High-energy Emissions from Neutron Star Mergers

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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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Imre Bartos (University of Florida)
Ik Siong Heng (University of Glasgow)

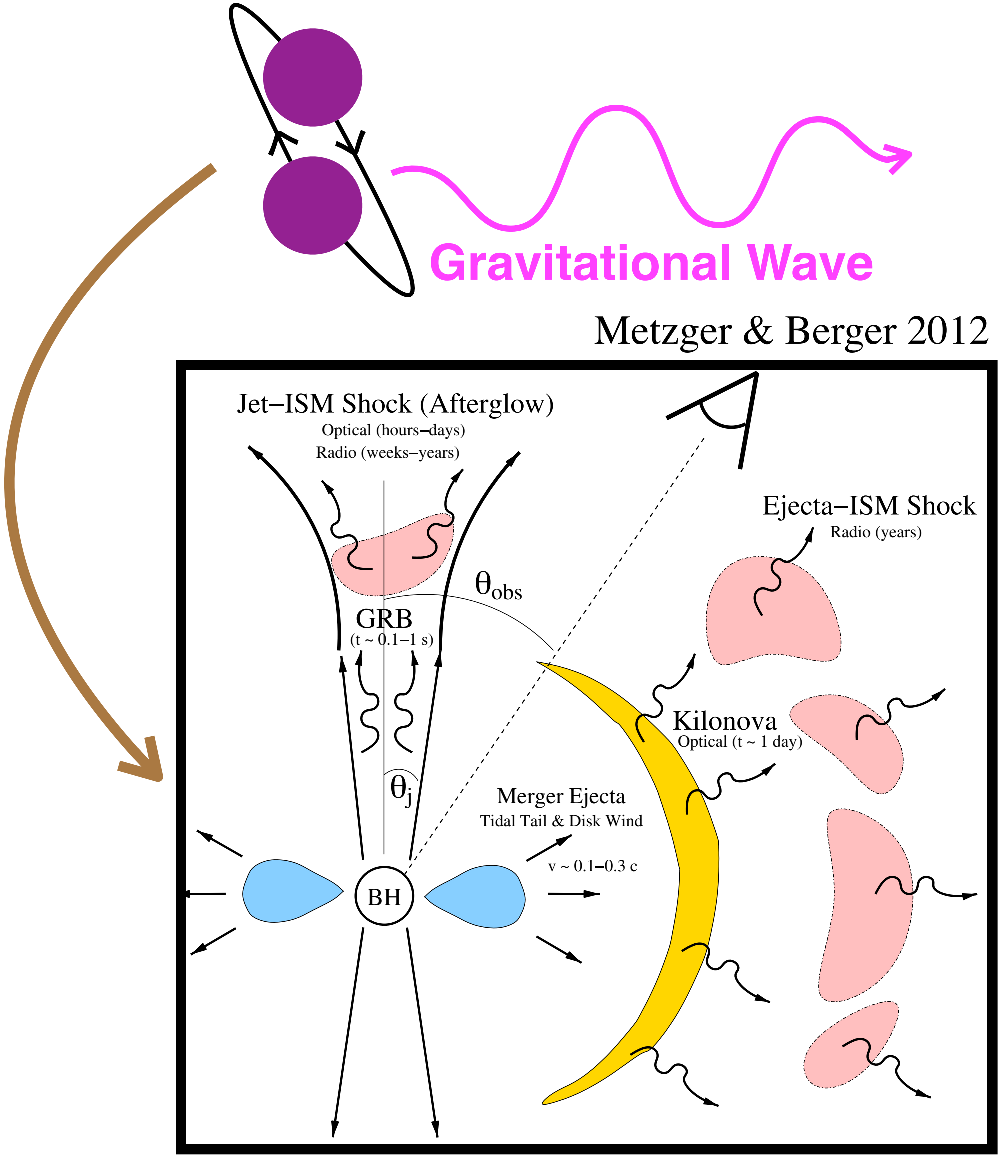
PennState

Outline

- NS mergers before GW 170817
- GW 170817
- HE-neutrinos from NS mergers
  (SSK, Murase, Bartos et al. 2018, PRD; SSK, Murase, Meszaros, Kiuchi, 2017, ApJL)
- Cosmic Ray production at NS merger remnants
  (SSK, Murase, Meszaros, ApJ accepted)
- Summary

NS mergers before GW170817

NS mergers as multi-messenger sources

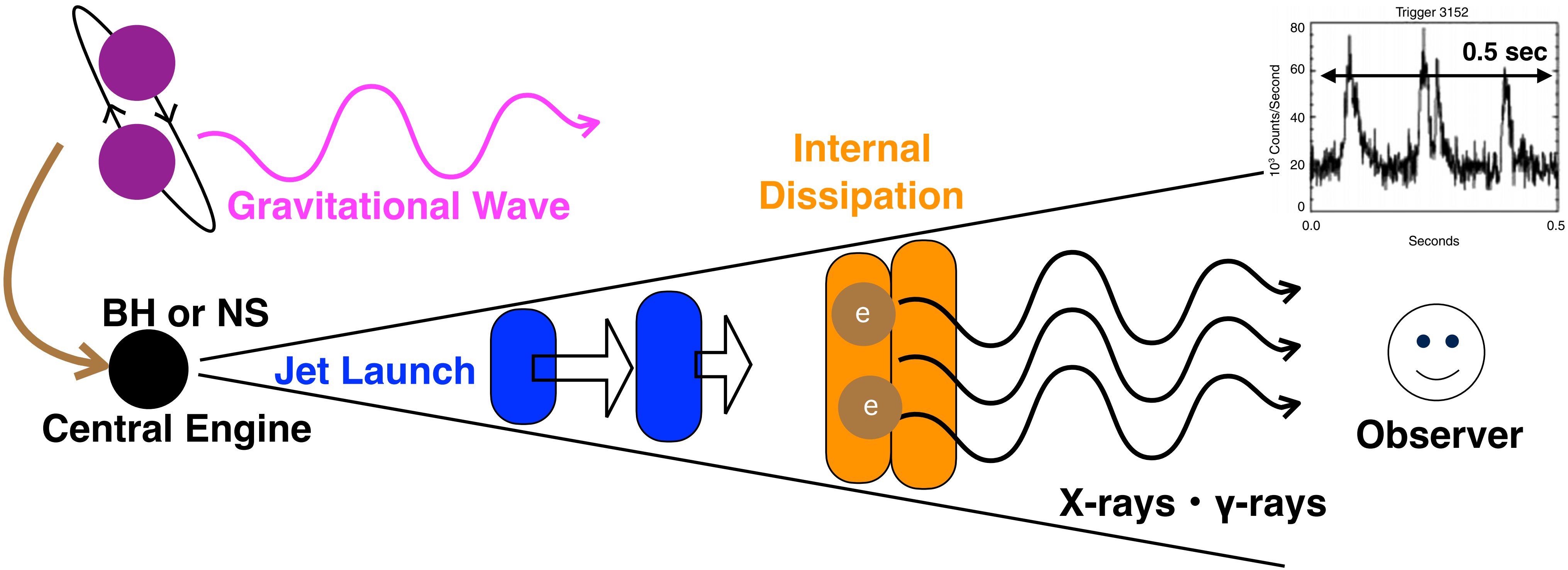


- Inspiral to merger:
  GW emission
- Progenitor of SGRBs:
  —> γ-ray, X-ray, neutrino
- Kilonova/Macronova
  —> Infrared, opt
- Afterglow
  —> Radio, X-ray, cosmic-rays

