High-energy Emissions from GW sources

Penn State (IGC Fellow)

Shigeo S. Kimura

References

1) Kimura, Murase, Meszaros, Kiuchi, 2017, ApJL, 848:L4
2) Kimura., Murase, Meszaros, Bartos, in prep
3) Murase, Toomey, Fang, Oikonomou, Kimura et al. 2018, ApJ, 854, 60

Collaborators

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PennState

Outline

- Introduction
- High-energy Neutrinos from SGRBs

  SSK, Murase, Meszaros, Kiuchi 17
- Sub-photospheric Neutrinos from NS mergers

  SSK, Murase, Meszaros, Bartos in prep
- Long-duration HE-photons from NS mergers

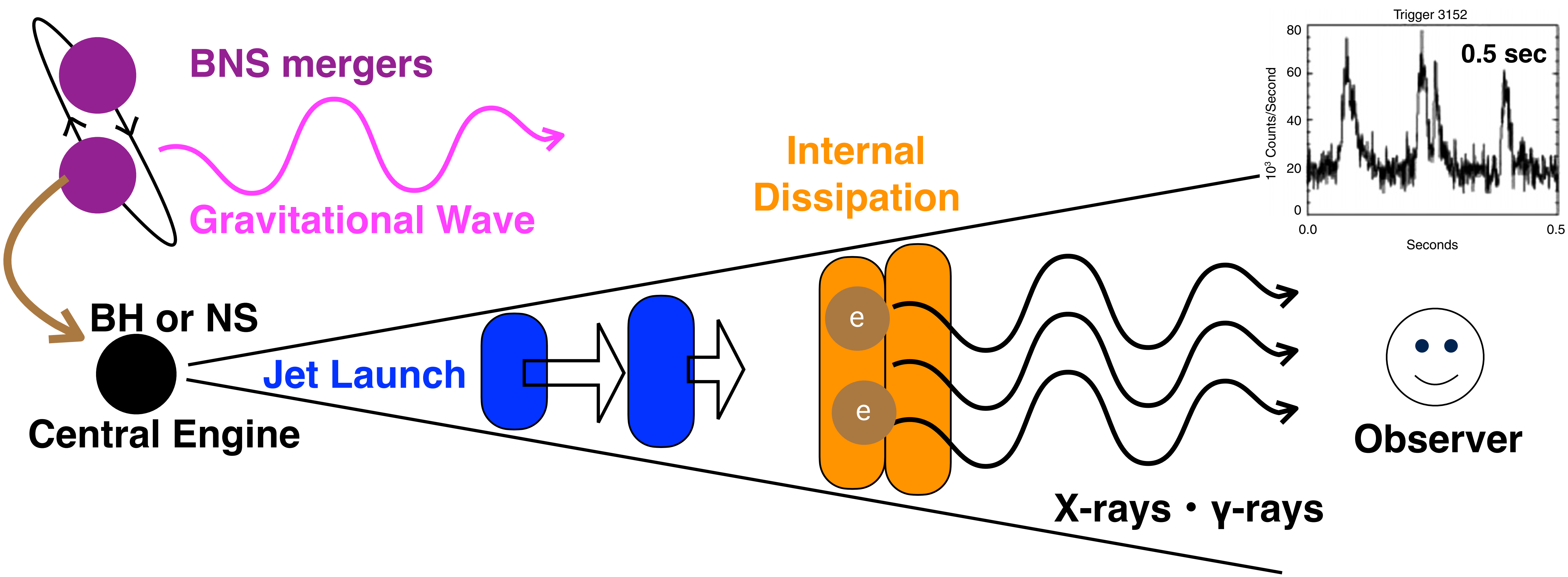
  Murase, +, SSK et al. 18
- Summary

Introduction

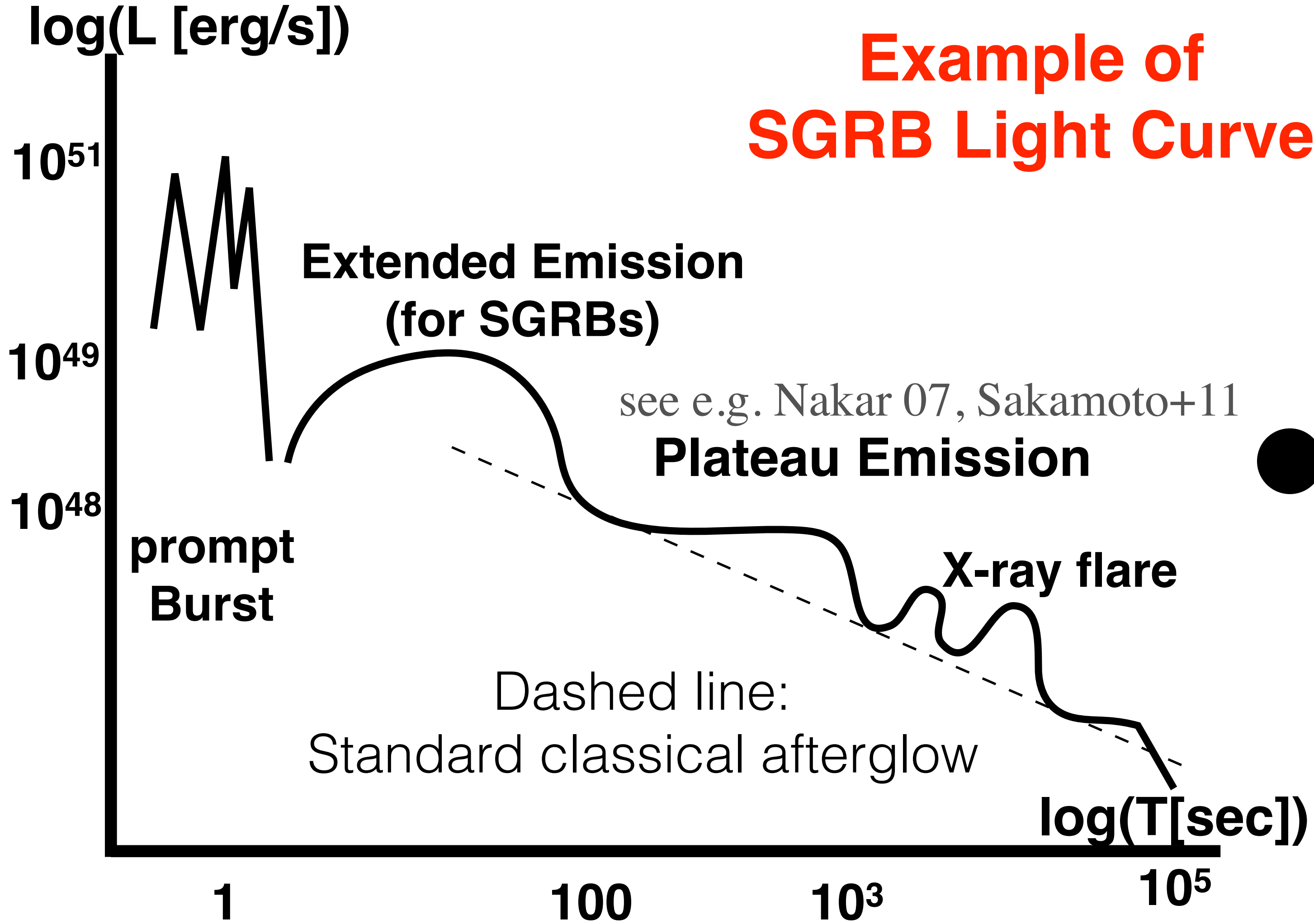
Short Gamma-ray Bursts

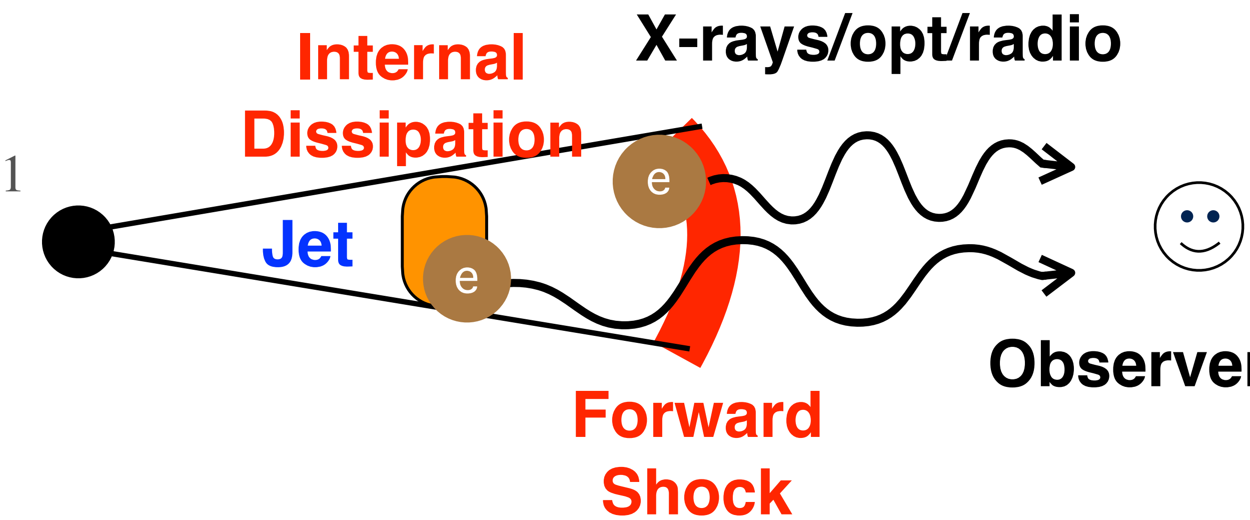
see e.g. Berger 2014

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



Afterglow of SGRBs

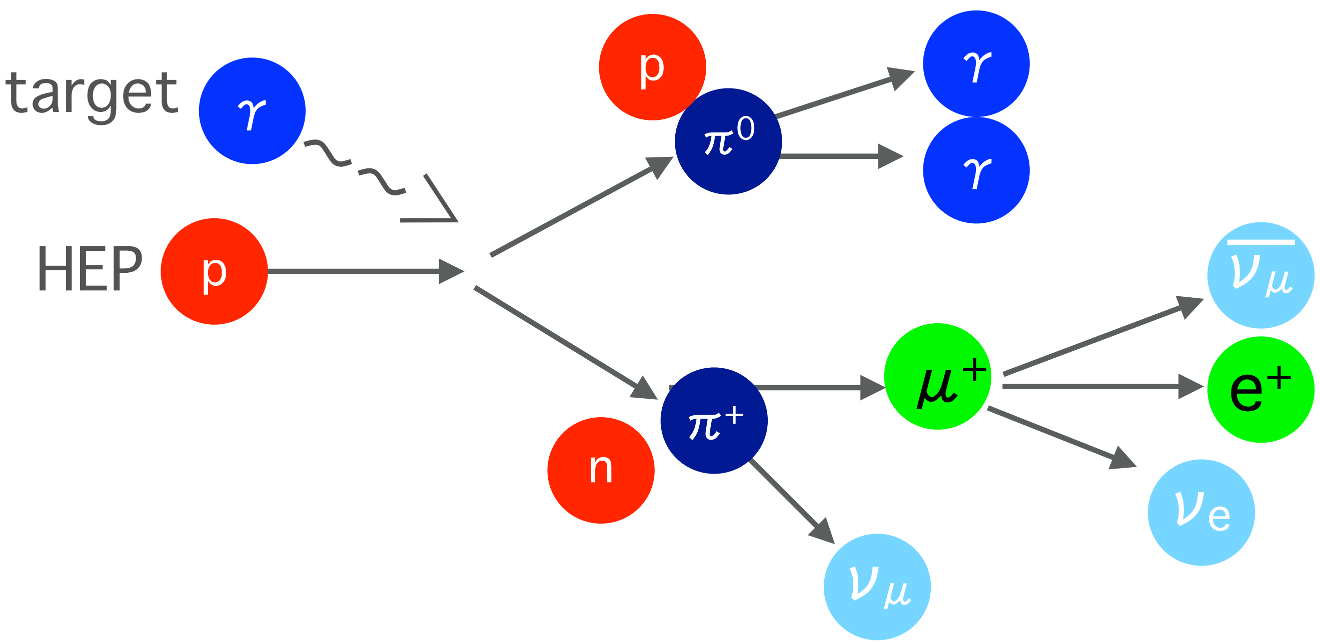


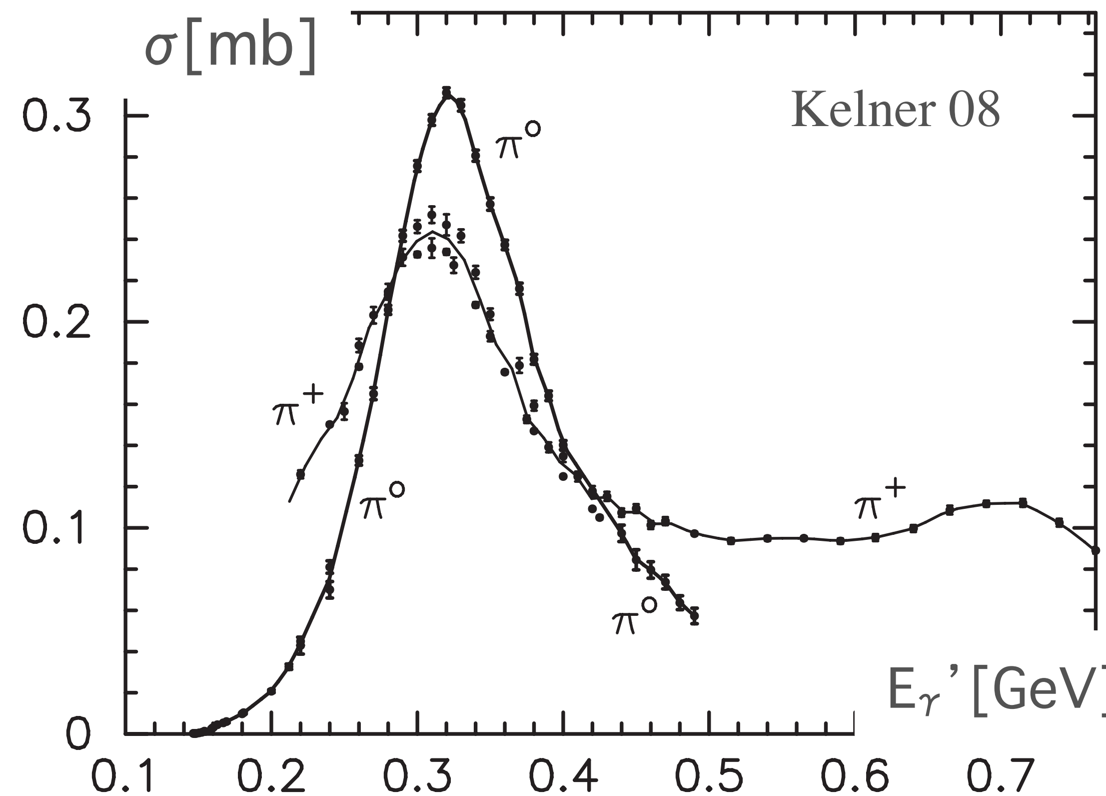


- Prompt emission is followed by afterglows
- Standard afterglow: Forward shock model, power-law decay
- Extended Emission, plateau emission, X-ray flares have similar features to prompt bursts —> **Late-time engine activity?**
- **Late time activities have comparable total energy to prompt burst**

