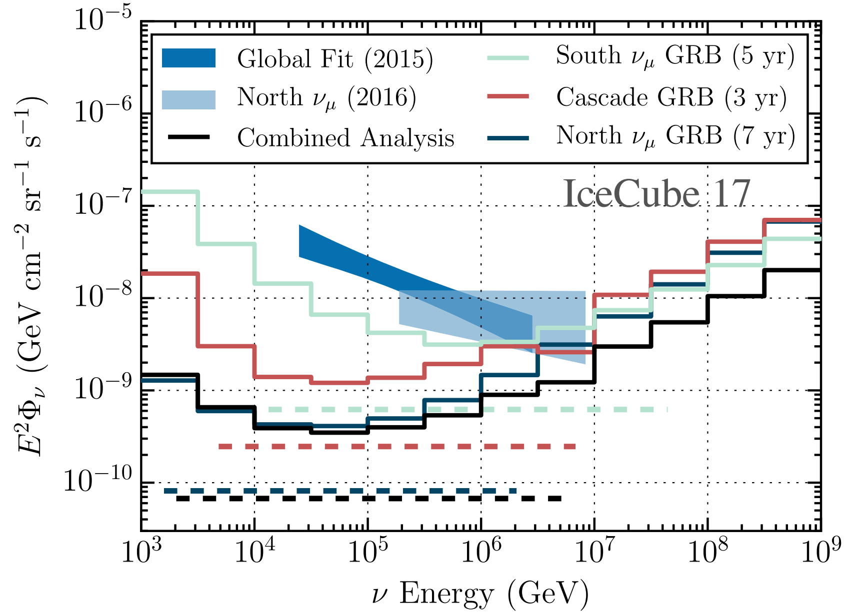
- Low detection sensitivity (~10^{-4} erg/cm^2 for PeV range)
- Low angular resolution (~1 deg for track, ~10 deg for shower)
- strong atmospheric noise (for lower energies of < 100 TeV)

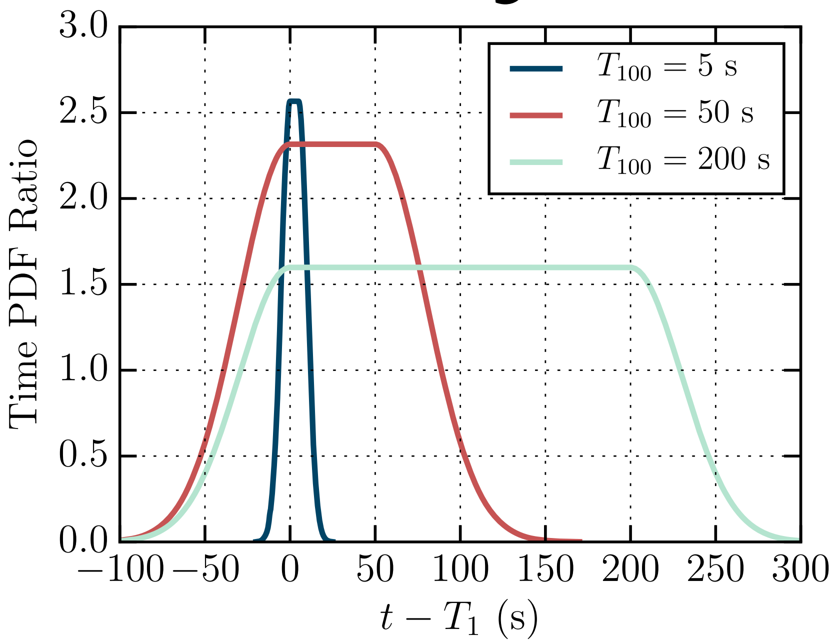
IceCube GRB Analysis



- Correlation analysis using both timing and position of GRB
  —> no correlated neutrino event so far
  —> GRB contribution to diffuse flux < 1%
- **This analysis focus on prompt emission**