Short Gamma-ray Bursts

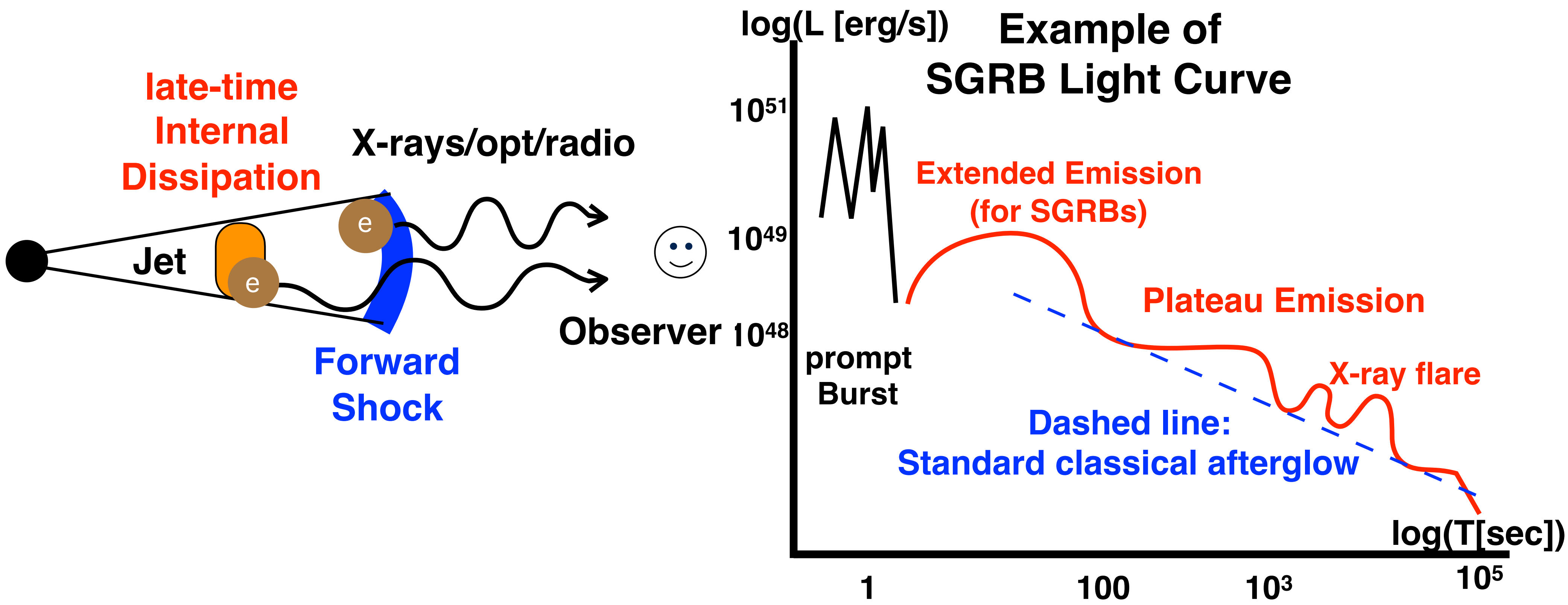
see e.g. Nakar 2007, Berger 2014

- Bright burst of gamma-rays at cosmological distance
- $L_{iso} \sim 10^{50} - 10^{52}$ erg/s, $T_{dur} \sim 1$ sec, $E_{pk} \sim 0.1$–1 MeV
- Central engine (BH or NS) produces jets
  —> internal dissipation produces X-rays and γ-rays



Afterglows of SGRBs

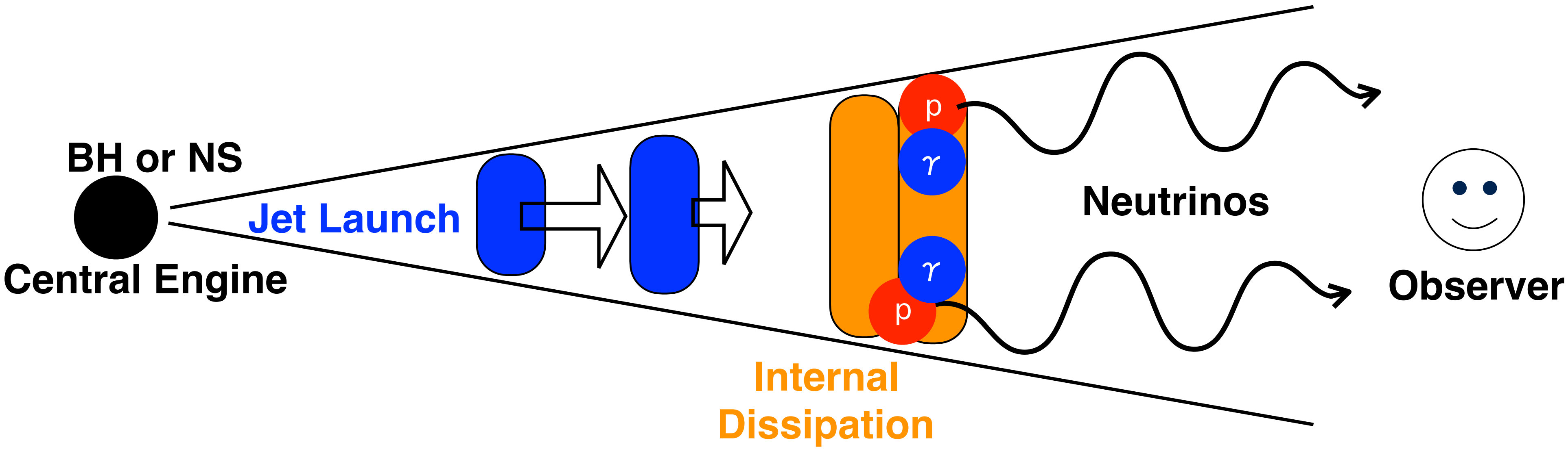
see e.g. Nakar 2007, Sakamoto et al. 2011, Kisaka et al. 2017



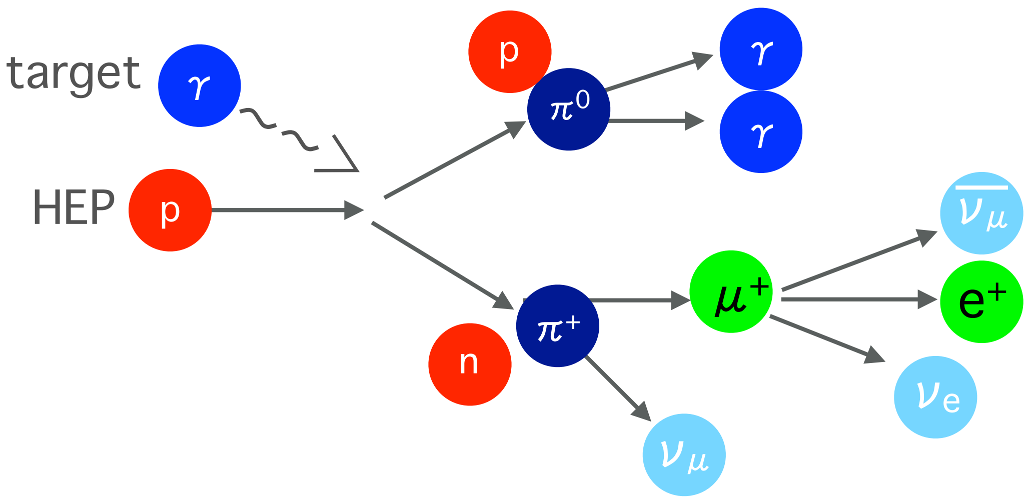
- Prompt emission is followed by afterglows
- Standard afterglow: Forward shock model, power-law decay
- Extended Emission, plateau emission, X-ray flares have similar features to prompt bursts —> **Late-time engine activity?**
- **Late time activities have comparable total energy to prompt burst**

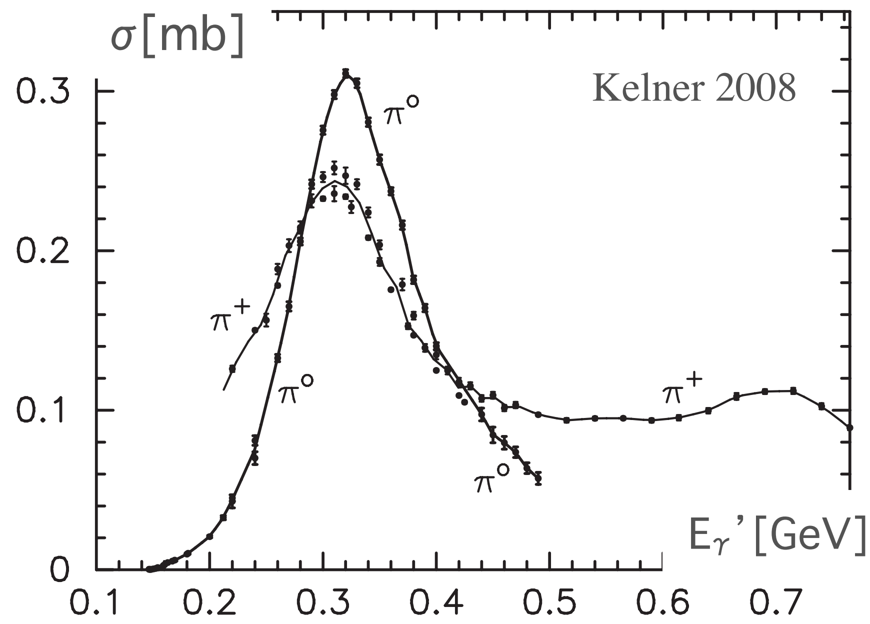
Waxman & Bahcall 1997

GRB Neutrinos



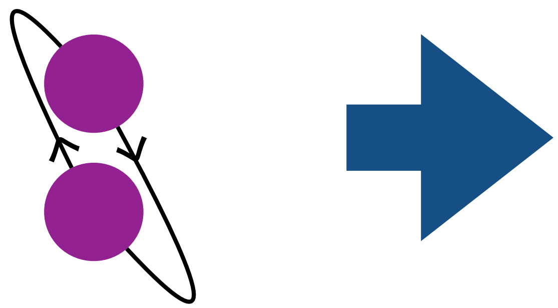
- Photomeson production (pγ)