GRB Neutrinos Waxman 97

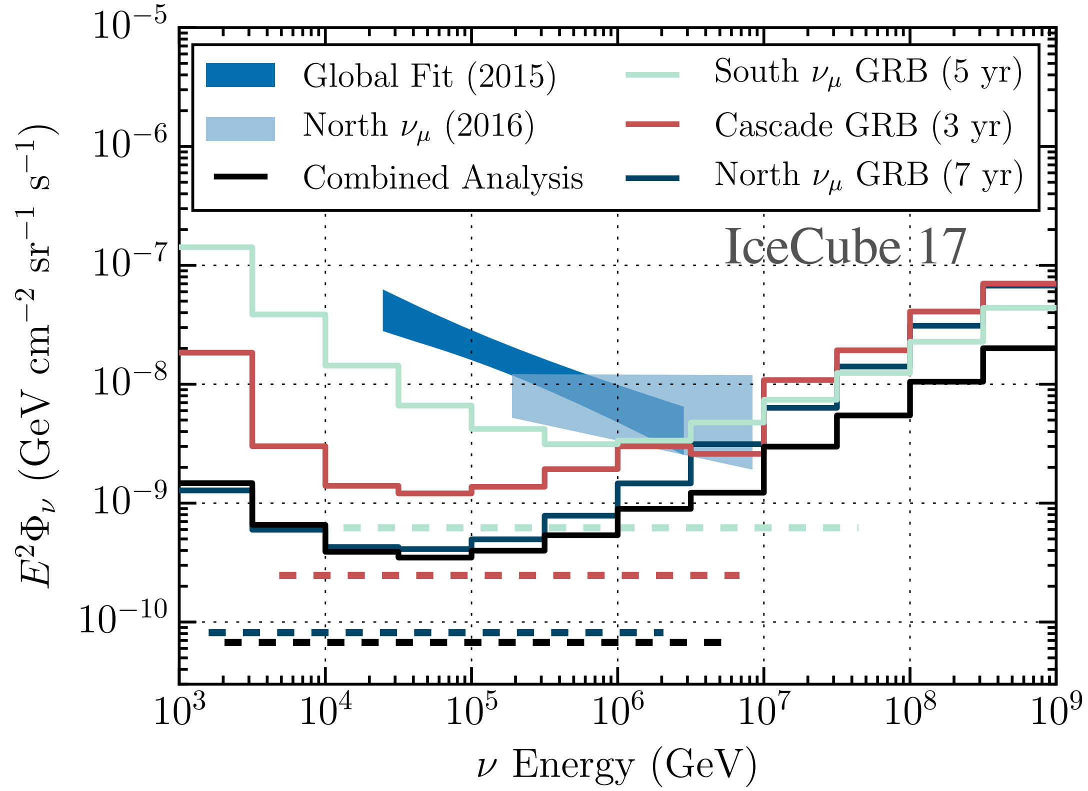
- Photomeson production (pγ)





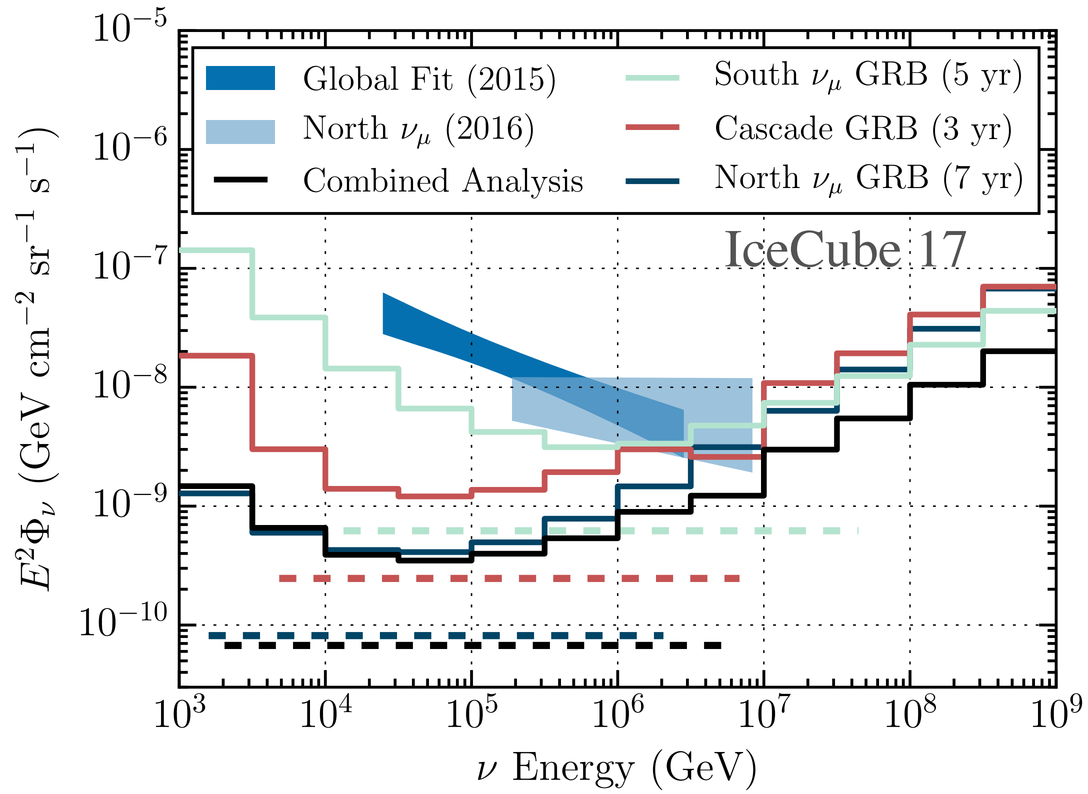
- Cosmic rays in the GRB emission region —> neutrino emissions through pγ interaction
- Peaky cross section: Target γ ~ 200 keV —> neutrino energy ~ 10 TeV
- Neutrino detection: **Evidence of hadronic Cosmic-rays**

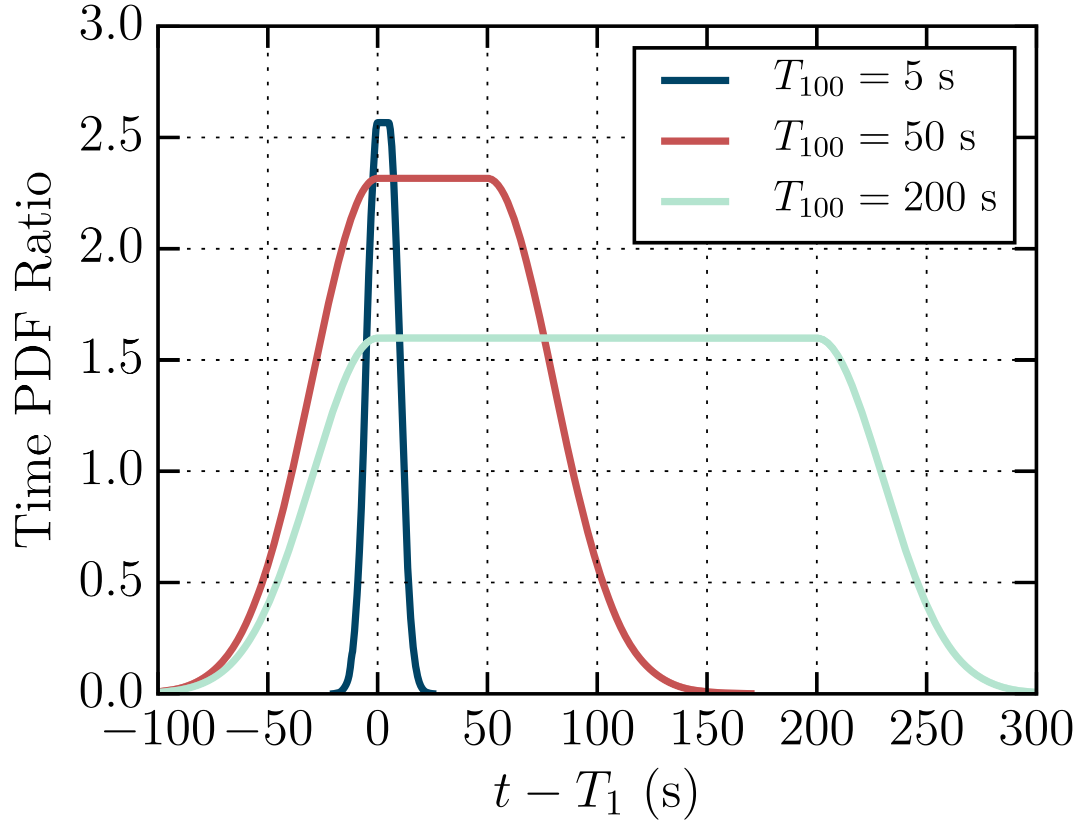
IceCube GRB Analysis



- Using the timing and position information of each GRB, IceCube put the limit on GRB associated neutrinos —> GRB contribution < 1%

IceCube GRB Analysis





These analyses focus on the prompt phase

afterglow phase is not constrained

SGRBs are minority

—> constraint is not strong

GW170817

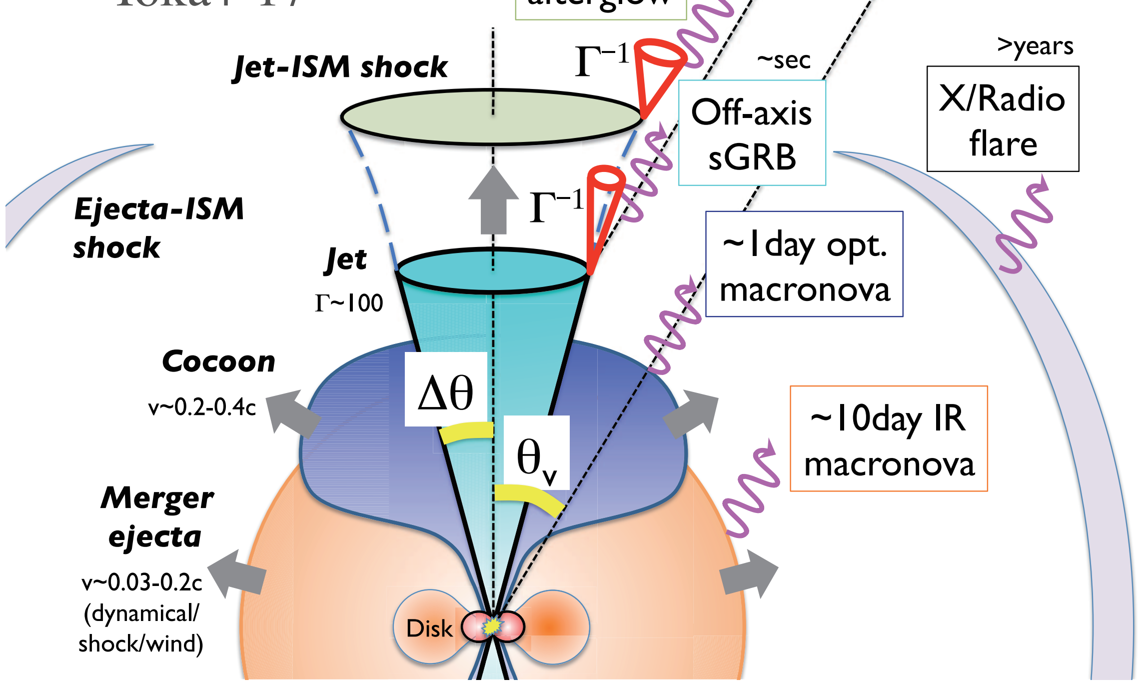
LIGO+ 17, J-GEM 17

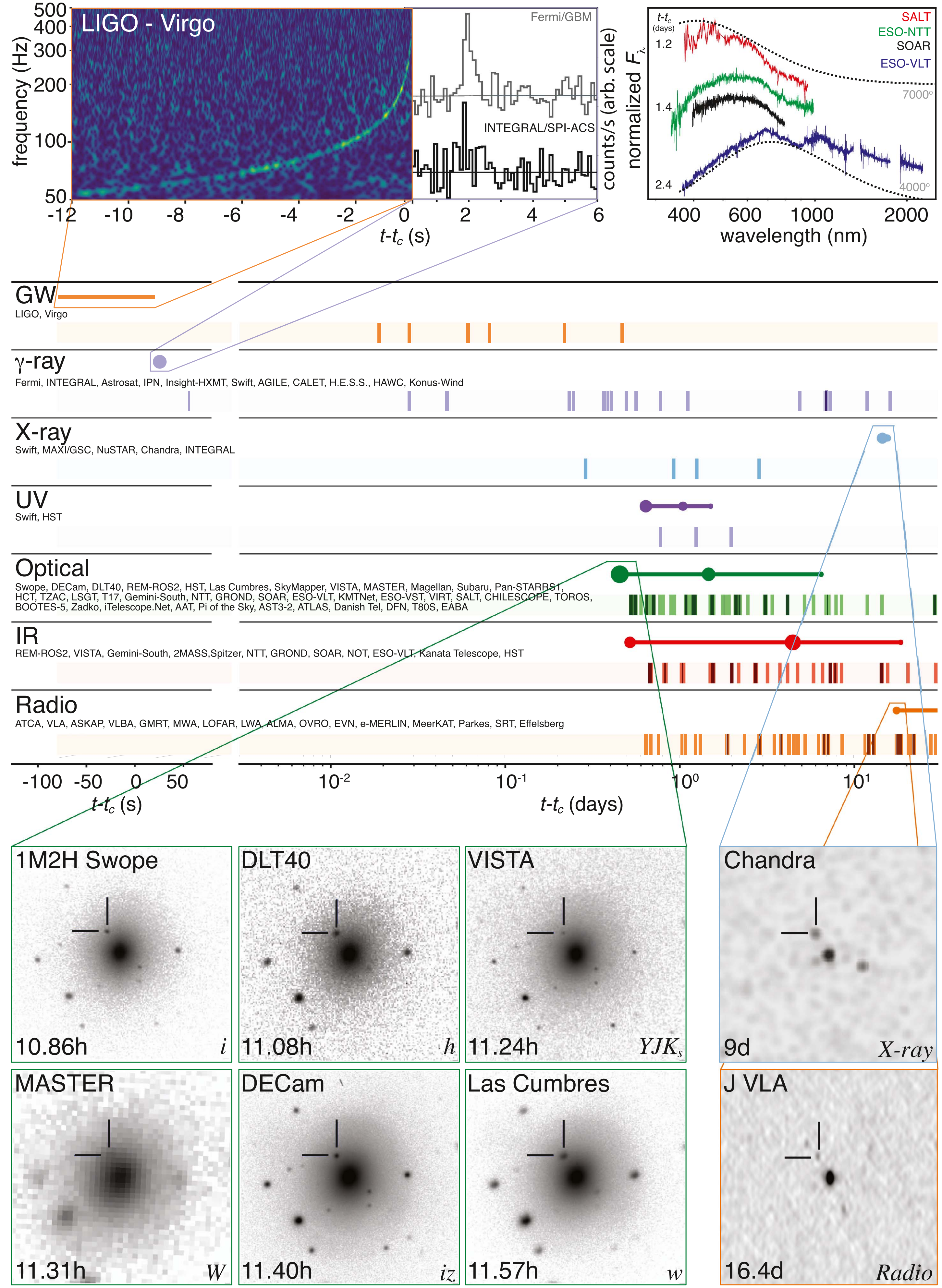
- The first detection of NS-NS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray

  Talk by Tanaka-san, Sakamoto-san, Mori-san, Hachiya-san, Kawabata-san, Kokeyama-san