IceCube GRB Analysis





These analyses focus on the prompt phase

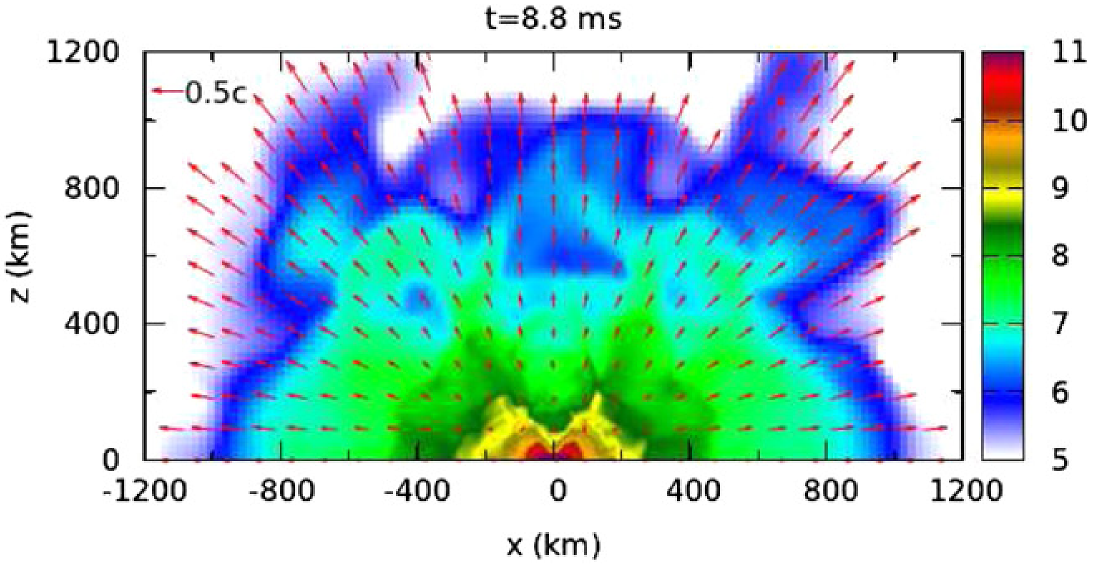
other phase is not constrained

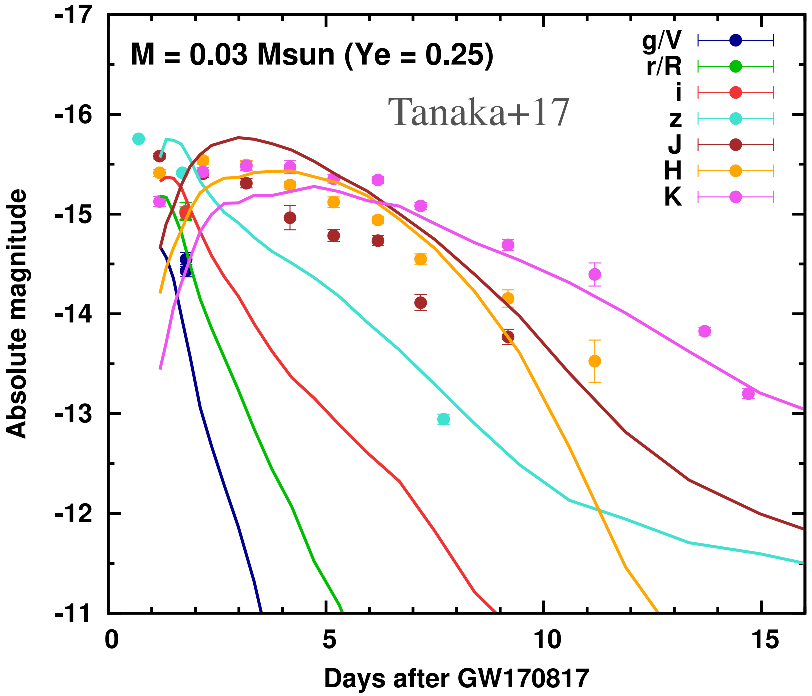
SGRBs are minority

—> constraint is not strong

Ejecta of NS Merger

Hotokezaka+13




Tanaka+17

- NS mergers creates fast & massive outflows
- Modelings of GW170817
  —> $M_{ej} \sim 0.01\text{-}0.05\ M_{sun}$, & $V_{ej} \sim 0.1\text{-}0.3c$
  —> $E_{k,NSM} \sim 10^{51}$ erg
- **higher velocity than SNe,**
- **comparable kinetic energy to SNe**