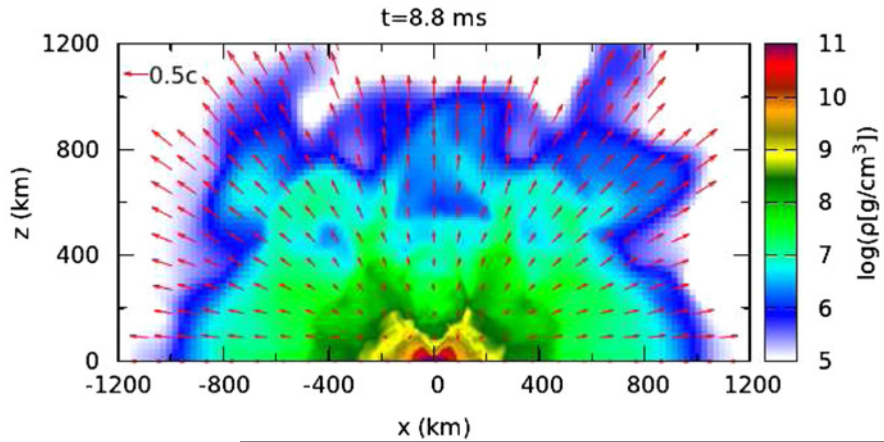




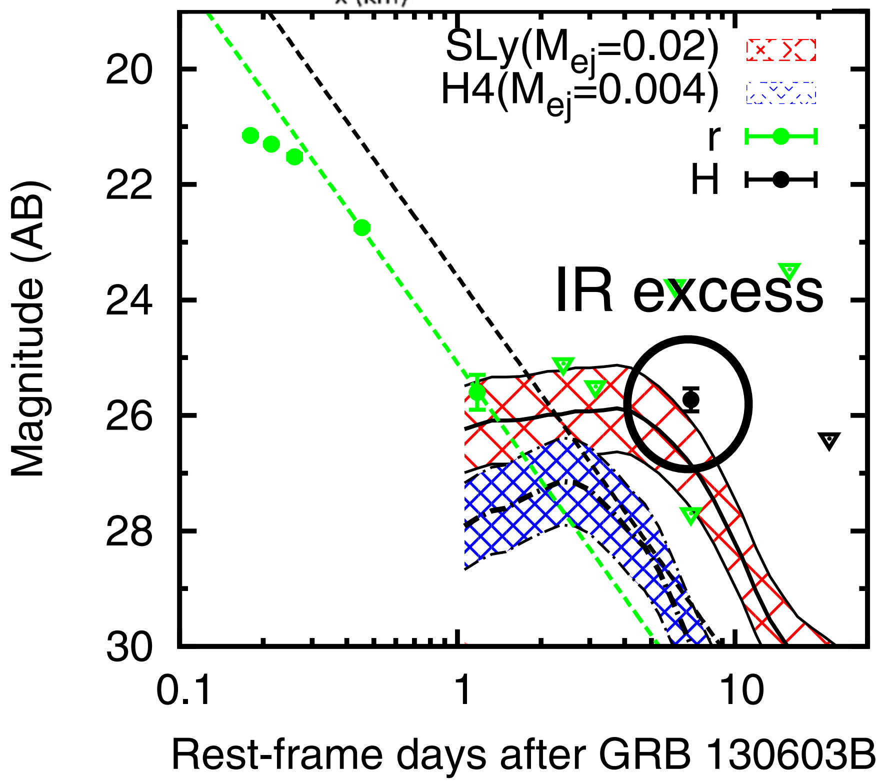
Hotokezaka et al. 2013

Macronova/Kilonova





- NS merger creates ejecta consisting of neutron-rich nuclei
- Decay of n-rich nuclei powers opt/IR transient for days
- a few macronova candidates are observed in afterglows of SGRBs as an excess in IR