- **Do NS-NS mergers emit high-energy γ-rays and neutrinos?**

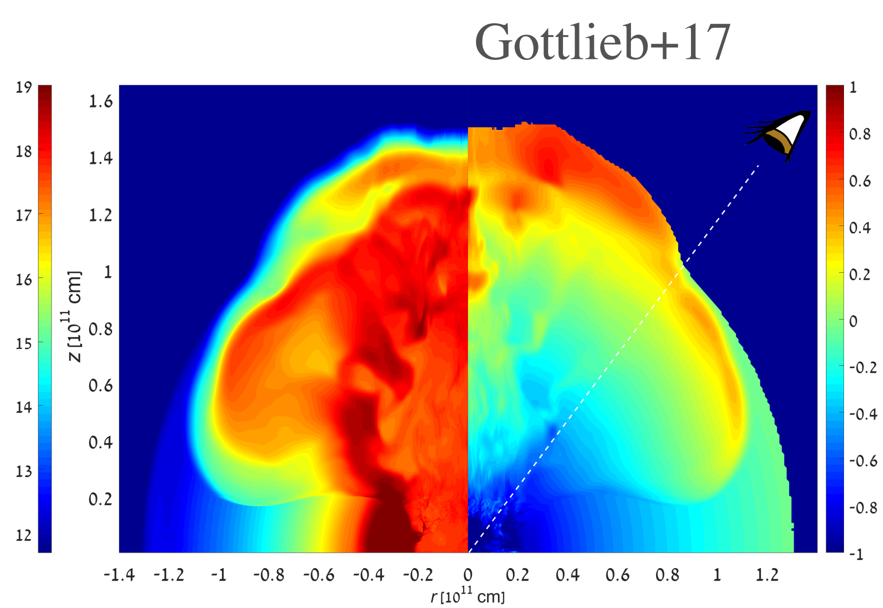
Ioka+ 17

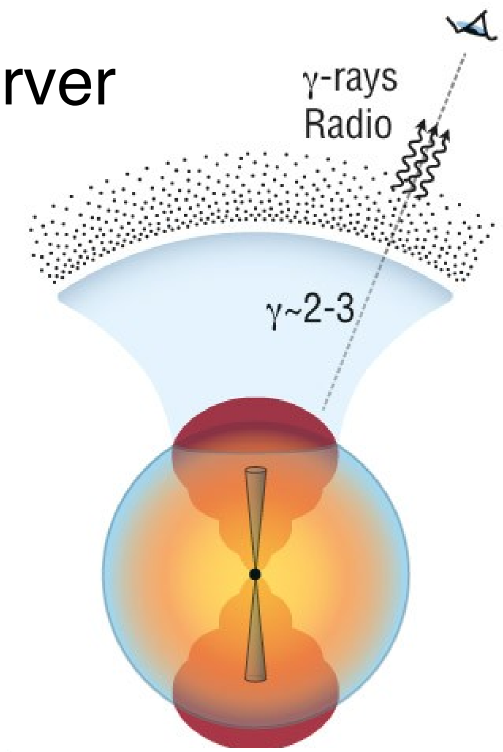




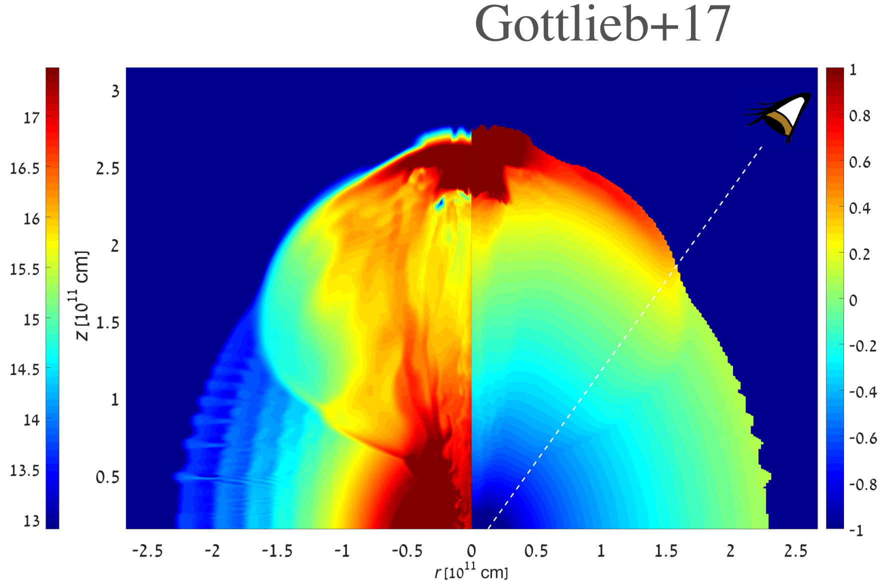
Choked or Successful?

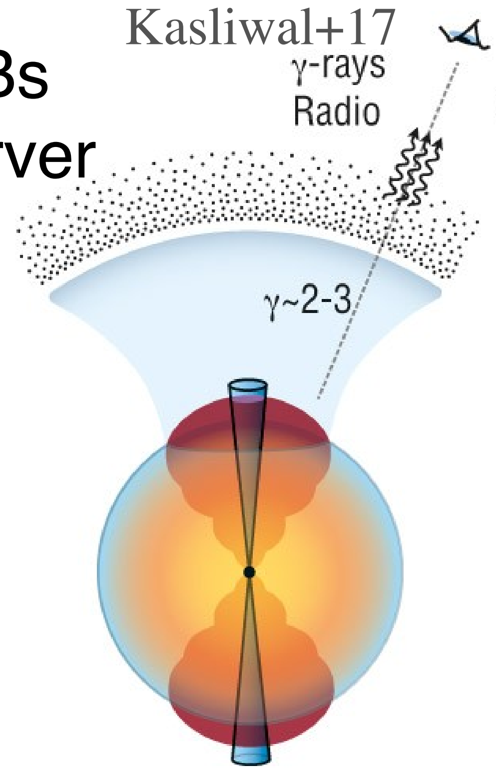
Choked Jet: Weak γ-rays
L_{iso}~10^{46} erg/s for on-axis observer



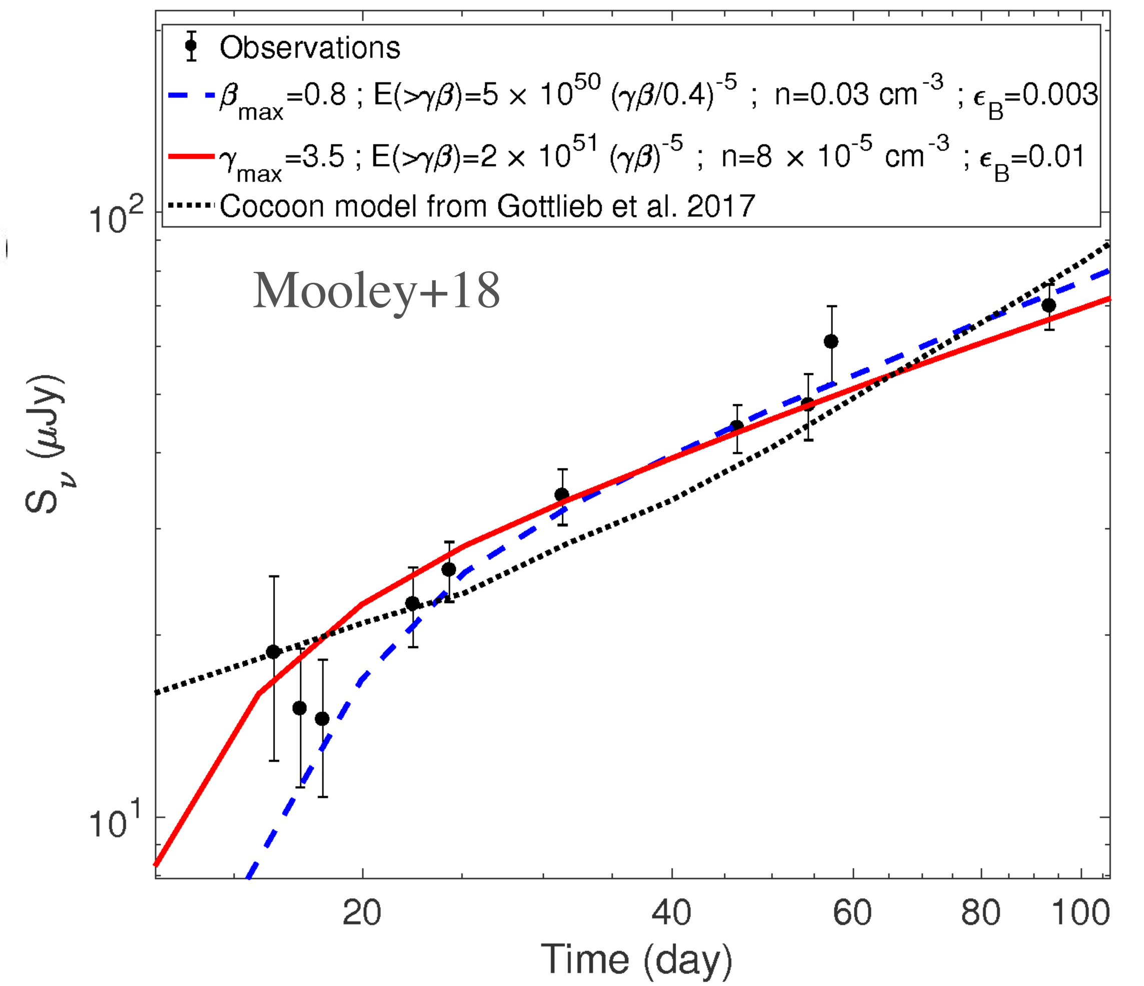


Successful Jet: classical SGRBs
L_{iso} >10^{50} erg/s for on-axis observer





- Both models can reproduce prompt γ-ray and afterglow of GW170817
- **Choked scenario implies new subclass of SGRBs**



High-energy Neutrinos from short gamma-ray bursts

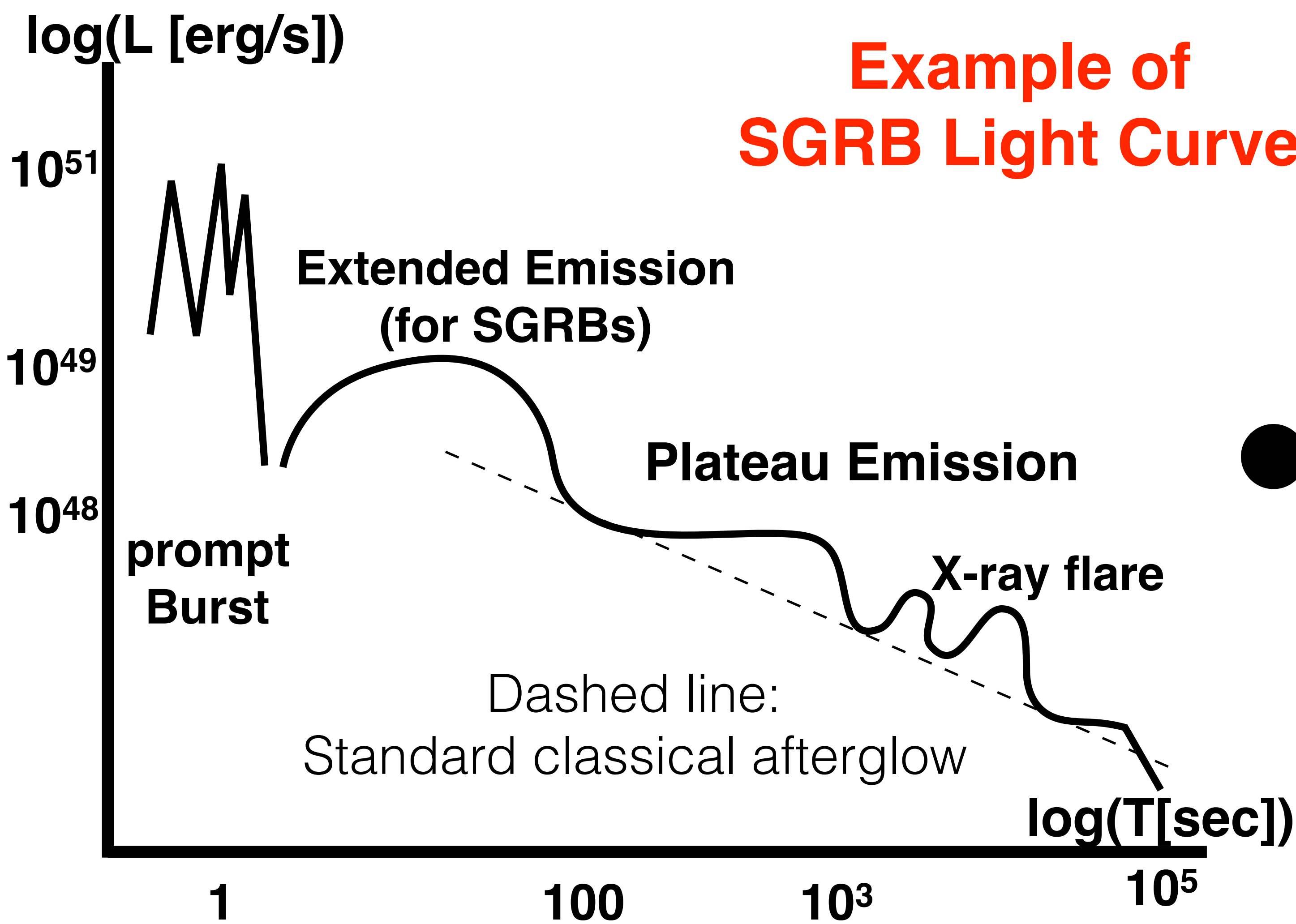
1) Kimura, Murase, Meszaros, Kiuchi, 2017, ApJL, 848:L4
(This work was done before the detection of GW170817)

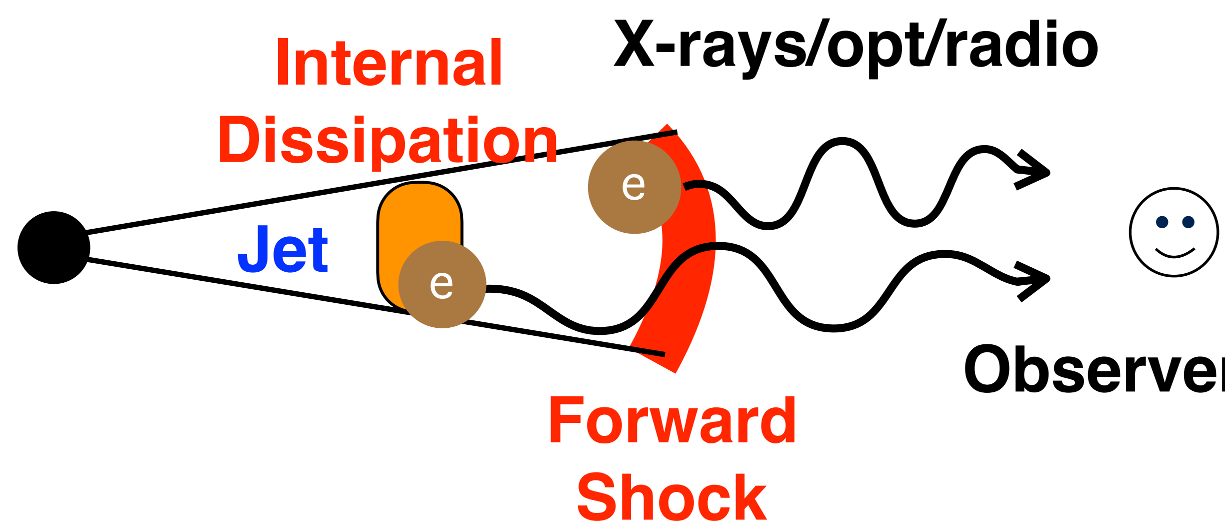
Questions:

Can SGRB emit observable neutrinos?

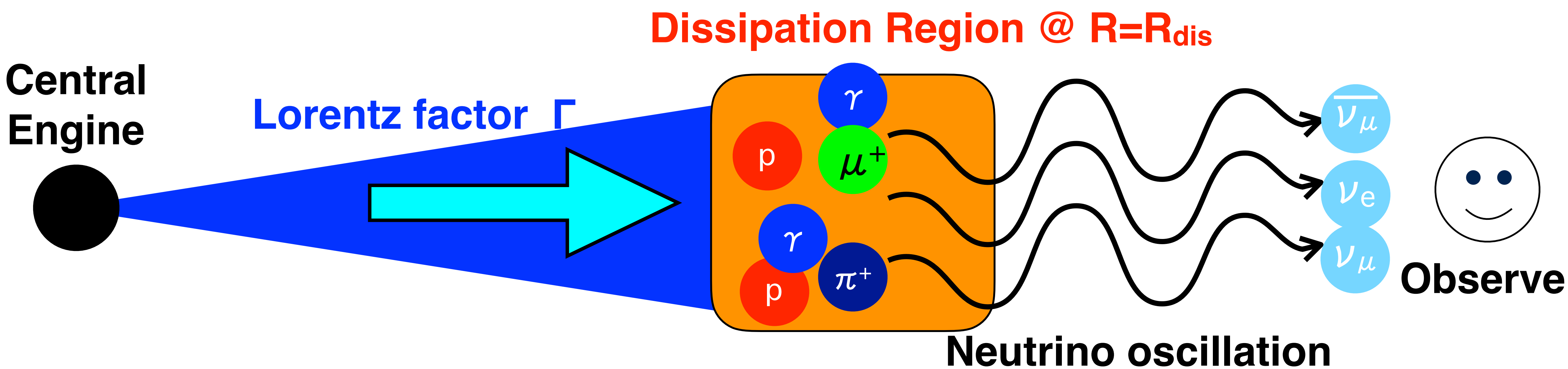
Which component can emit observable neutrinos?

Can we expect simultaneous detection with GW?