e.g. LIGO+17

Detection Probability

- Expected number of ν events:

$$\overline{\mathcal{N}_\mu} = \int \phi_\nu A_{\rm eff}(\delta,\ E_\nu) dE_\nu,$$

- Detection probability is poisson:

$$p_k \ = \ \overline{\mathcal{N}}^k \exp(-\overline{\mathcal{N}})/k!$$

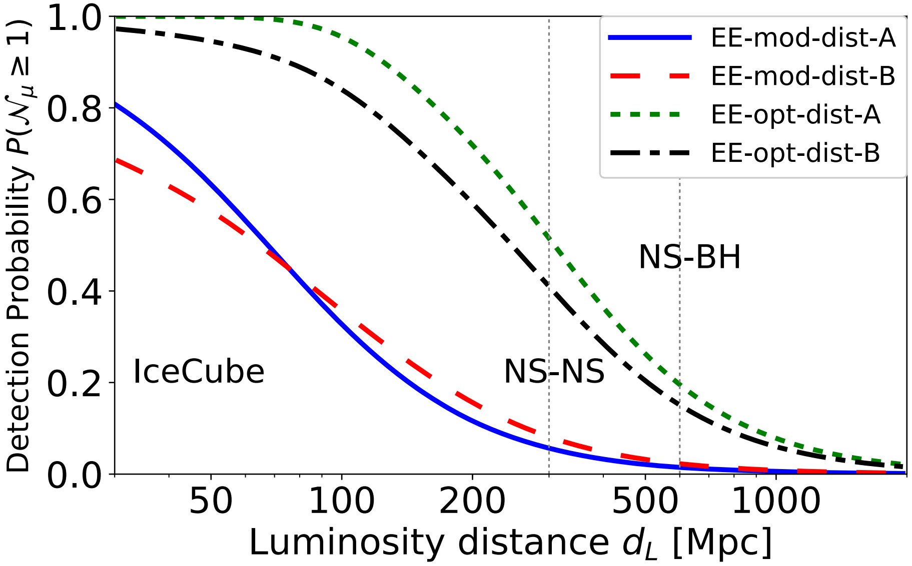
- Assume distribution of Γ

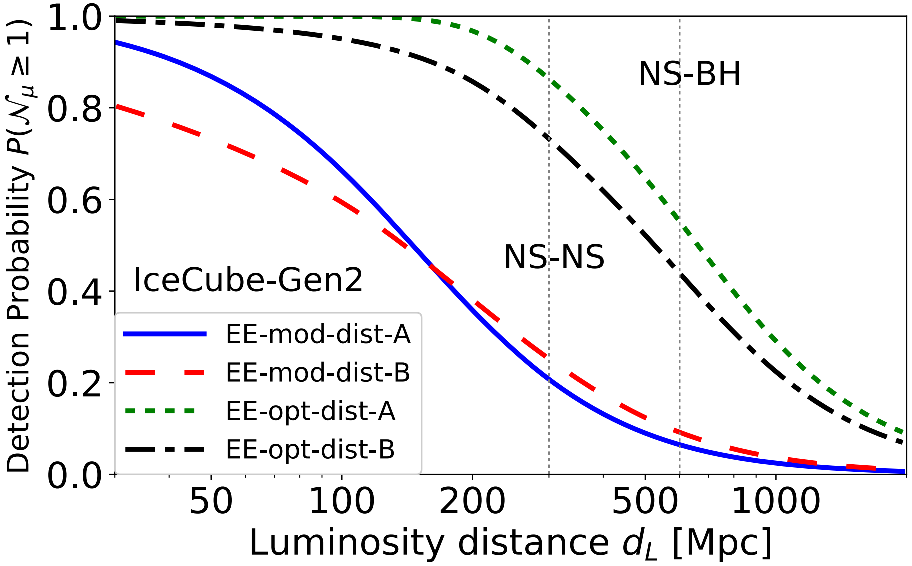
$$F(\Gamma) = \frac{dN_\Gamma}{d\ln\Gamma} = F_0 \exp\left(-\frac{(\ln(\Gamma/\Gamma_0))^2}{2(\ln(\sigma_\Gamma))^2}\right)$$