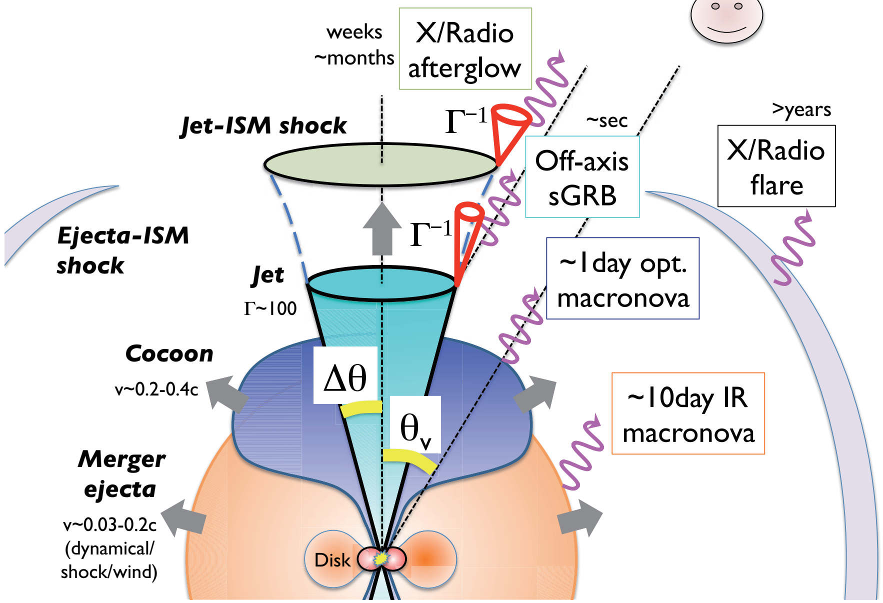
GW 170817

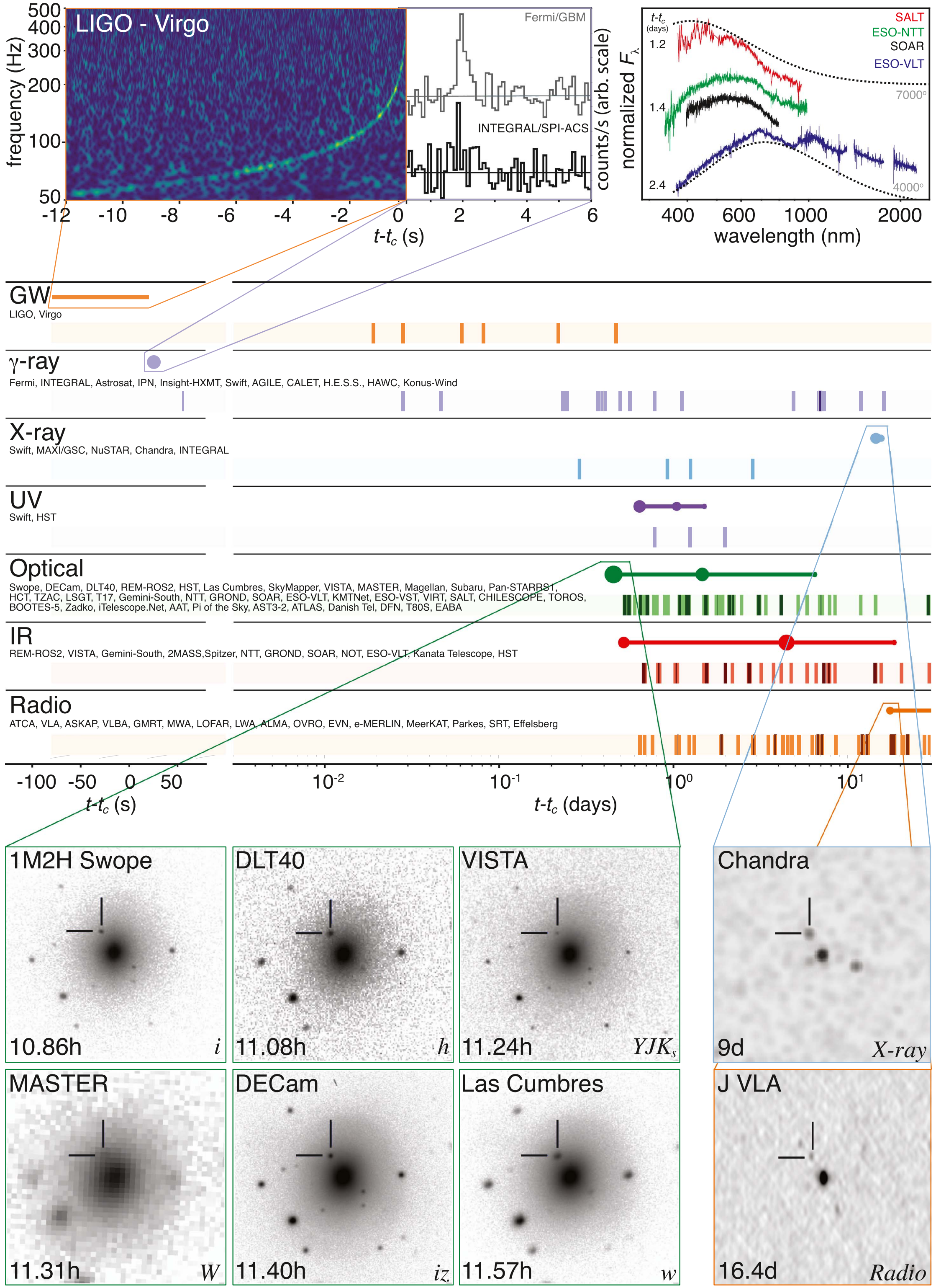
GW170817

LIGO 2017 (Multi-messenger paper)