Multi-component One-zone model

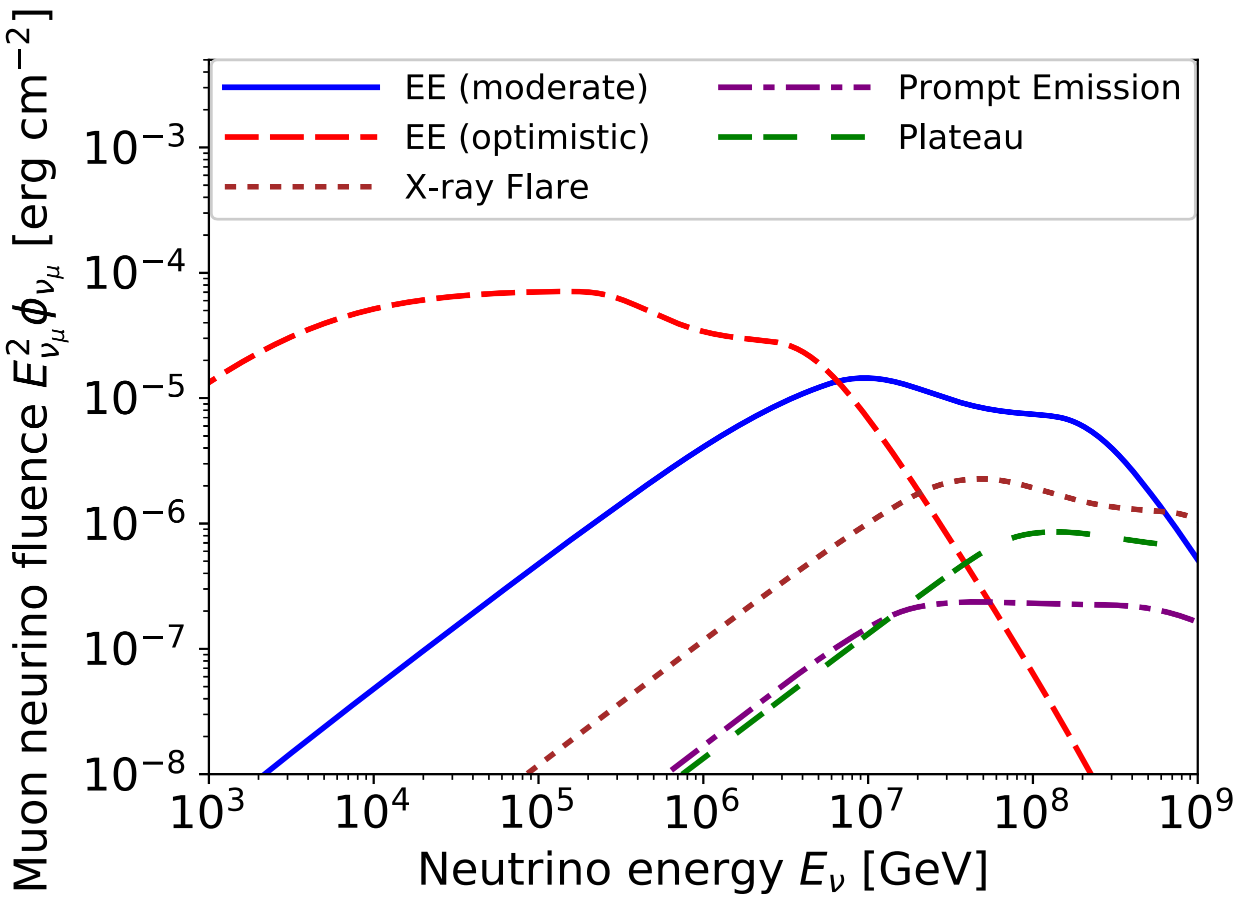


- Calculate ν fluence from each component by one-zone model
- Power-law proton injection: $E_p^2 dN_p/dE_p \sim \xi_p E_{\gamma,iso} / \ln(E_{p,max}/E_{p,min})$
- Proton cooling processes: synchrotron & adiabatic coolings
- μ and π also cool down by synchrotron & adiabatic coolings

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

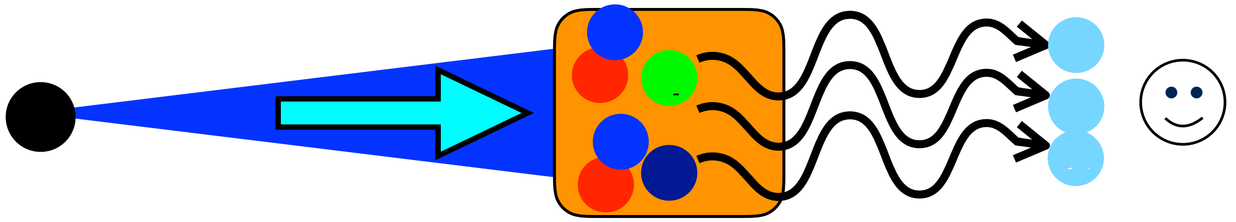
$$f_{p\gamma} = t_{p\gamma}^{-1} / t_{p,\mathrm{cl}}^{-1} \qquad f_{\sup \pi} = 1 - \exp(-t_{\pi,\mathrm{cool}}/t_{\pi,\mathrm{dec}})$$

Neutrino Fluence



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
- $\Gamma\downarrow$ or $R_{dis}\downarrow$ —> photon density ↑ —> fluence ϕ↑



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:

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

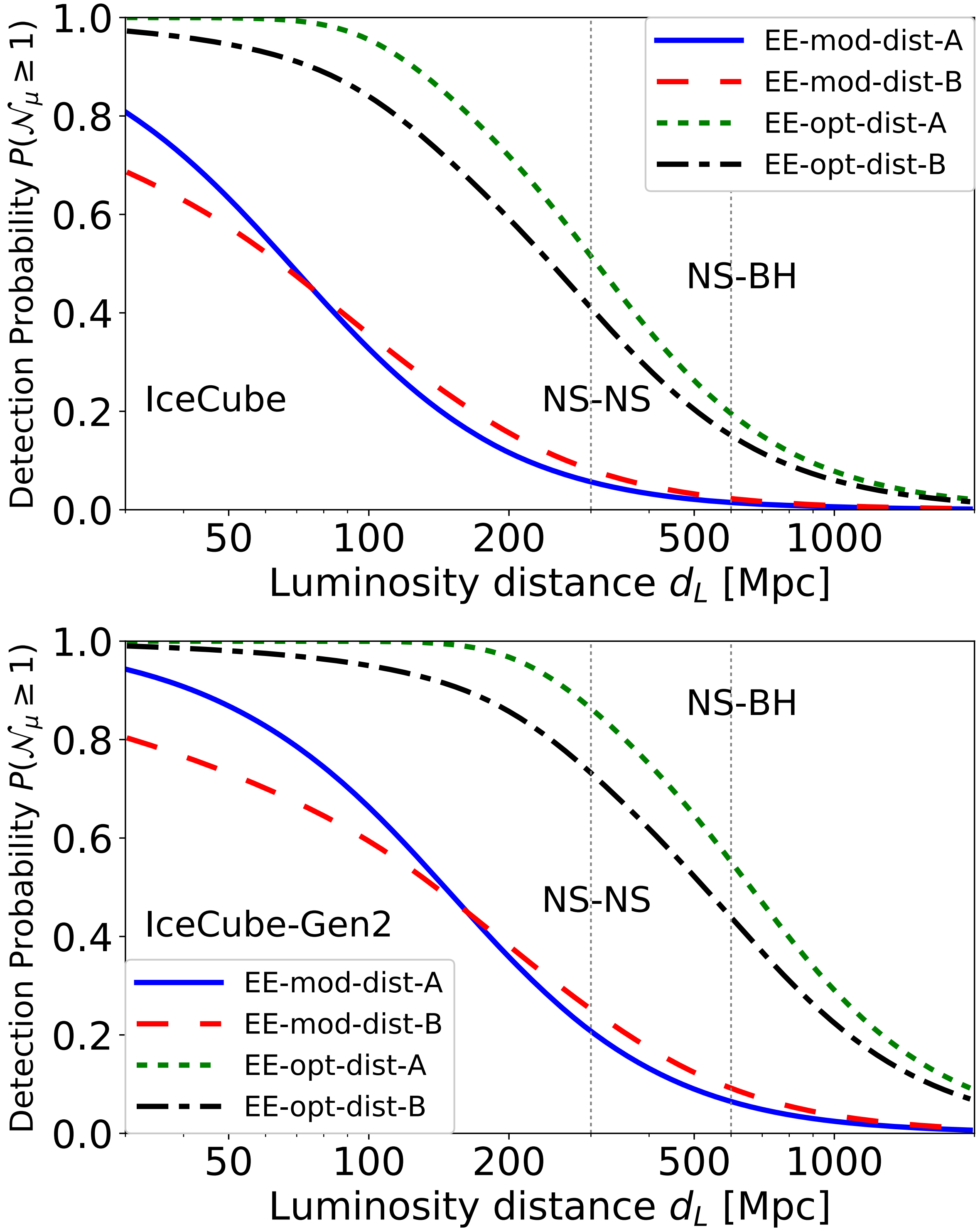
- Assume distribution of Γ

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

- Estimate the detection probabilities

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

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



Detection Probability

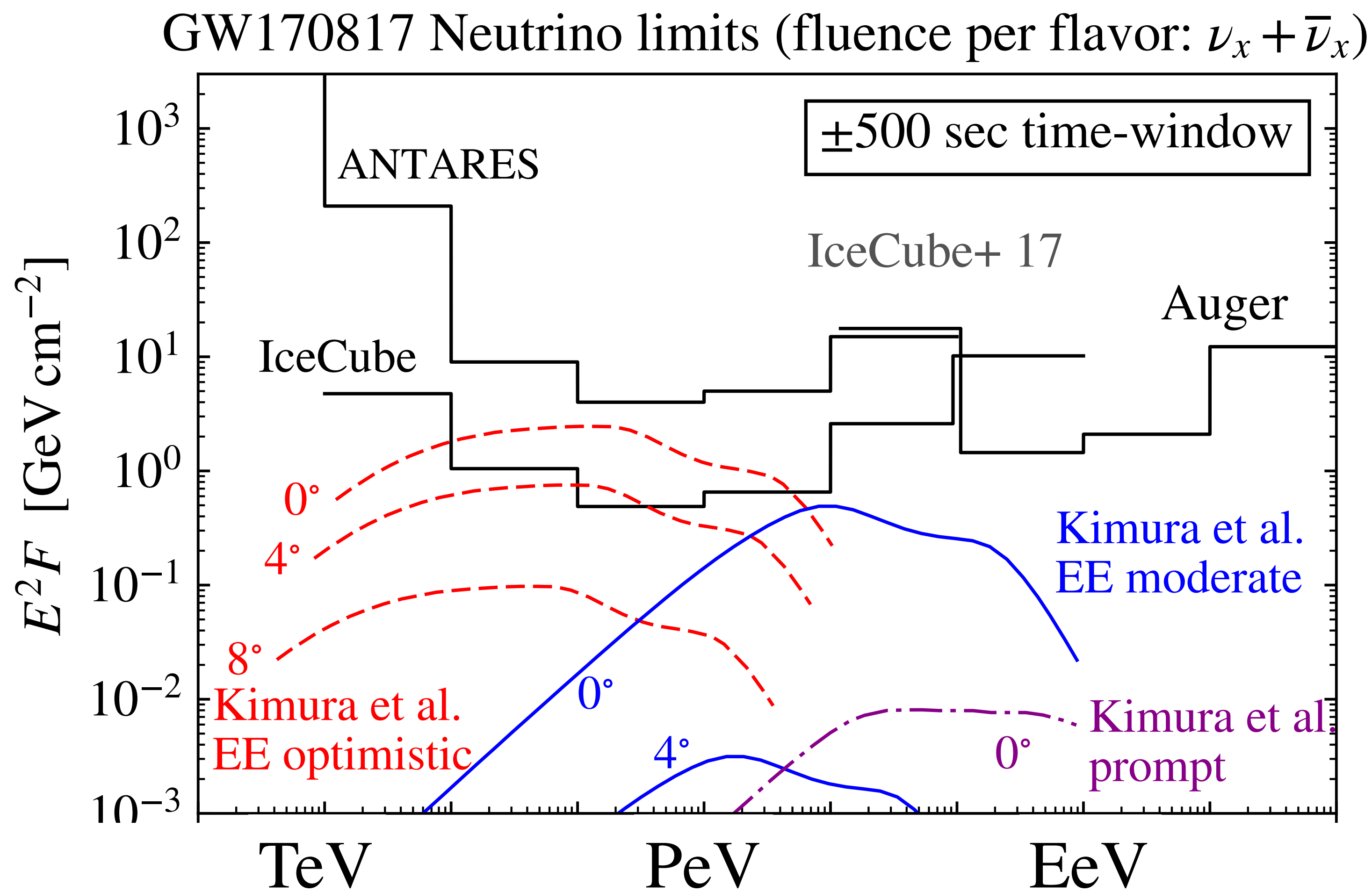
Detection probability in ΔT $\mathcal{P}_{\Delta T} = 1 - P_0^N,$

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
NS–BH ($\Delta T = 5$ years)	IC (all)	Gen2 (all)
EE-mod-dist-A	0.12–0.28	0.45–0.88
EE-mod-dist-B	0.18–0.39	0.57–0.88
EE-opt-dist-A	0.85–0.99	1.00–1.00
EE-opt-dist-B	0.77–0.97	0.99–1.00

Wanderman & Piran 15, Nakar + 06

- R_{SGRB}~ 4 —10 Gpc^{-3} yr^{-3} & half of SGRBs have EE —> N ~ 2-5 for NS-NS (10 yr), N~9-22 for NS-BH (5 yr)
- For optimistic case, simultaneous detection with GW is highly probable even with IceCube
- Fore moderate case, IceCube-Gen2 is likely to detect neutrinos

Implications for GW170817



- There is no extended emission from this event —> neutrinos from EE should not observed
- The jet may be off-axis —> the flux is considerably lower
- This event is in southern sky —> atmospheric noise is strong for lower energy

Sub-photospheric Neutrinos from Neutron Star Mergers

2) Kimura., Murase, Meszaros, Bartos, in prep

Preliminary

Questions:

Can the choked jet produces detectable neutrinos?