- Estimate the detection probabilities

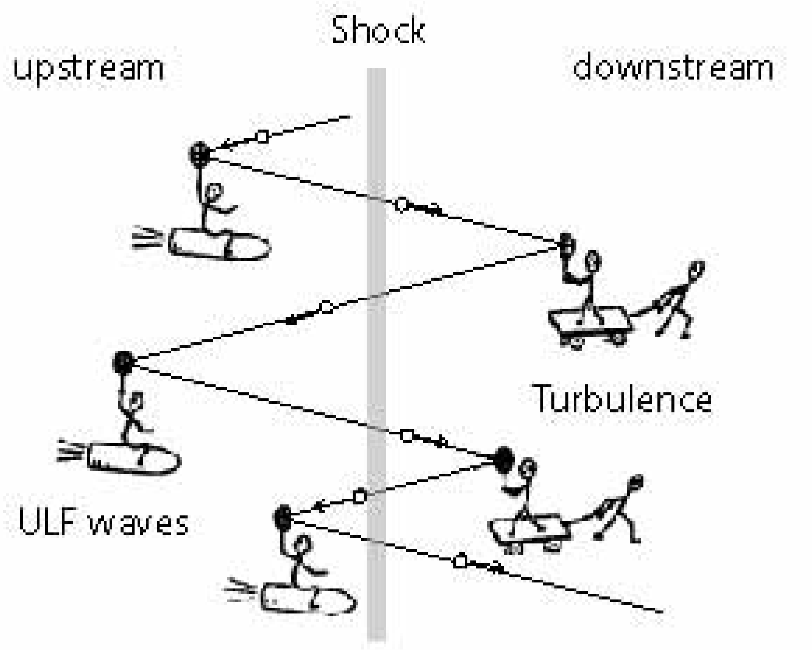
$$P_k = \int d\Gamma F_\Gamma p_k$$

$$P(\mathcal{N}_\mu \geqslant 1) = 1 - P_0$$



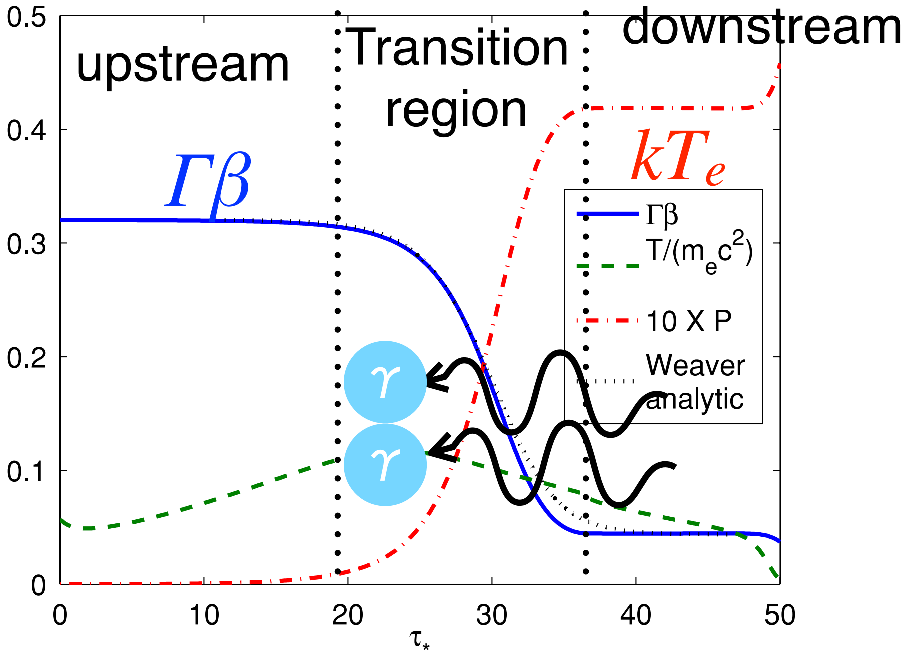


Particle Acceleration



Treumann+ 08

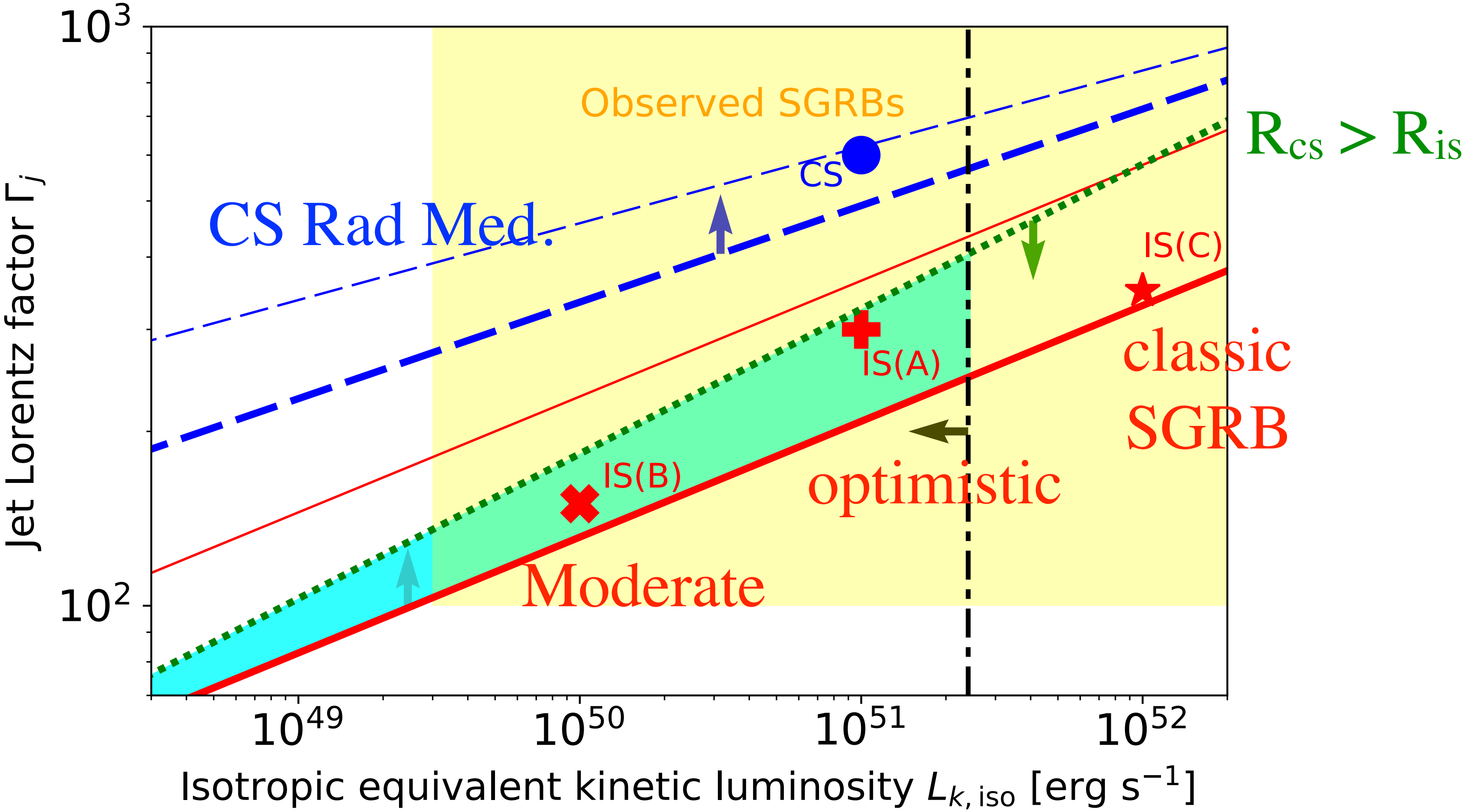
Diffusive acceleration