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

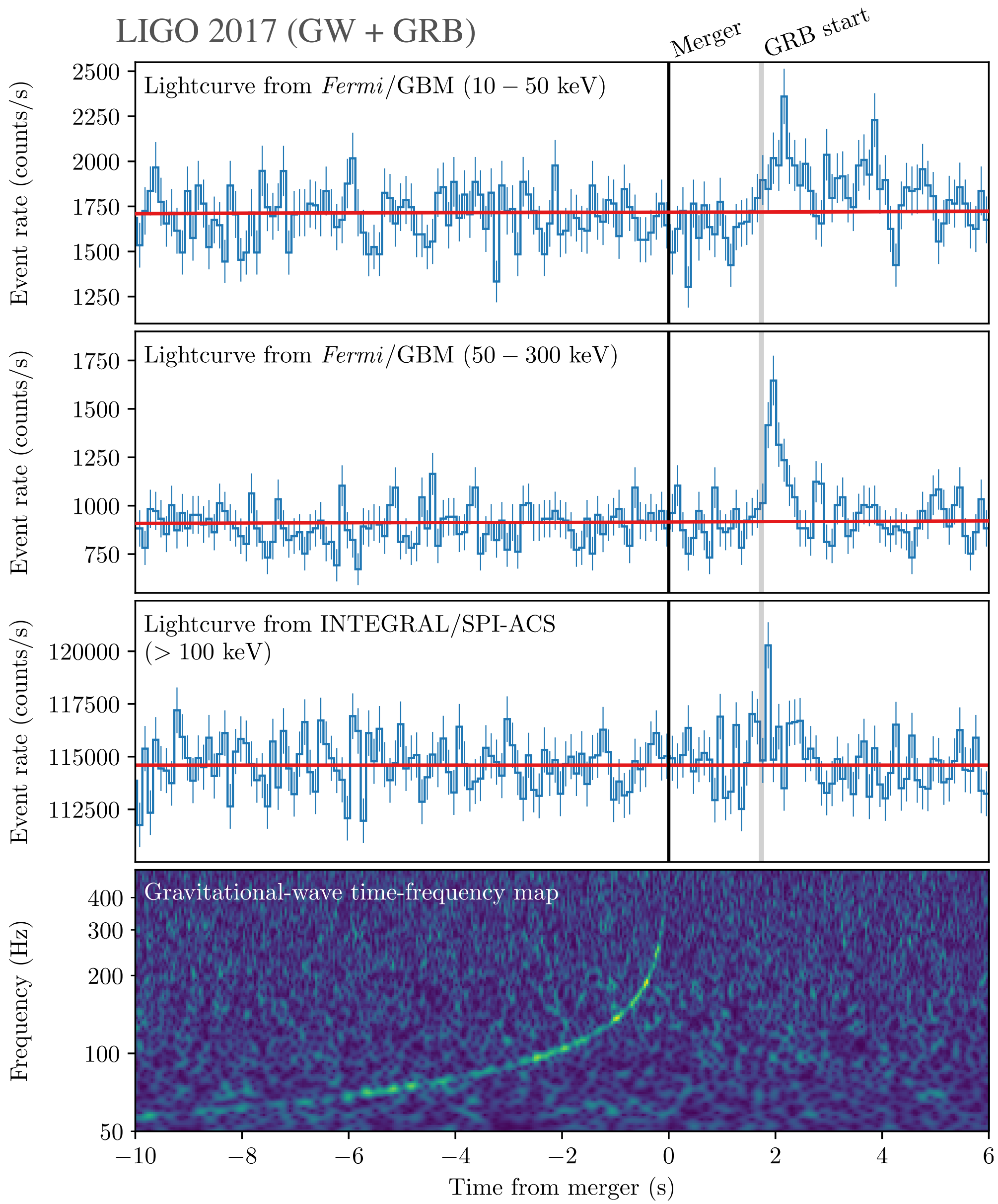
Ioka & Nakamura 2018

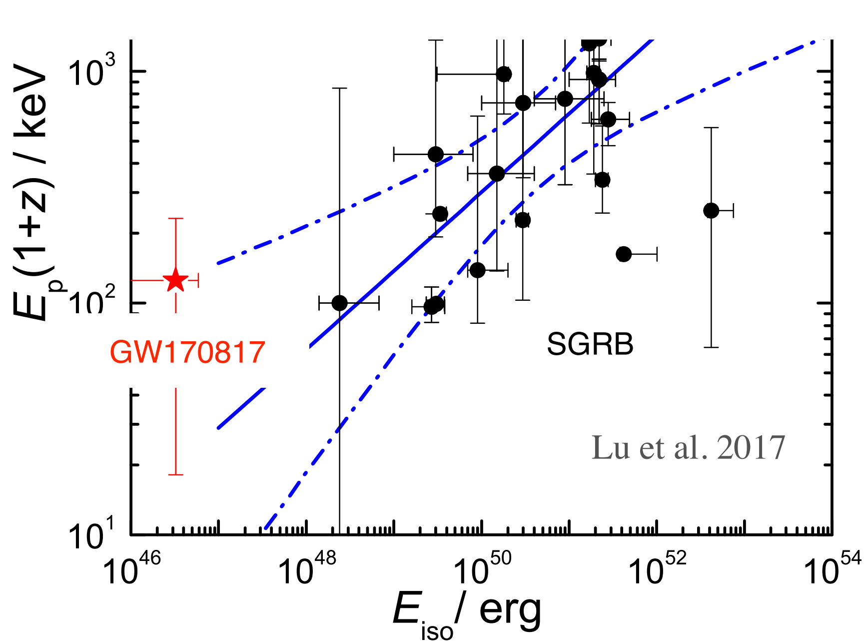




Prompt emission

unusually faint SGRBs



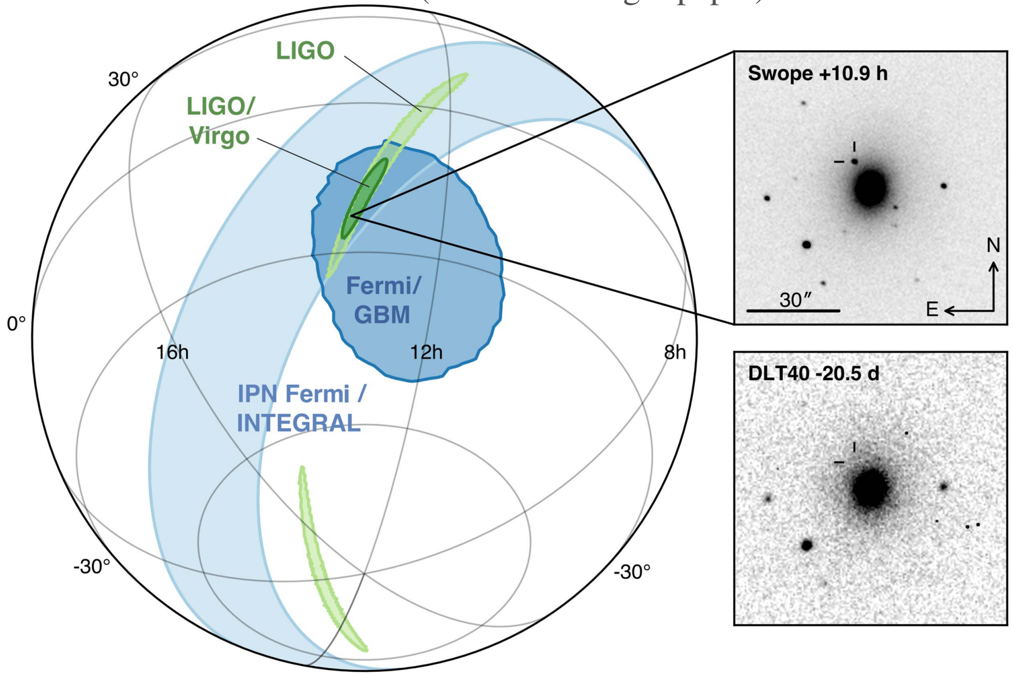


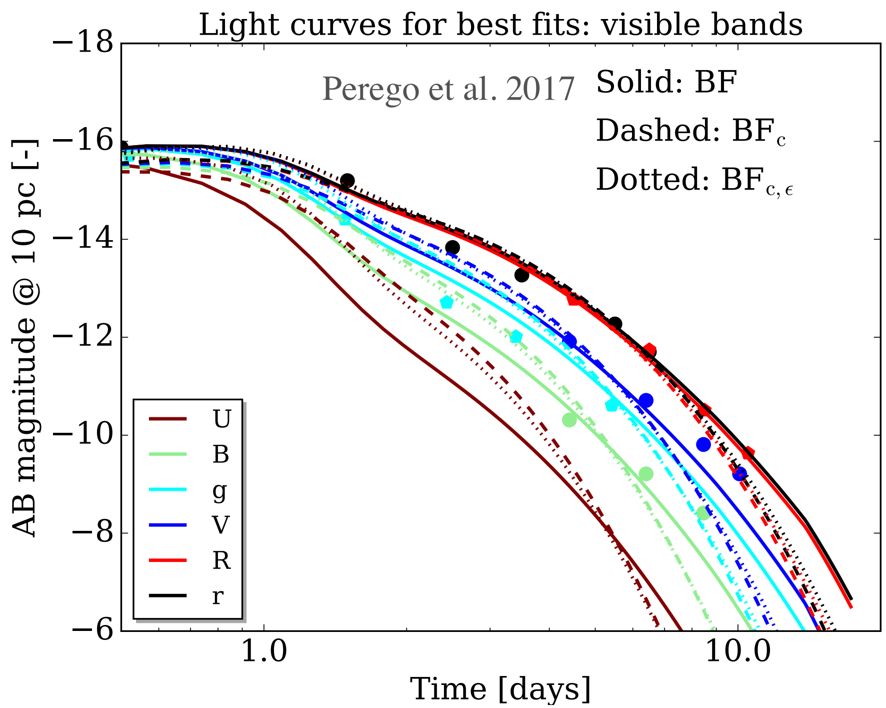
- t_{lag} ~ 2 sec; t_{dur} ~ 2 sec;
- Faint prompt gamma ray: Lγ ~ 10^{46} erg/s

Kilonova/Macronova

BNS merger produces r-process elements

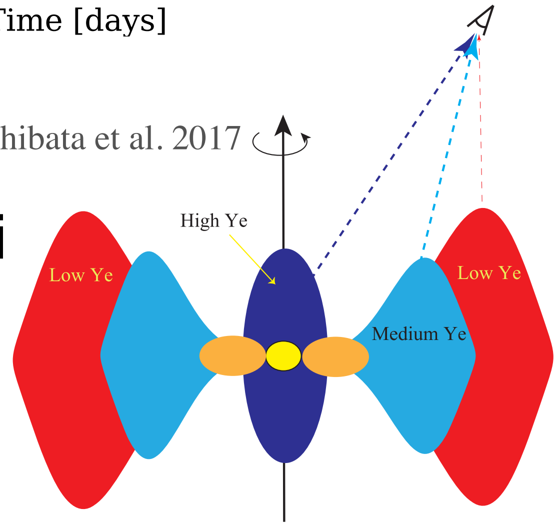
LIGO 2017 (Multi-messenger paper)





- Identify host galaxy: NGC 4993 @ 40 Mpc
- Powered by radioactive decay of neutron-rich nuclei
- Requires Multi-component model:
  Fast-Blue (~0.3c) and **Slow-Red** (~0.1c)

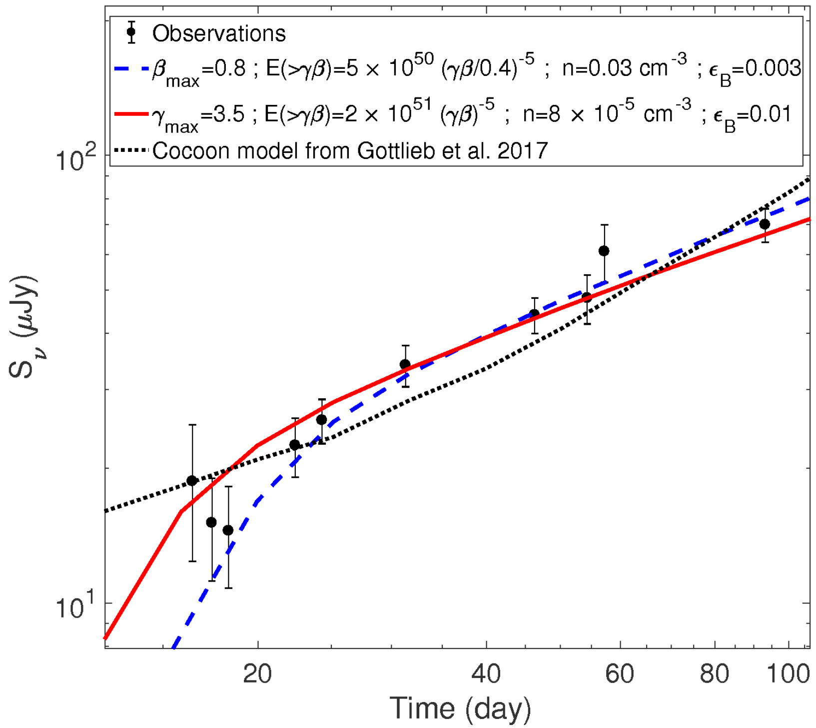
Shibata et al. 2017



Afterglow

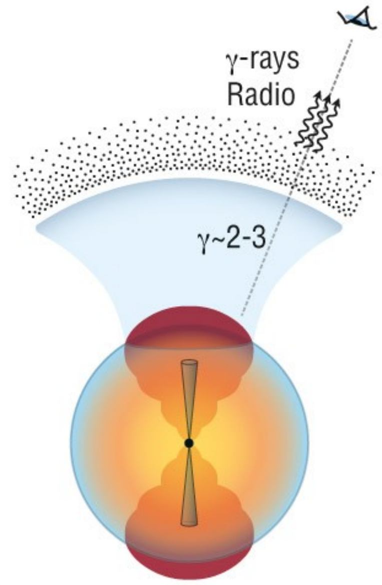
Mooley et al. 2018; Lazzati et al. 2018; Margutti et al. 2018

slowly brightening emission requires structure



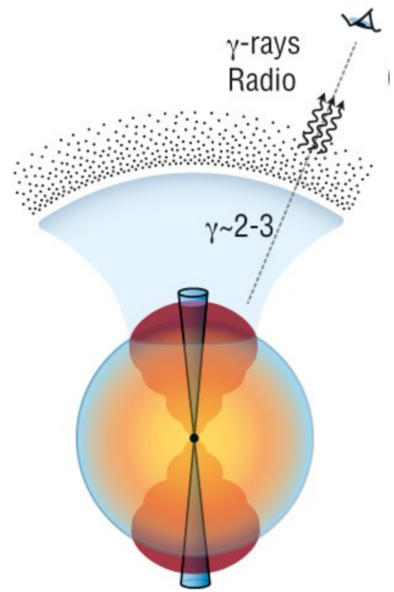
- Flux ~ $t^{0.7}$
  top-hat model is ruled out
  two models are proposed