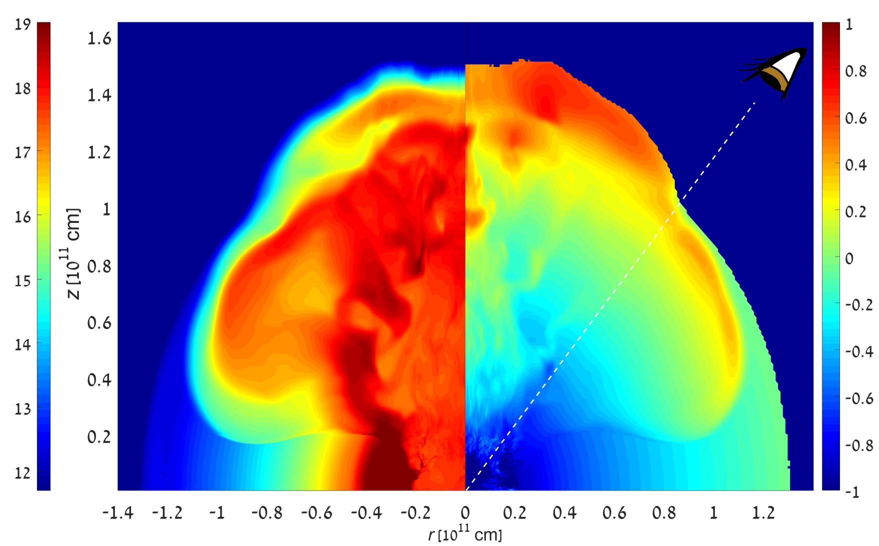
choked jet —> EM are hidden by ejecta

—> neutrinos are only an available signal

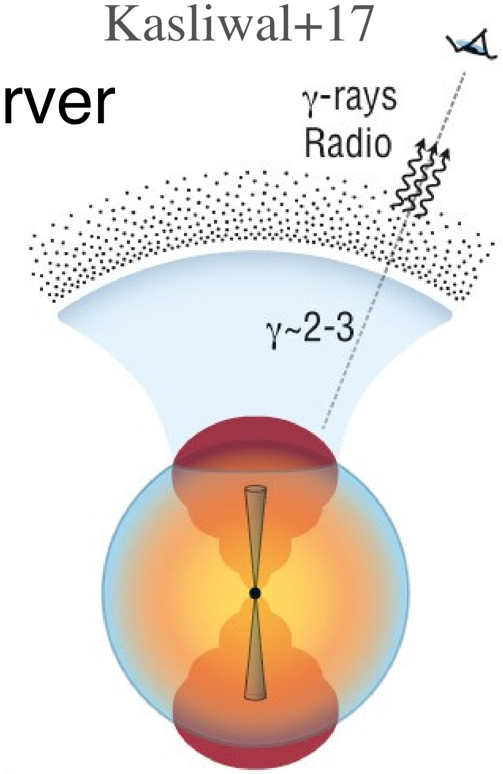
Choked Jet: Weak γ-rays

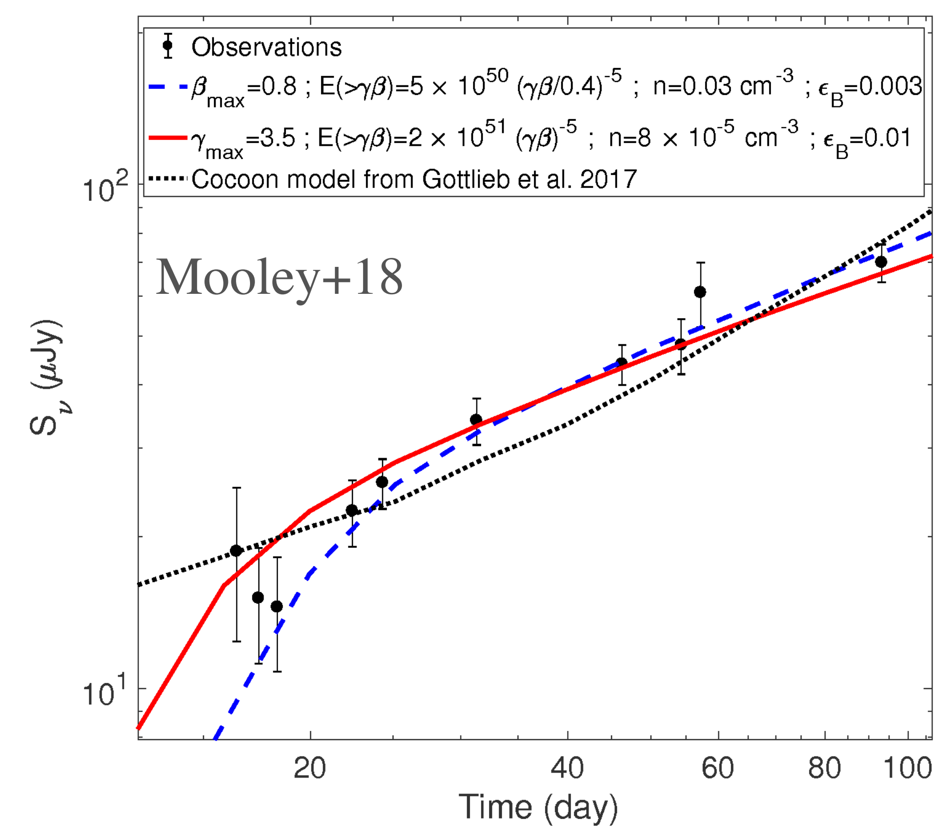
L_{iso}~10^{46} erg/s for on-axis observer

Gottlieb+17



Kasliwal+17

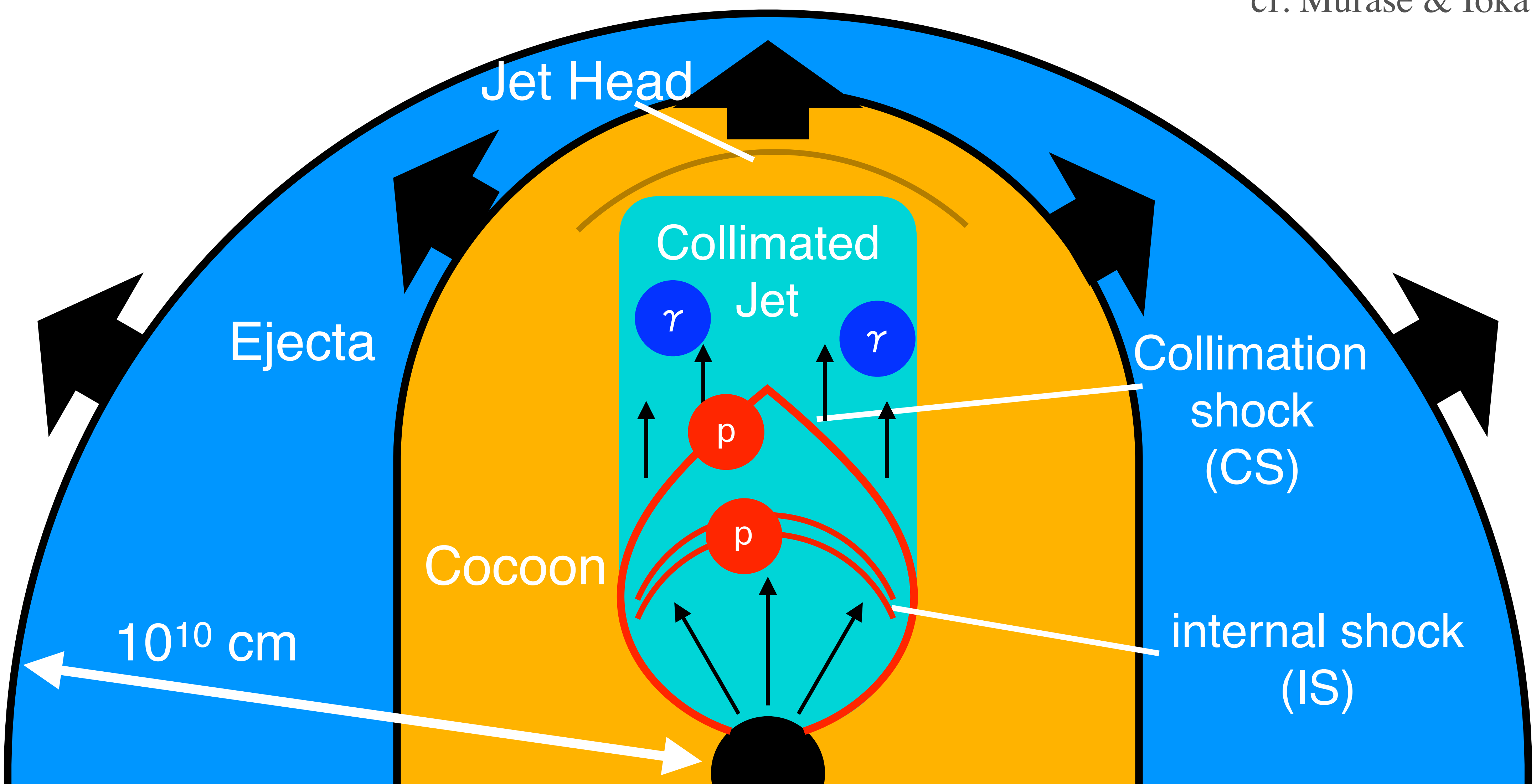




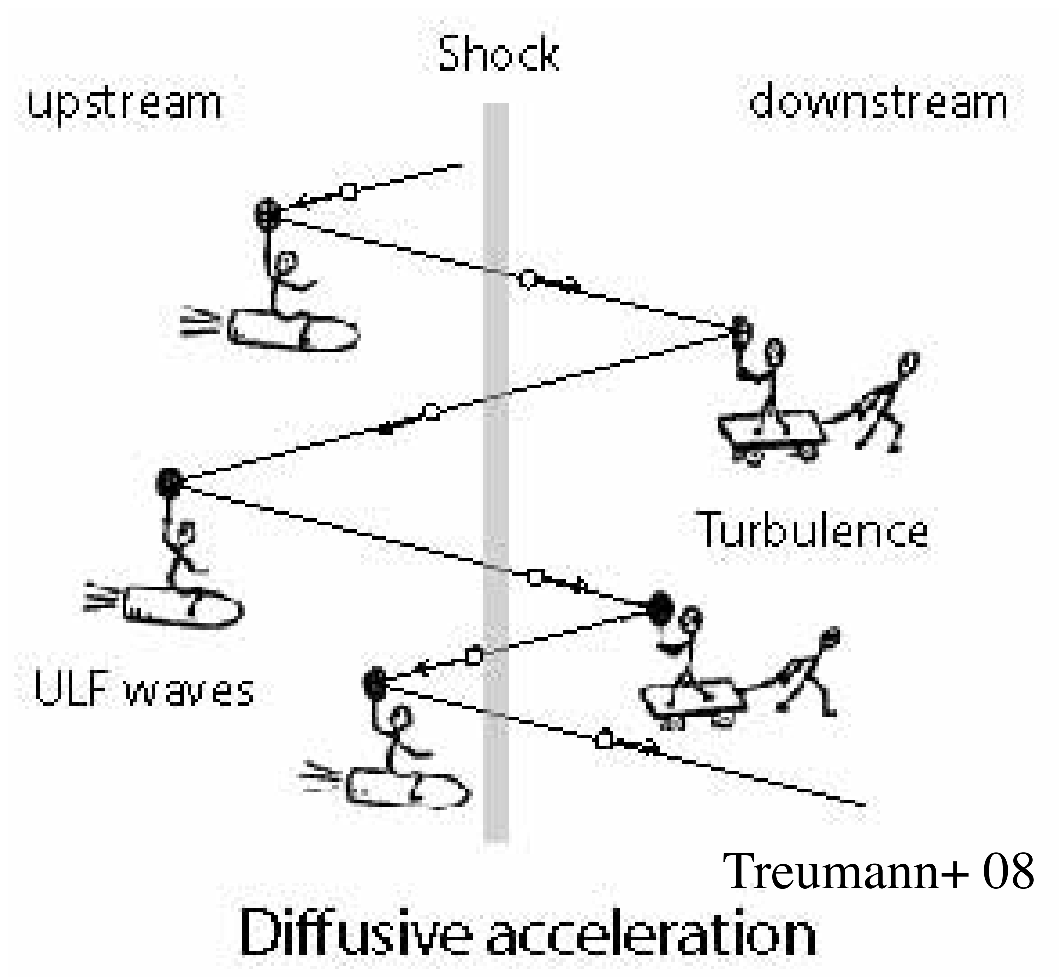
Schematic Picture

- swept-up ejecta forms cocoon surrounding the jet —> push the jet inward —> form collimation shock
- Velocity fluctuations induce the internal shocks at the pre-collimated jet

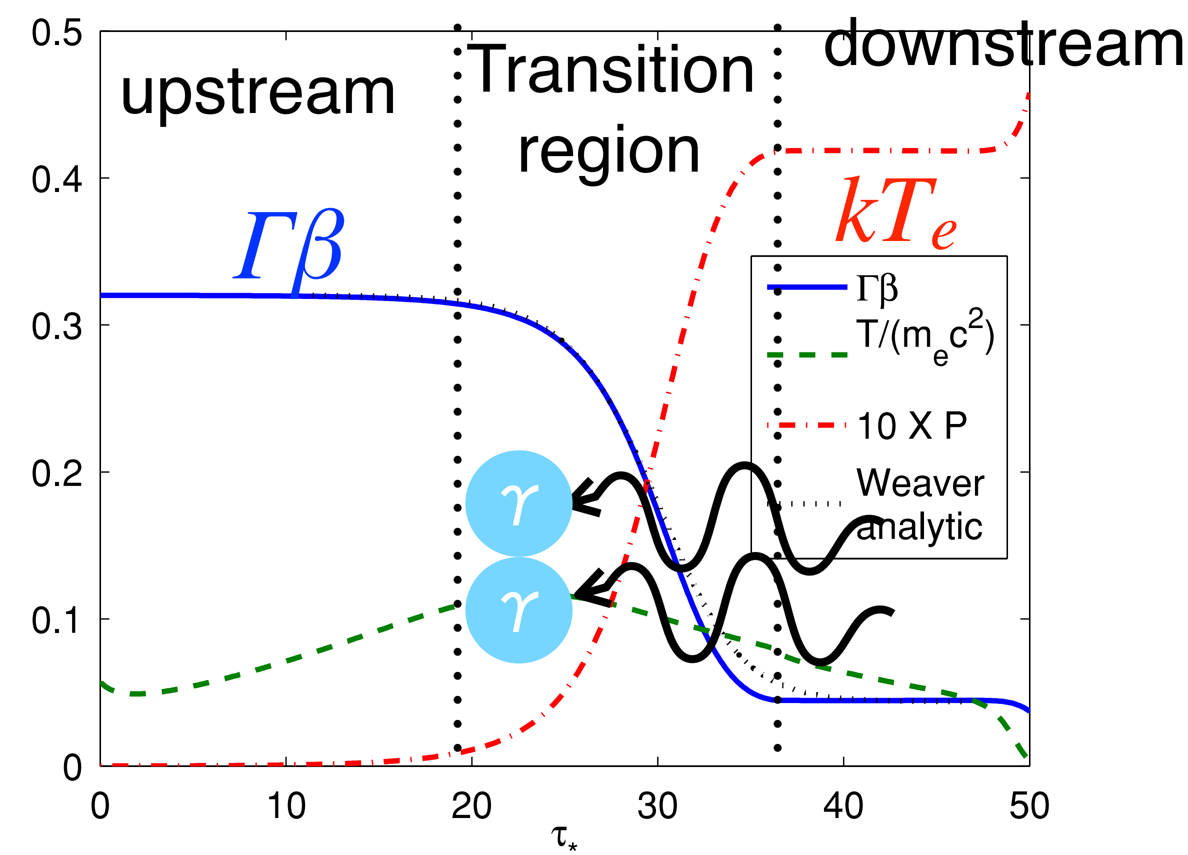
cf. Murase & Ioka 13



Particle Acceleration



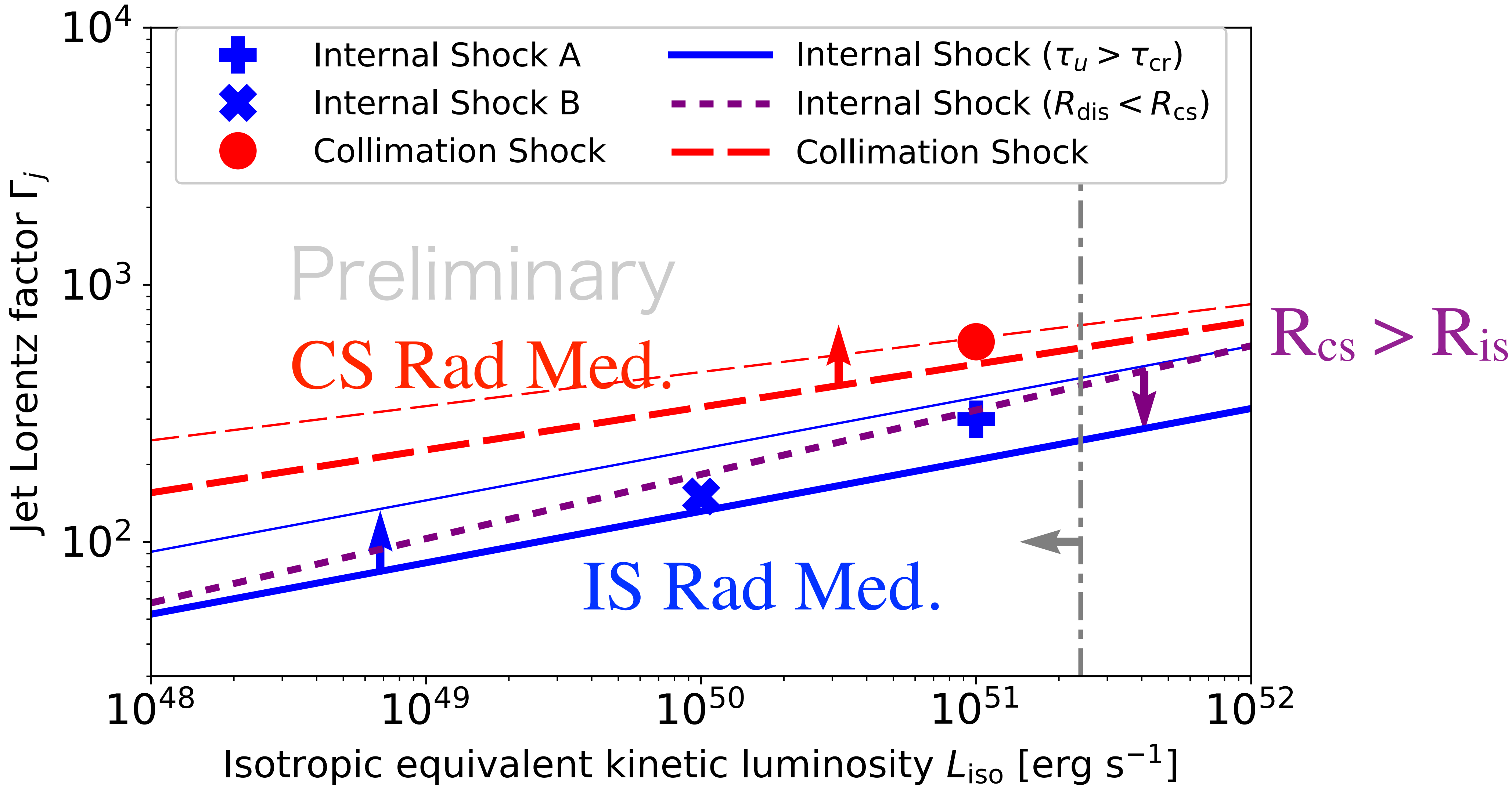
Treumann+ 08



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])