Budnik+10

- Particle acceleration requires **sharp velocity jump** in λ_{mfp}
- **High upstream density** —> **no particle acceleration**
  (high density —> radiation pressure dominant @ down stream
  —> photons diffuse to upstream —> decelerate the upstream fluid
  —> gradual velocity change [Radiation Mediated Shock])

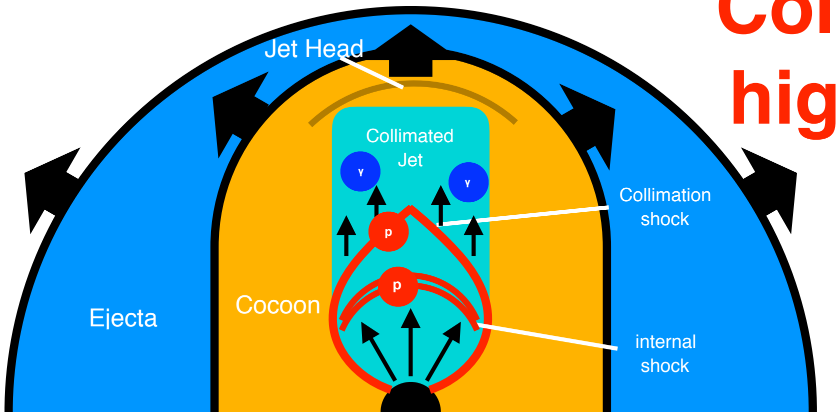
Particle Acceleration



- Cosmic-ray production requires high Lorentz factor jets
  $\Gamma \sim 200$ for internal shocks, $\Gamma \sim 500$ for collimation shocks
- High Γ for internal shock leads to larger dissipation radius
  —> inconsistent with our assumption