Choked Jet model



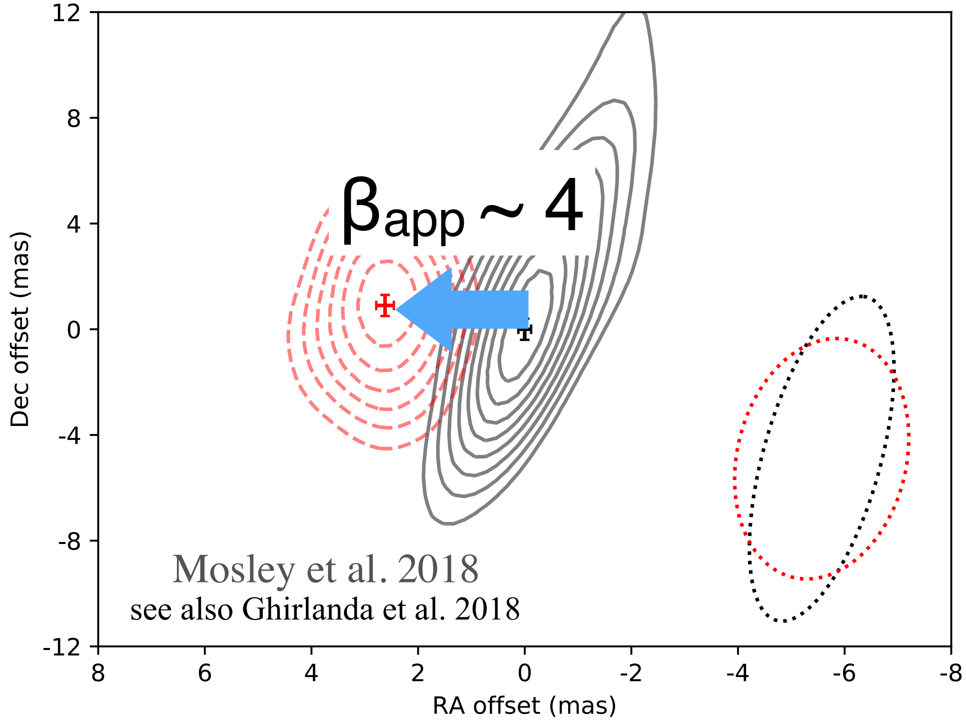
- Weak γ-rays for on-axis observer
- quasi-isotropic cocoon with radial structure

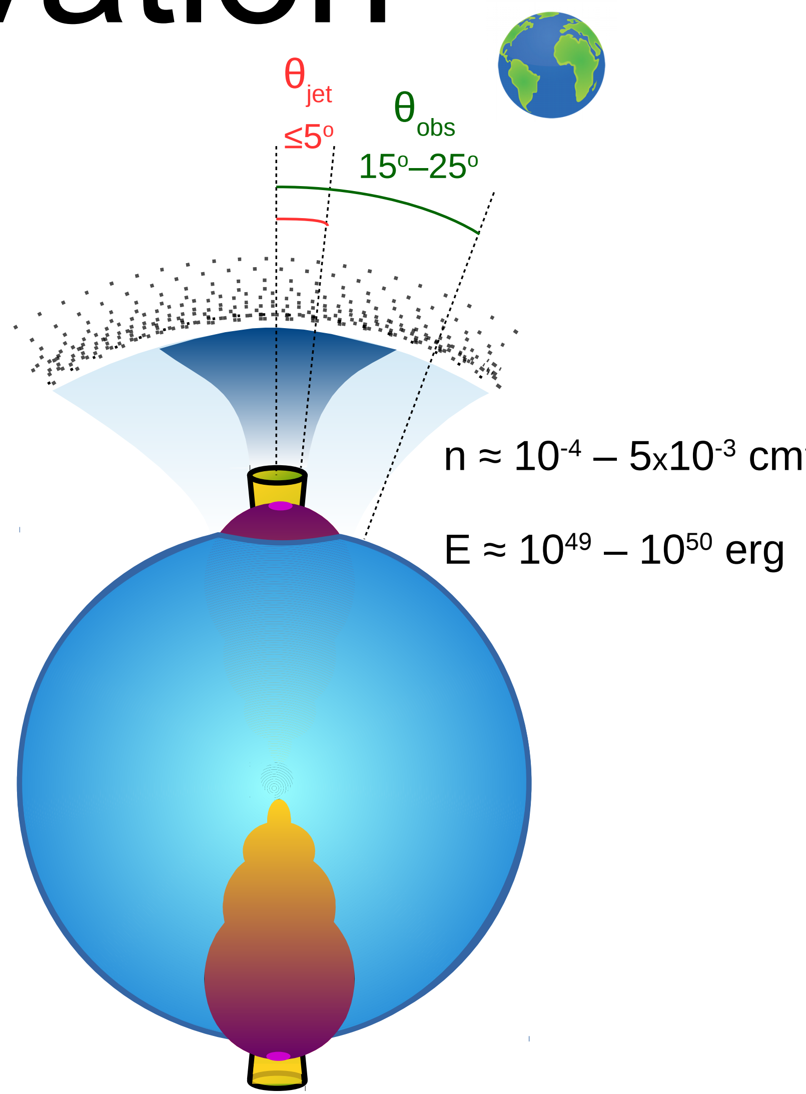
Successful Jet model



- strong γ-rays for on-axis observer
- Polar structure with collimated jet

VLBI Observation





- Superluminal motion
  —> **collimated relativistic jet**
- $E_{iso} \sim 10^{52}$ erg, $\Theta_j \sim 0.05$ rad
  —> consistent with canonical SGRBs

Summary of GW170817

- **First NS-NS merger event seen by GWs and EMs**
- Opt/UV/IR counterparts
  —> r-process element production
- Radio & X-ray afterglows
  —> consistent with SGRBs seen by off-axis observer

NS mergers trigger SGRBs
NS mergers produce heavy elements

Questions after GW170817

- Can we detect HE neutrinos from NS mergers?
- What happens if they have late time activities?
- What is expected for Choked jet events?
- Hadronic CR production by NS mergers?

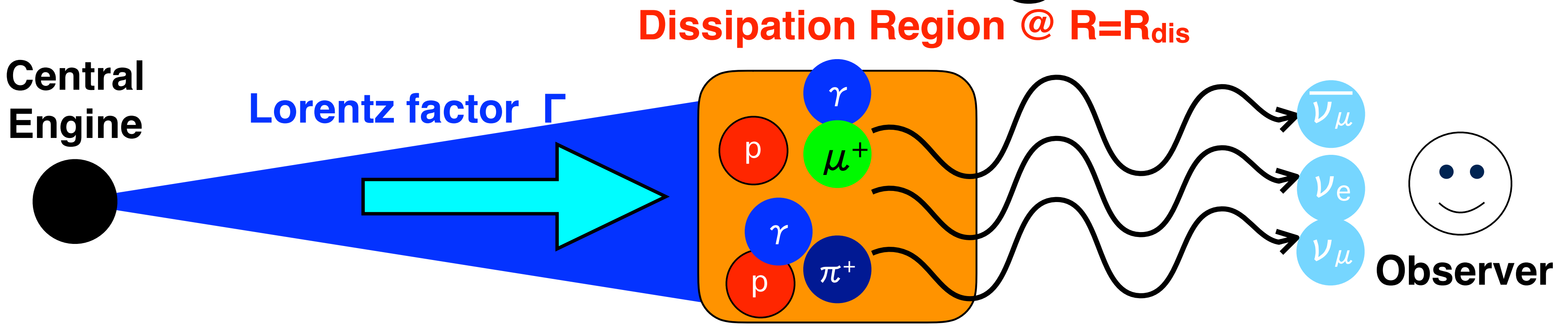
- **Estimate Neutrino Emissions including late-time activity and choked events**
- **Discuss CR production by NS mergers**

High-Energy Neutrinos from Neutron Star mergers

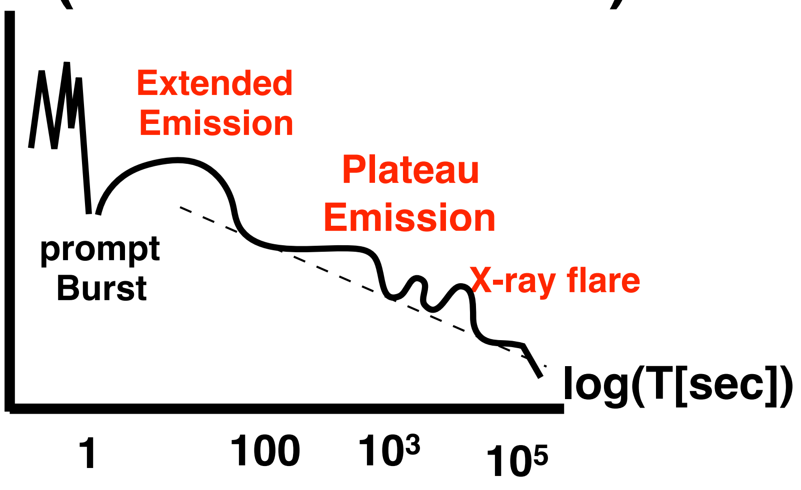
1. High-Energy Neutrino from successful SGRBs
SSK, Murase, Meszaros, Kiuchi, 2017, ApJL, 848, L4
(This work was done before the detection of GW170817)