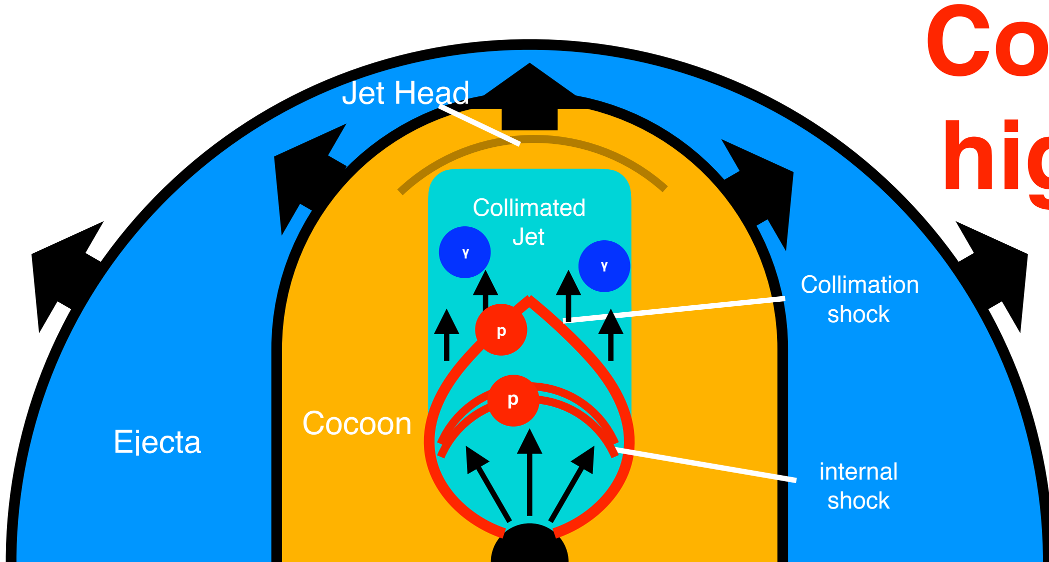
Particle Acceleration



- 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

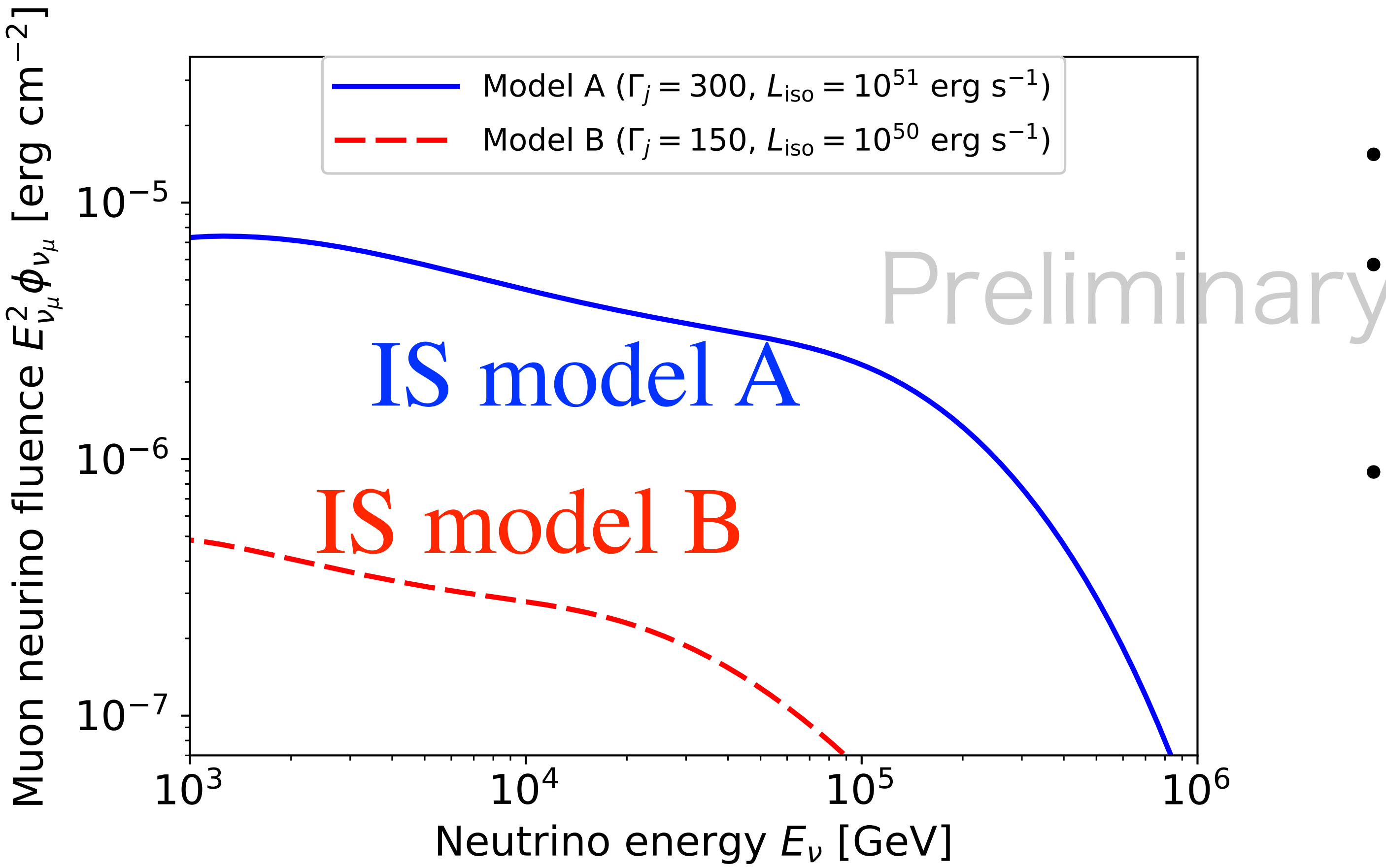
Critical Energies

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



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

Neutrino Emission from IS



Detection Probability for a single event

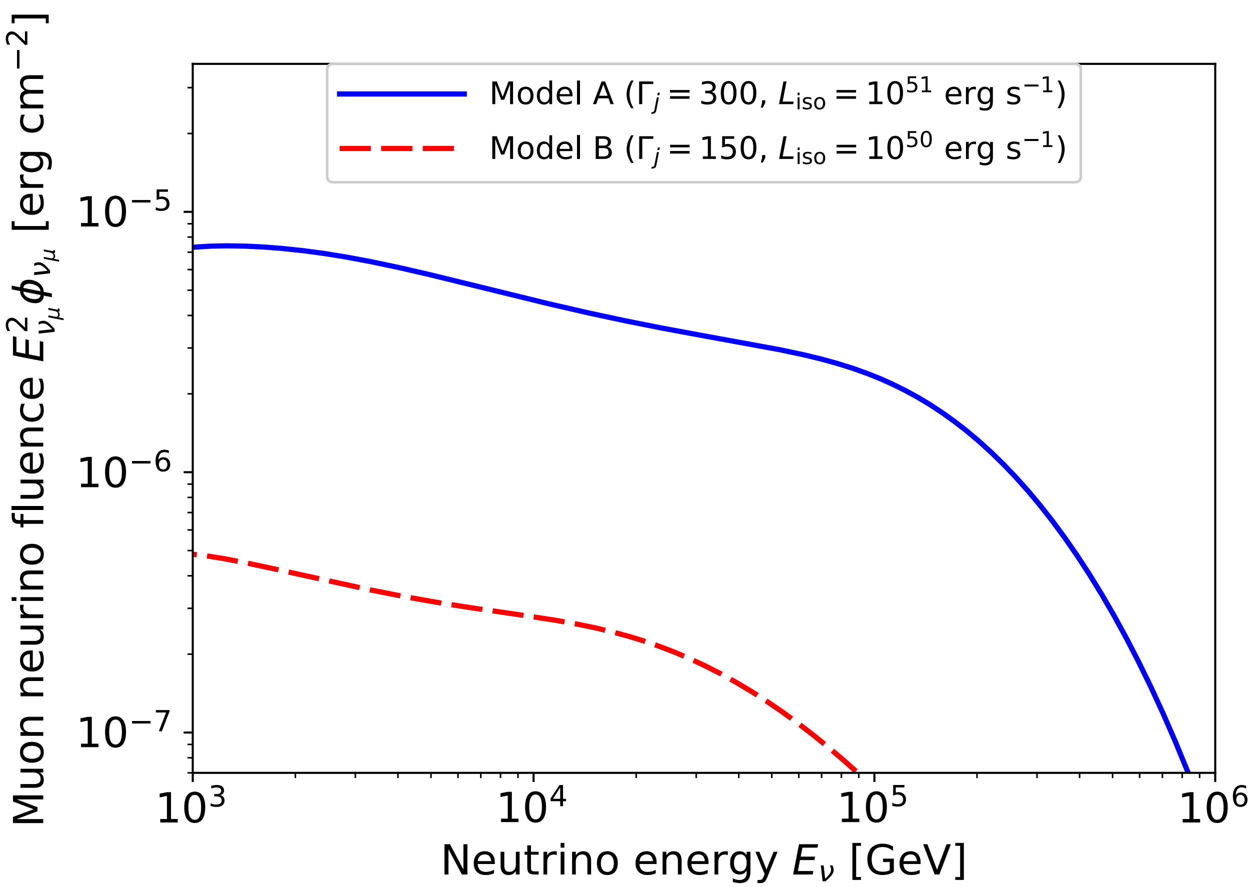
model	p_1 (IC)	p_1 (Gen2)	p_2 (Gen2)
A	0.11	0.40	0.093
B	6.2×10^{-3}	0.026	3.5×10^{-4}

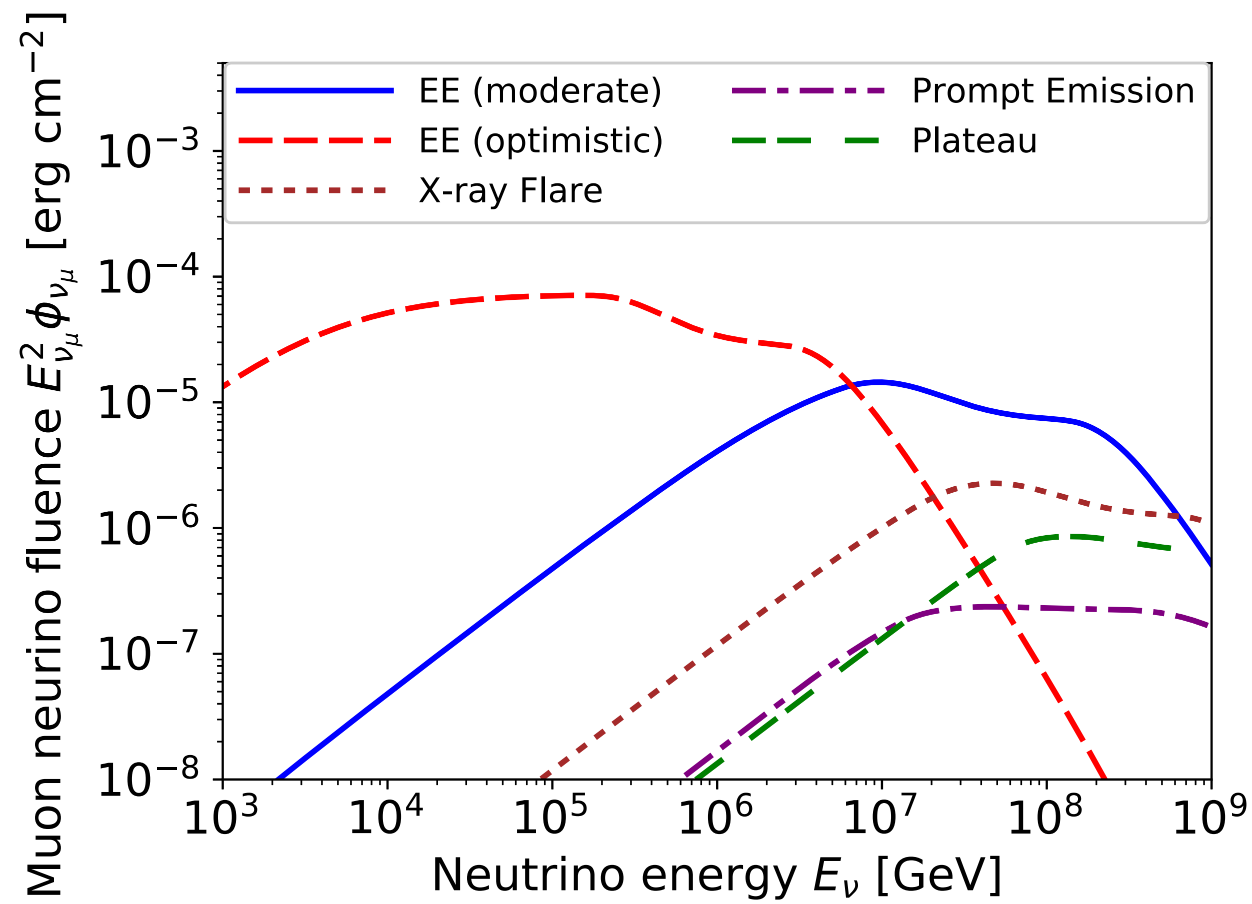
Detection probability for a given interval

model	P_{1yr} (IC)	P_{3yr} (IC)	P_{1yr} (Gen2)	P_{3yr} (Gen2)
A	0.38	0.76	0.88	0.998
model	P_{1yr} (IC)	P_{10yr} (IC)	P_{1yr} (Gen2)	P_{10yr} (Gen2)
B	0.025	0.23	0.10	0.67

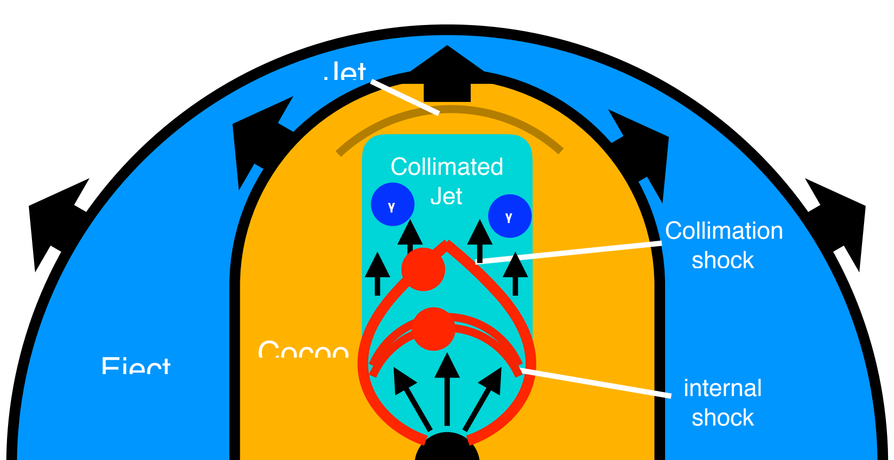
- d_L=300 Mpc
- 1-100 TeV neutrinos for IS good for IceCube detection
- Merger rate:
  R~1500 Gpc^{-3} yr^{-1}
  Beaming factor: f_b~ 0.045
  —> on axis event rate
  R_{on}~ 4 yr^{-1}
  in northern hemisphere
- IceCube can detect neutrino with a few years operation
- Gen2 can detect with 10 year operation even with conservative case

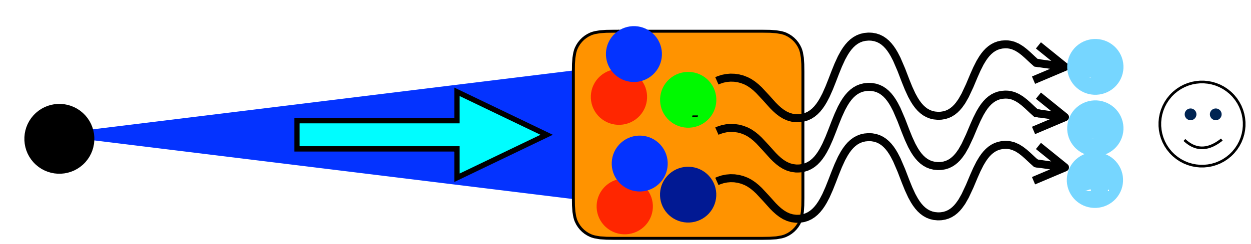
Choked or Successful?