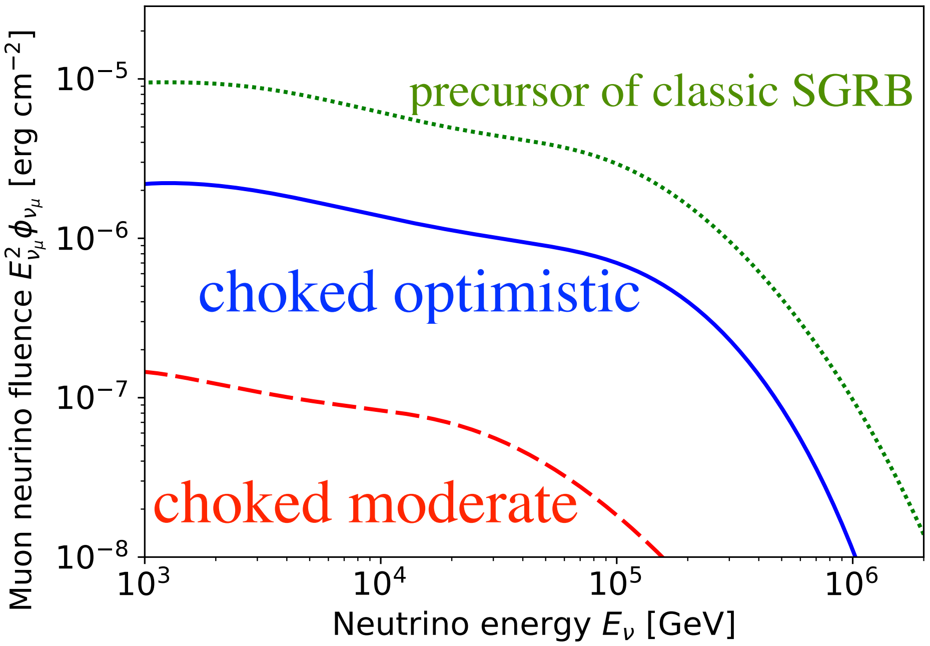
Critical Energies

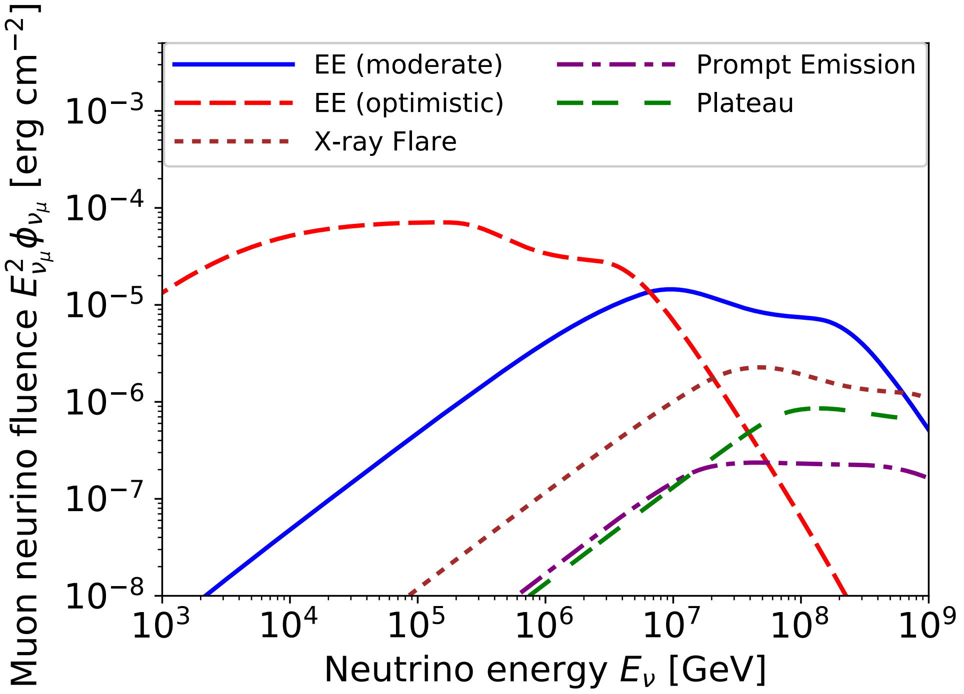
- High-photon density —> photomeson production limits acceleration $E_{p,max} \sim 1$ PeV for CS, $E_{p,max} \sim 10$ PeV for IS
- Strong magnetic field —> synchrotron is effective $E_{\pi,syn} \sim 0.2$ TeV for CS, $E_{\pi,syn} > 100$ PeV for IS
- High baryon density —> Hadronic collisions is important $E_{\pi,had} \sim 1.5$ TeV for CS, $E_{\pi,had} \sim 5$ PeV for IS
- Small dissipation radius: —> adiabatic cooling is effective for IS: $E_{\pi,ad} \sim 1$ PeV



Collimation shock cannot produce high-energy neutrinos of > 10 TeV

Choked or Successful?





- E < 300 TeV
- E > PeV