2. Trans-Ejecta Neutrinos from Choked Jets
SSK, Murase, Bartos et al. 2018, PRD, 98, 043020

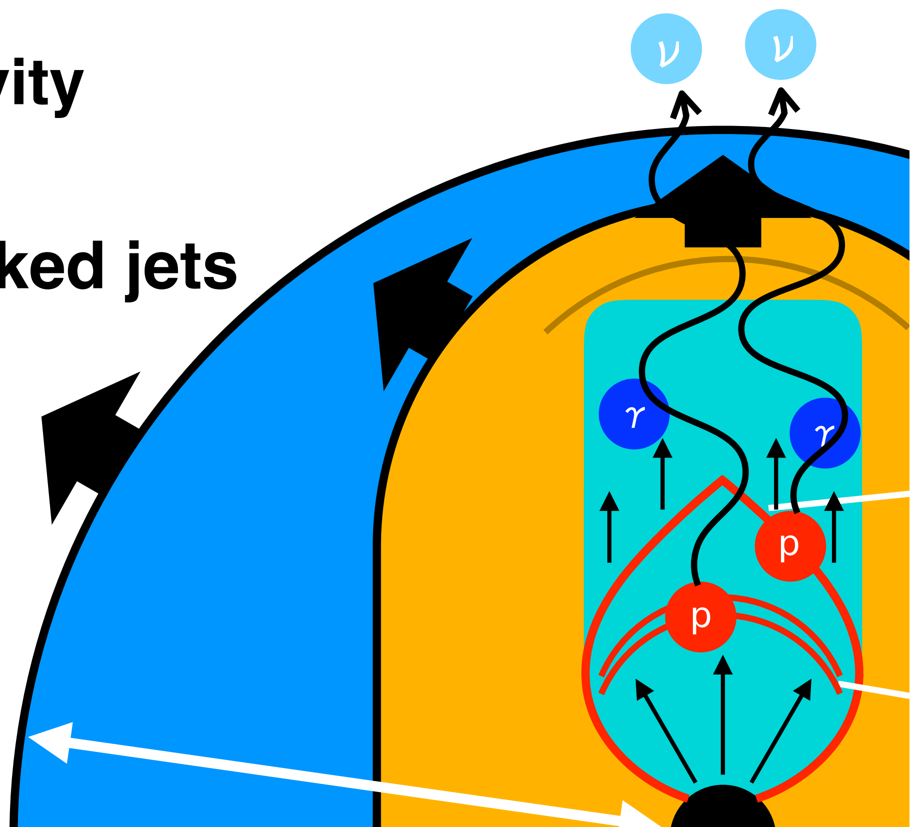
Neutrino emissions from BNS mergers



- **Successful jets with late time activity (canonical SGRBs)**



- **Choked jets**



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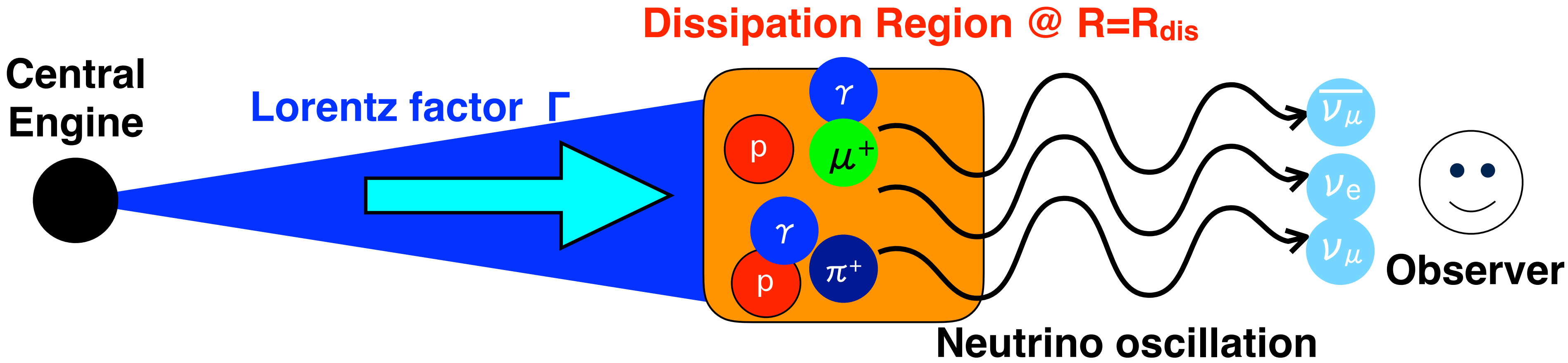
Multi-component One-zone model

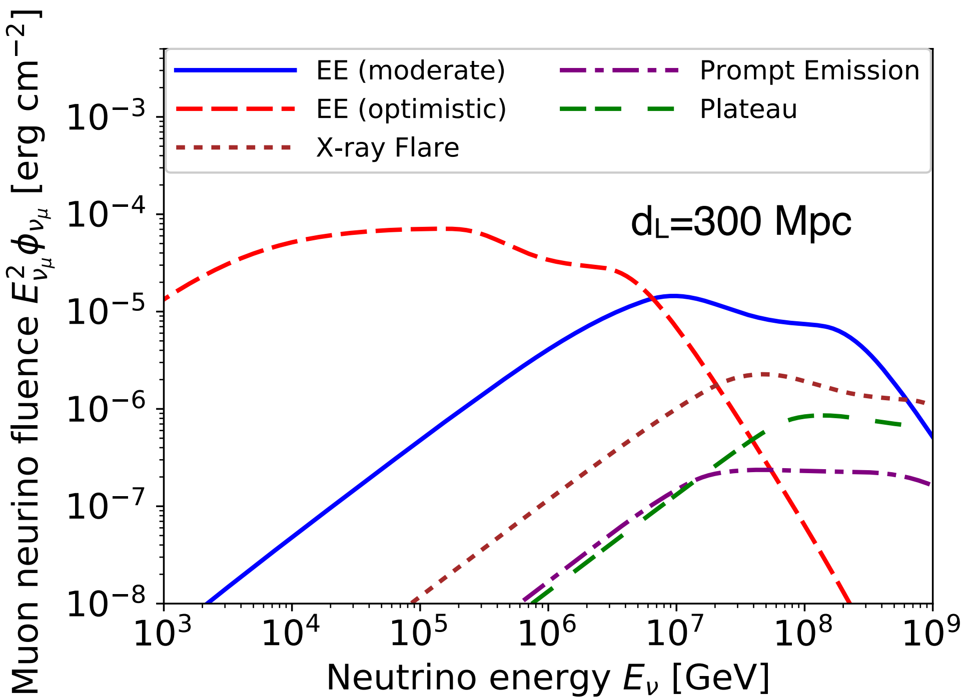


- Calculate ν fluence from each component by one-zone model
- Power-law proton injection with index 2:
  $E_p^2 dN_p/dE_p \sim \xi_p\, E_{\gamma,\mathrm{iso}} / \ln(E_{p,\mathrm{max}}/E_{p,\mathrm{min}})$
- Proton cooling processes: synchrotron & adiabatic coolings
- μ and π also cool down by synchrotron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

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

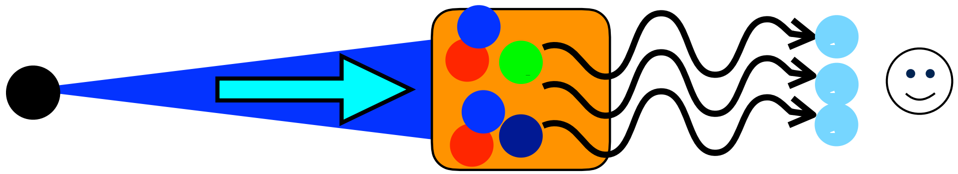
$$f_{p\gamma} = t_{p\gamma}^{-1} / t_{p,\mathrm{cl}}^{-1} \qquad f_{\sup\pi} = 1 - \exp(-t_{\pi,\mathrm{cool}}/t_{\pi,\mathrm{dec}})$$

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}

- Two breaks: soft photon spectrum & pion cooling
- Extended emission (EE) can produce neutrinos efficiently
- Γ ↓ or R_{dis}↓ —> photon density ↑ —> fluence ϕ↑