- E < 300 TeV
- E > PeV

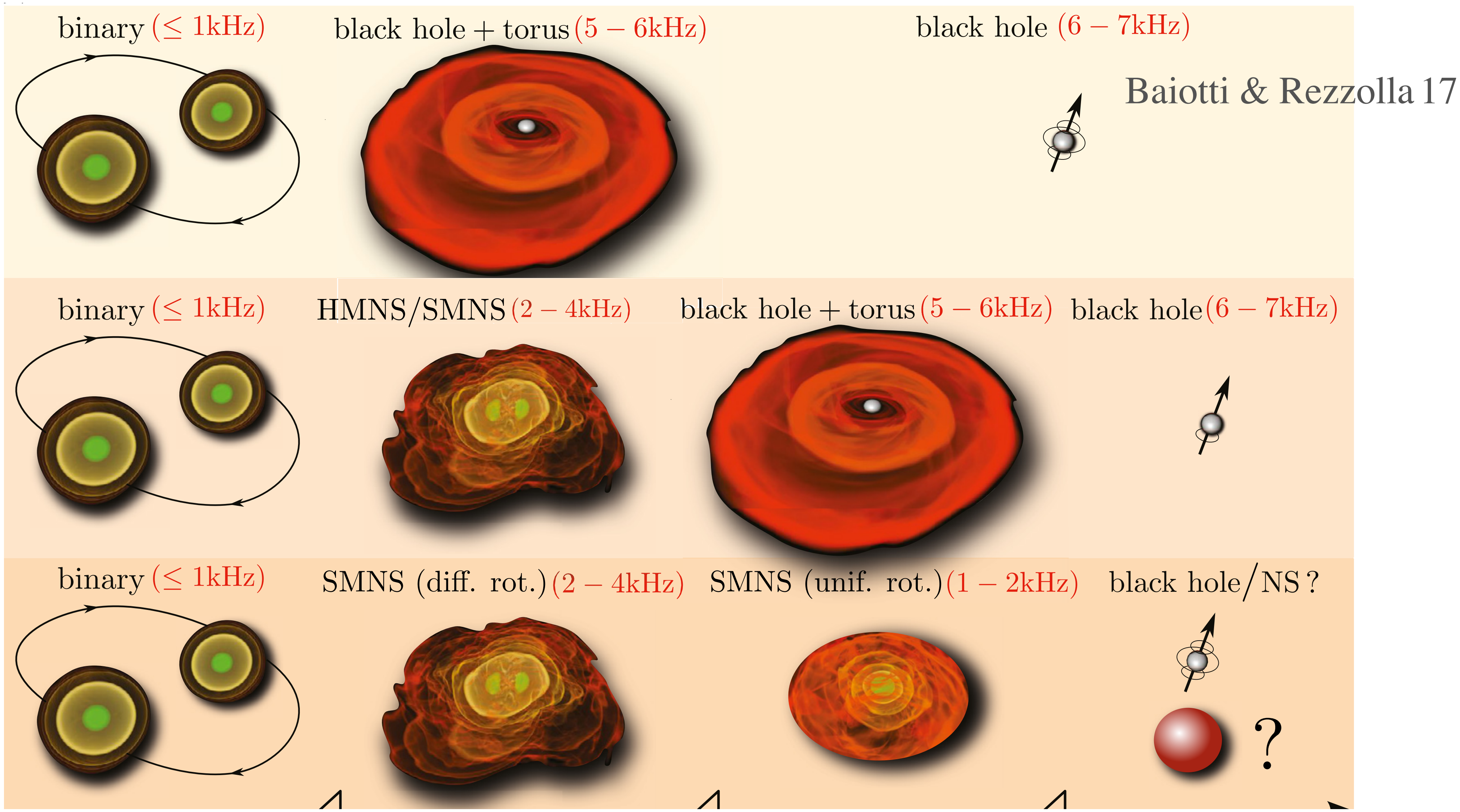




Long-duration High-energy Photons from NS mergers

3) Murase, Toomey, Fang, Oikonomou, Kimura et al. 2018, ApJ, 854, 60
(Most part of this work was done before the report of GW170817)

Central Remnant?

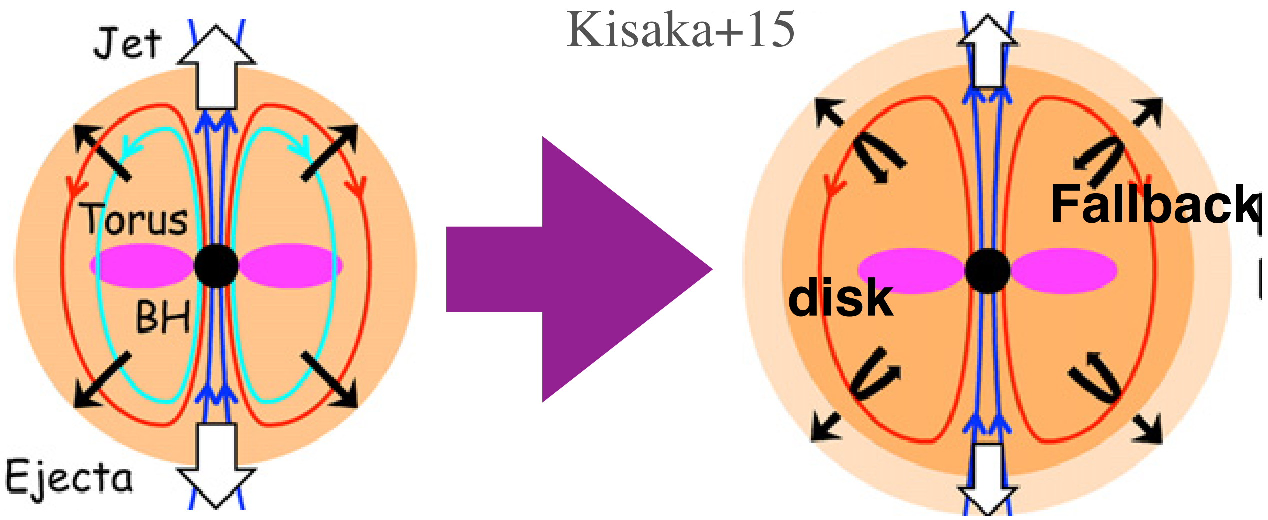


- How long is lifetime of HMNS?
- Final remnant is BH or NS?

Emission by Remnant

cf. Talk by Mori-san

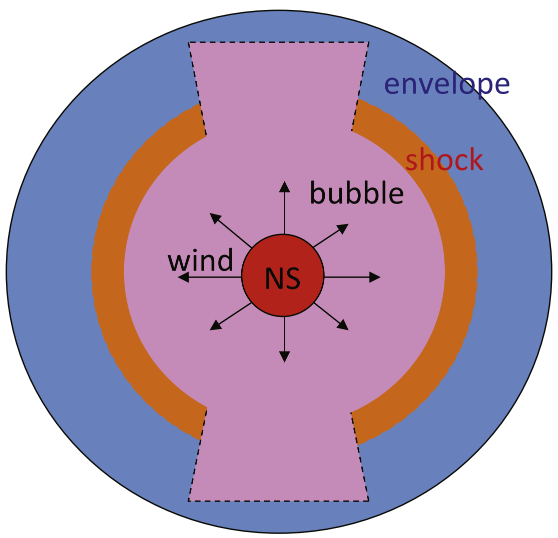
- BH: fallback accretion
  —> Remnant accretion disk



$$\dot{M}_d(t) = \frac{2M_d}{3t_{\rm eje}}\left(\frac{t}{t_{\rm eje}}\right)^{-5/3}$$

- NS: spindown energy
  —> Wind nebula formation

Murase+15

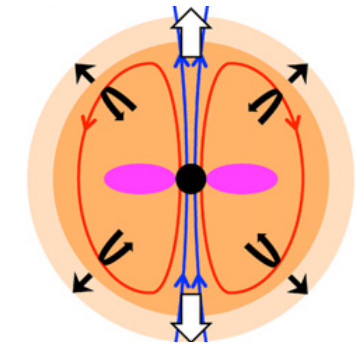


$$t_{\rm sd} \approx \frac{P_i^2 \mathcal{I} c^3}{2\pi^2 B_*^2 R_*^6}$$

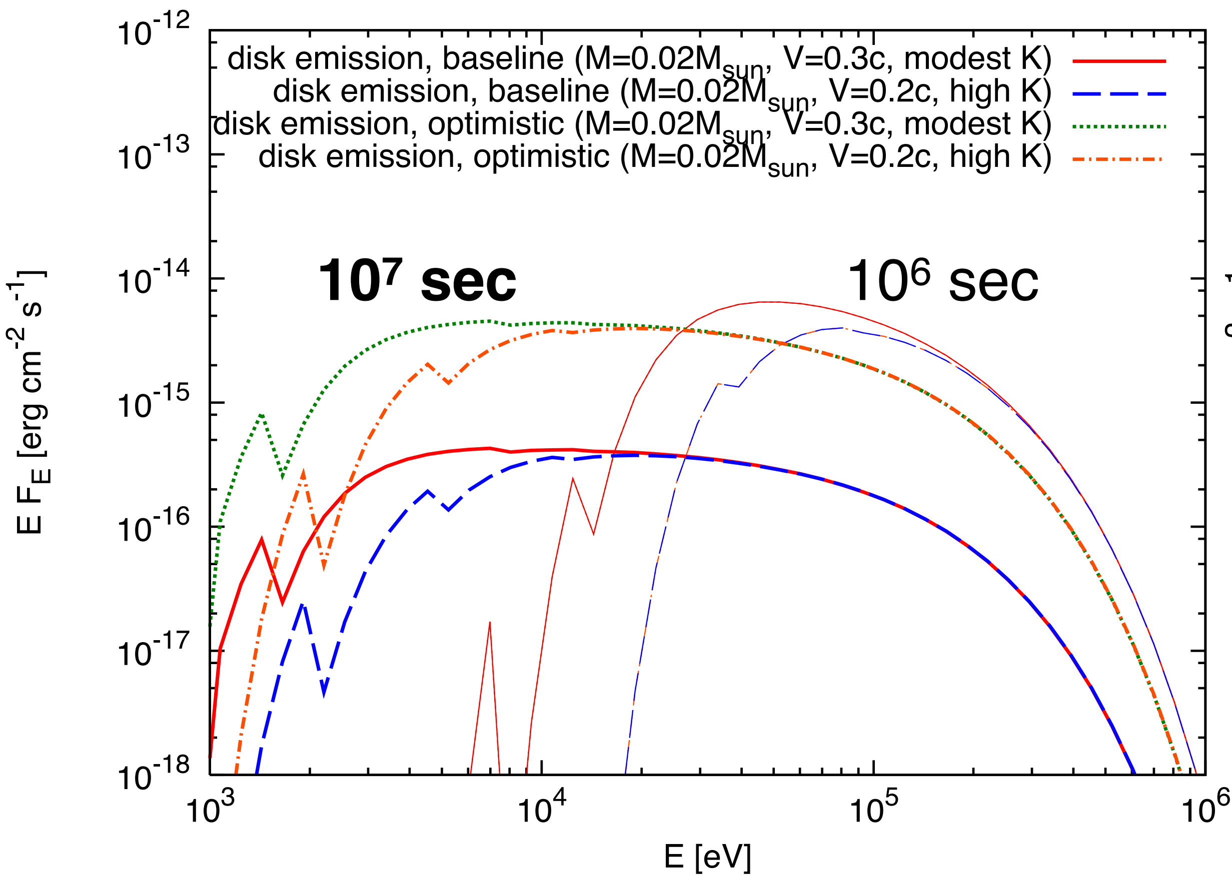
$$L_{\rm inj} \approx L_{\rm sd} \approx \frac{4\pi^4 B_*^2 R_*^6 P^{-4}}{c^3}$$

- The ejecta absorbs high-energy photons until their optical depth becomes lower than unity
  —> observable after around 10 - 30 days

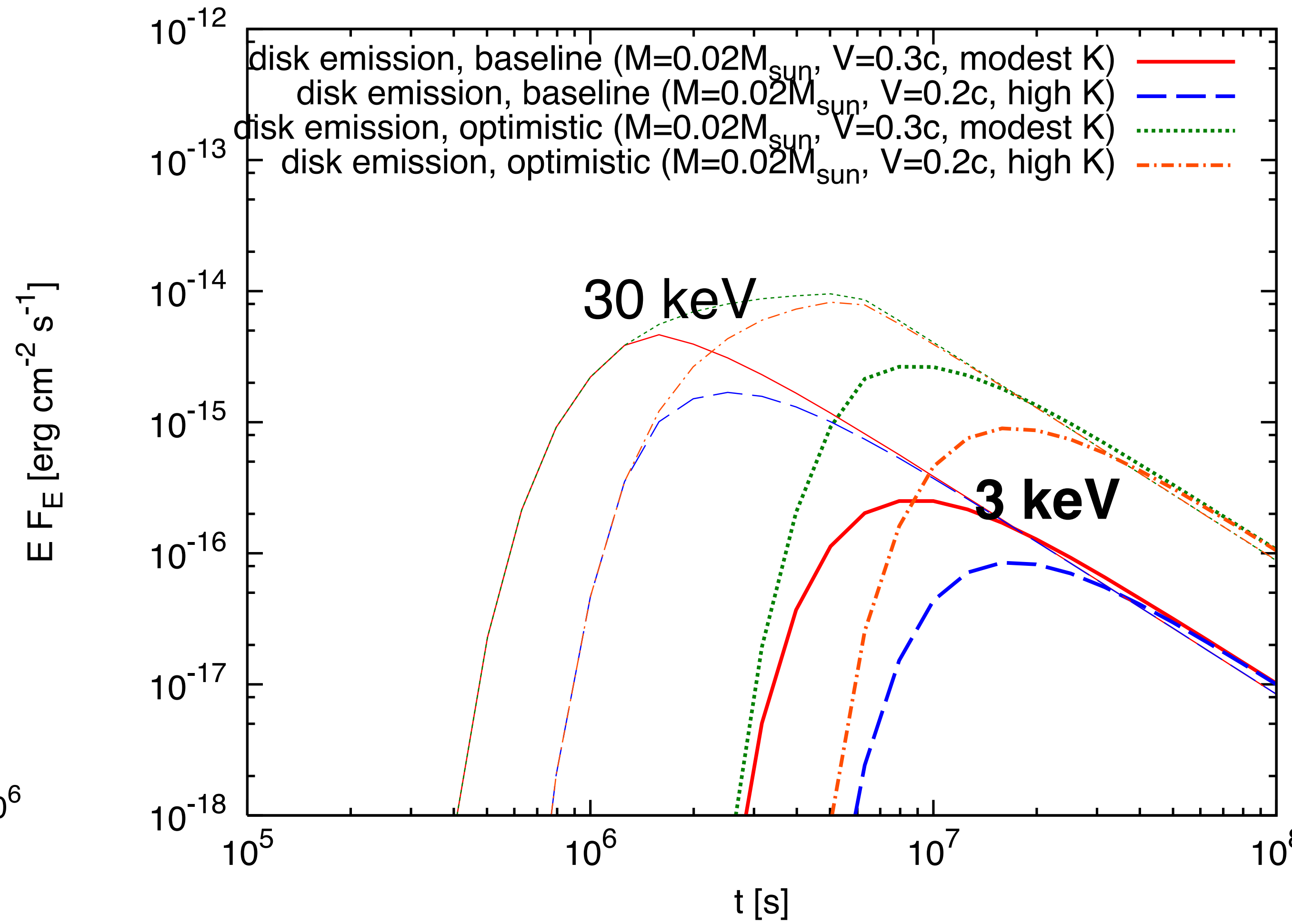
Remnant Disk Emission



Spectrum

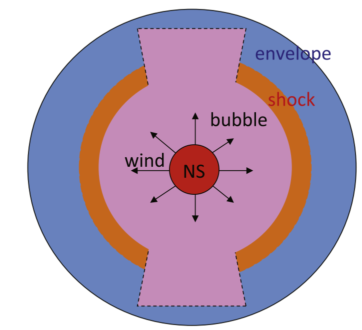


Light Curve

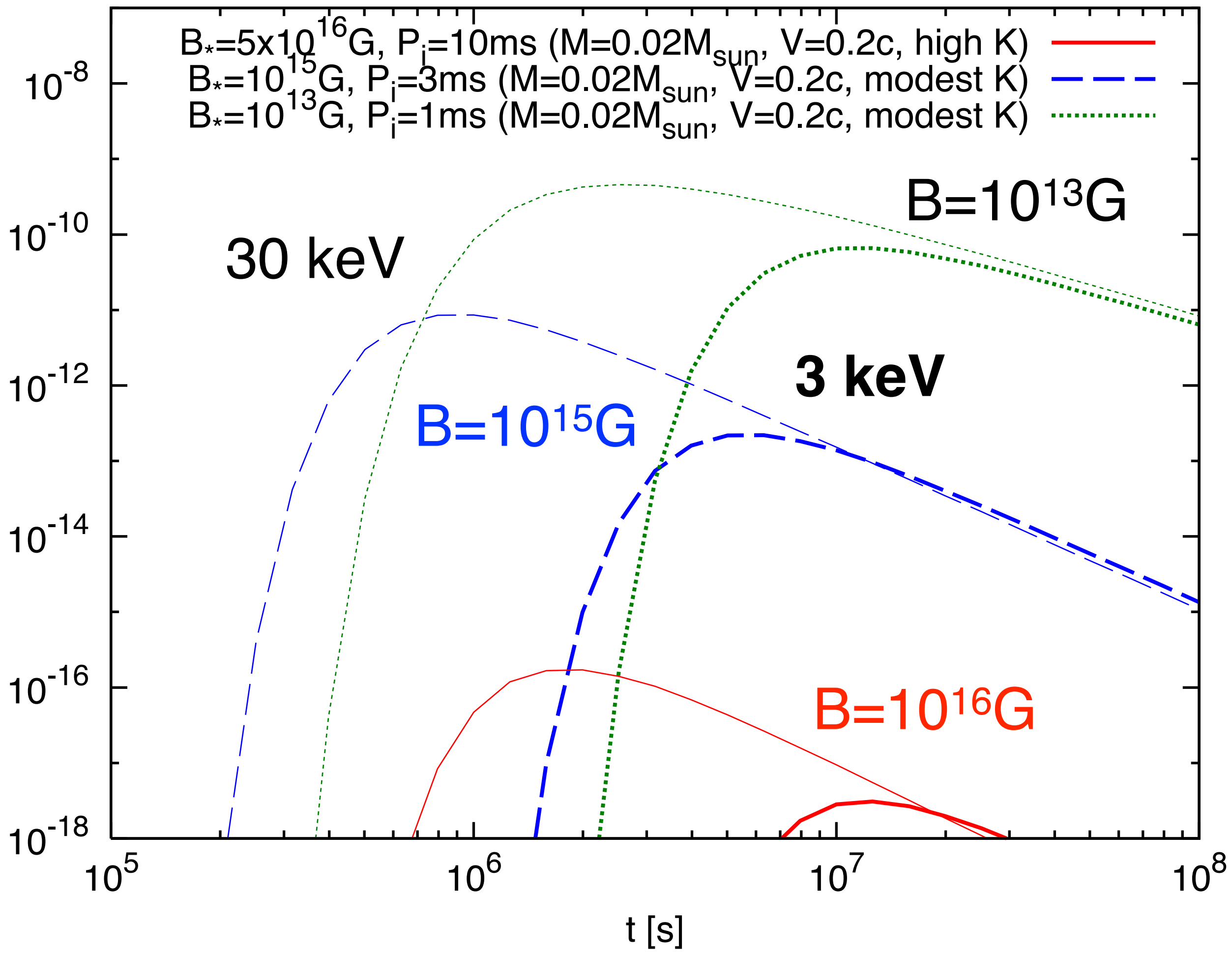


- Opacity for hard X-ray is lower than that for soft X-ray —> Hard X rays become bright earlier
- Observable by NuSTAR, but not detected @ GW170817

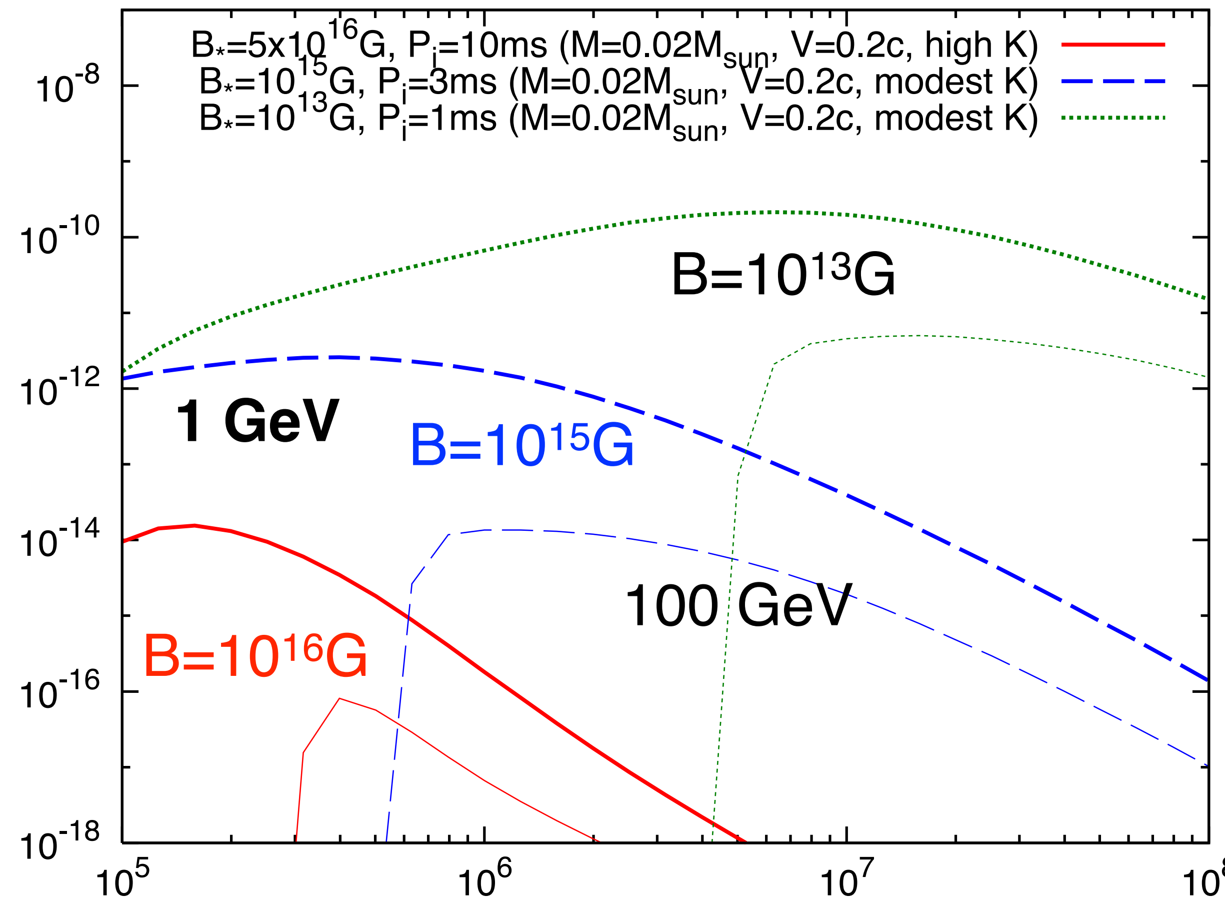
Wind Nebulae Emission



X-ray Light Curve



γ-ray Light Curve

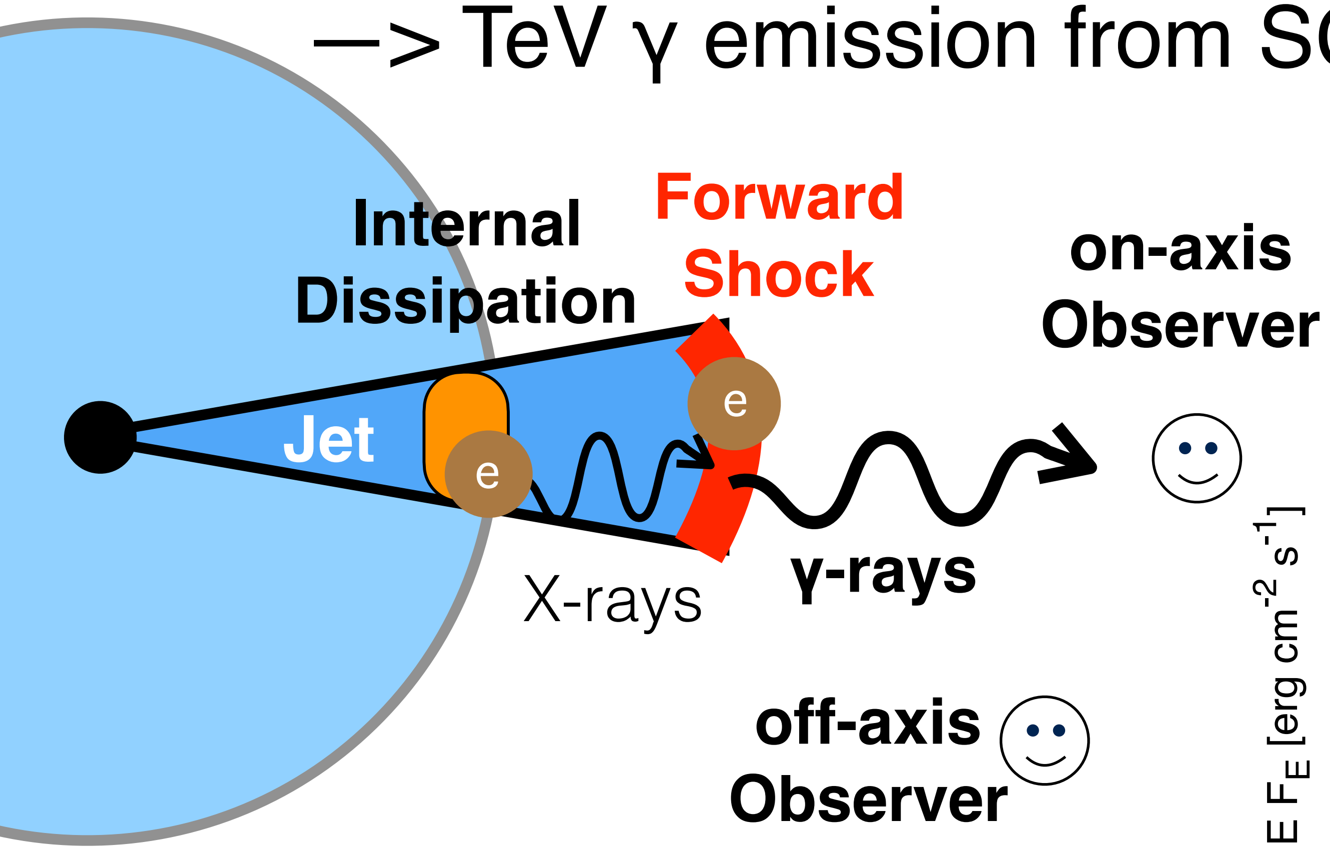


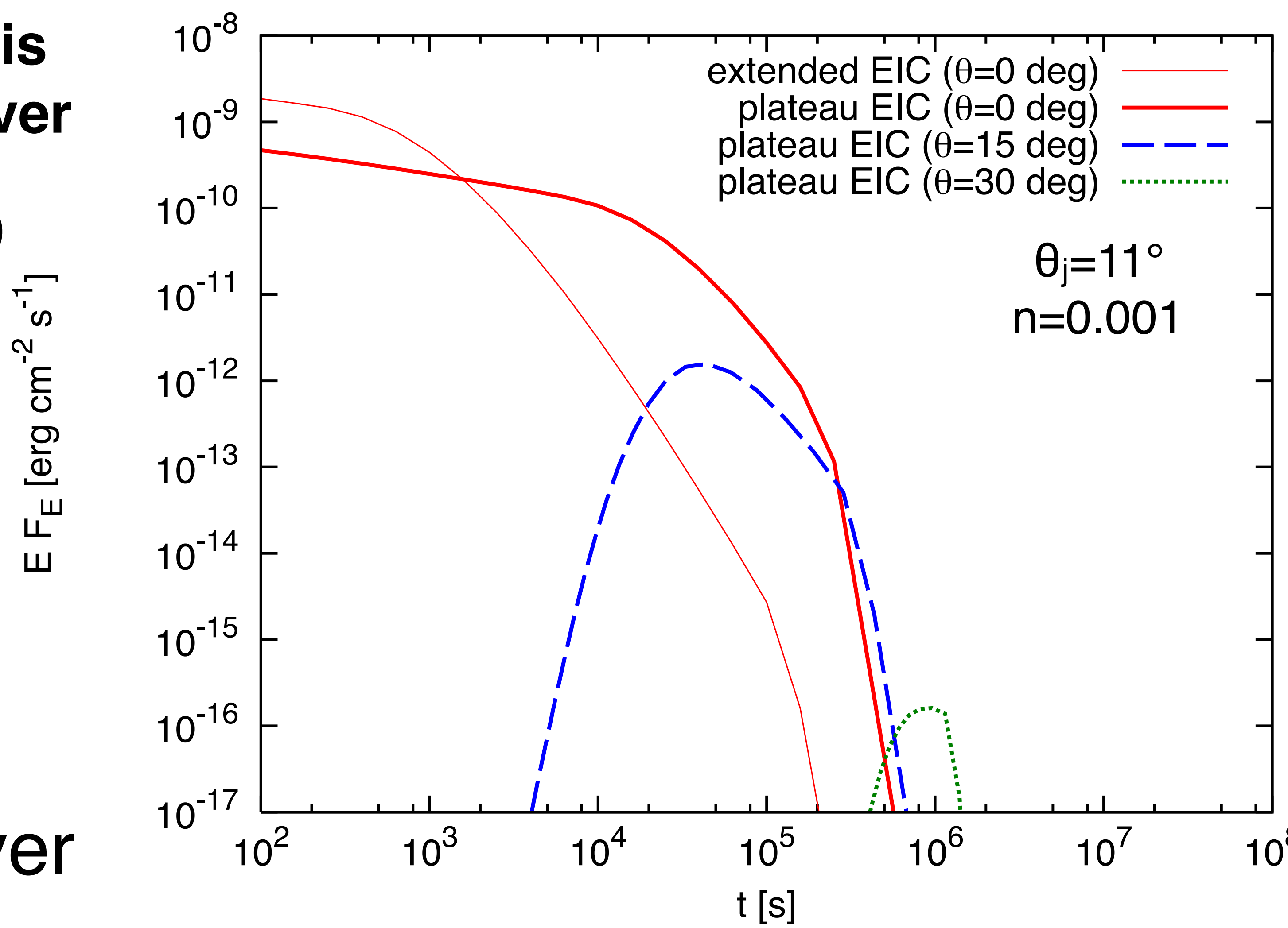
- Very bright X-rays & γ-rays unless $B > 10^{16}$ G for $P \sim 10$ ms
- B should be very high ($\sim 10^{16}$ G) or lifetime is short to avoid non-detection for lower P

Inverse Compton Emission from Delayed Jets

cf. Talk by Inoue-san

- Photons of EE/Plateau are up-scattered @ forward shock —> TeV γ emission from SGRBs





- Detection might be possible for on-axis observer
- Very weak for off-axis observer

Summary

Summary

- **Neutrino detection is a smoking-gun for hadronic CRs**
- Neutrinos associated with SGRBs are **detectable with IceCube-Gen2** if SGRBs accompanies extended emissions
- Sub-photospheric neutrinos are detectable with IceCube if internal shocks are formed in the pre-collimated jets
- BNS mergers might emit high-energy photons