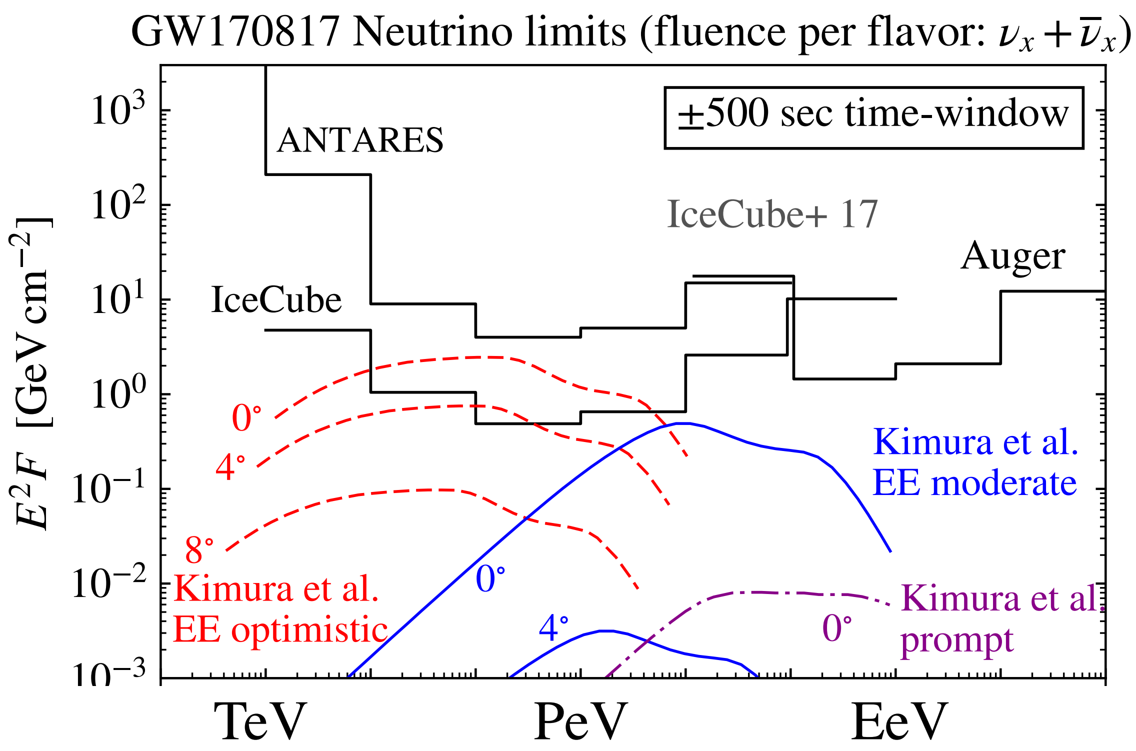
Coincident Detection Probability with Gravitational Waves

NS–NS $(\Delta T = 10 \text{ years})$	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

- Assume that all the NS mergers within 300 Mpc are detected by GW
- R_{SGRB}~ 4 —10 Gpc^{-3} yr^{-3} & half of SGRBs have EE
  —> **N ~ 2-5 for NS-NS (10 yr) within GW horizon (300 Mpc)**
- 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



- The jet is off-axis —> the flux is considerably lower
- This event is in southern sky
  —> atmospheric noise is strong for lower energy
- Extended emission is not observed from this event
  —> neutrinos from EE should not be observed

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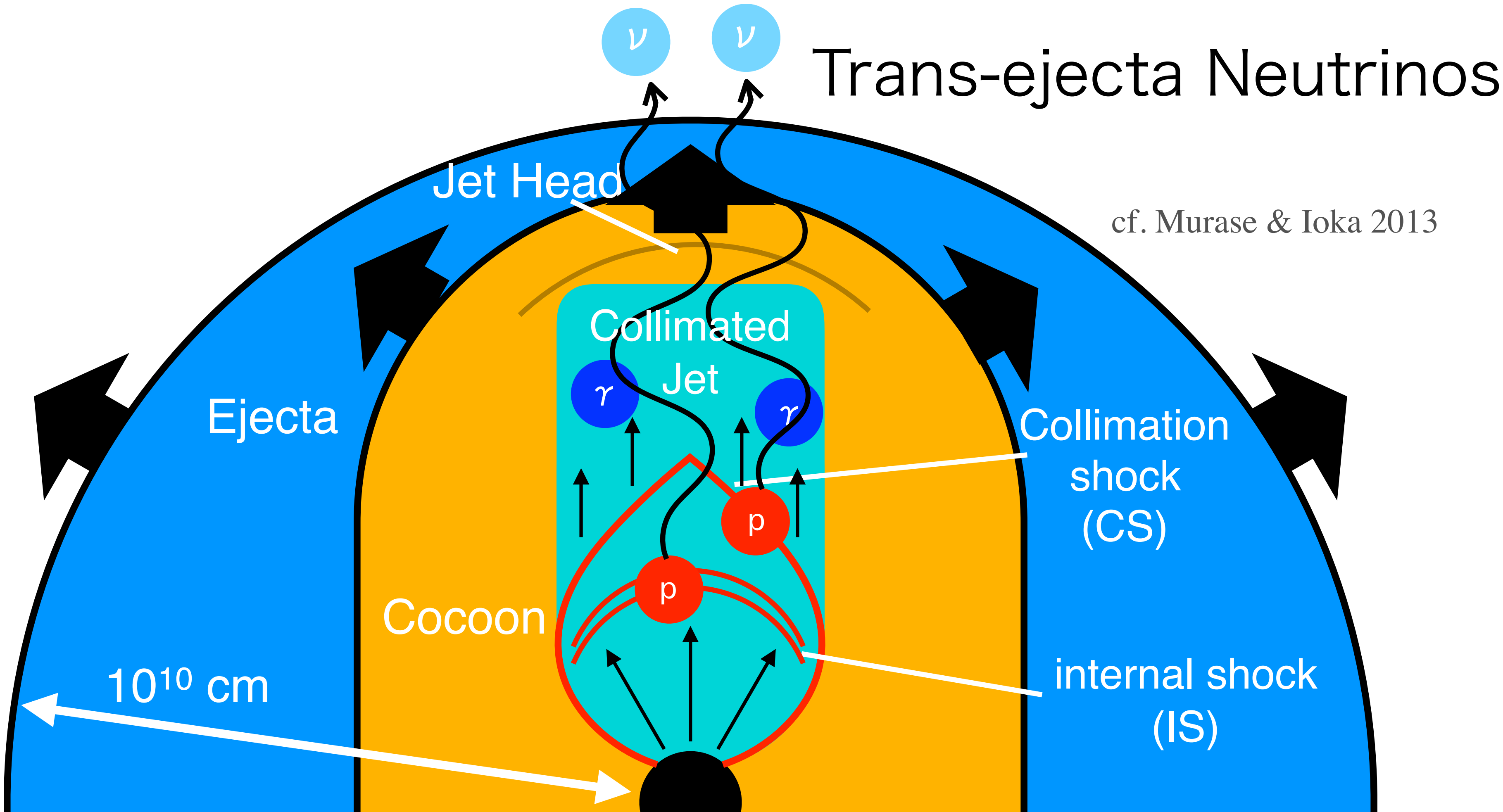
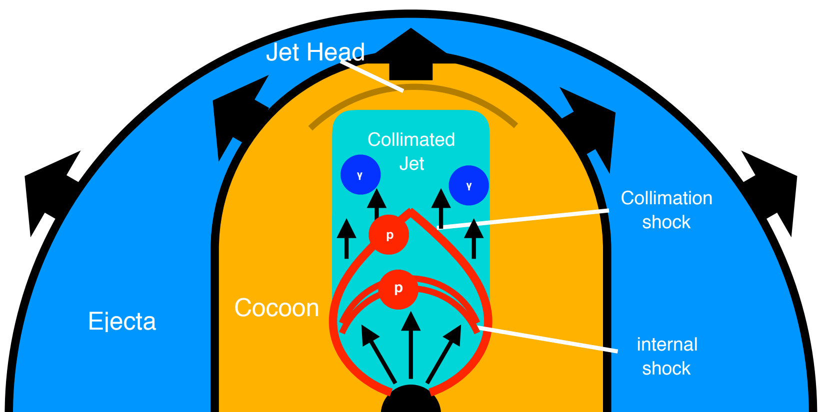
Schematic Picture

- swept-up ejecta forms cocoon surrounding the jet —> push the jet inward —> form **collimation shocks**
- Velocity fluctuations —> **internal shocks**
- **Jet head cannot accelerate particles due to high density**

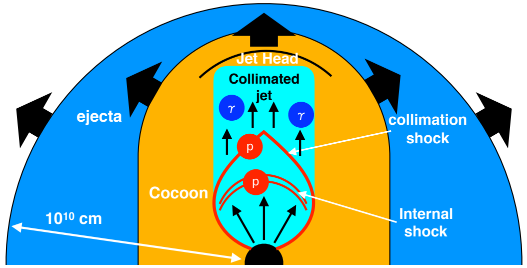


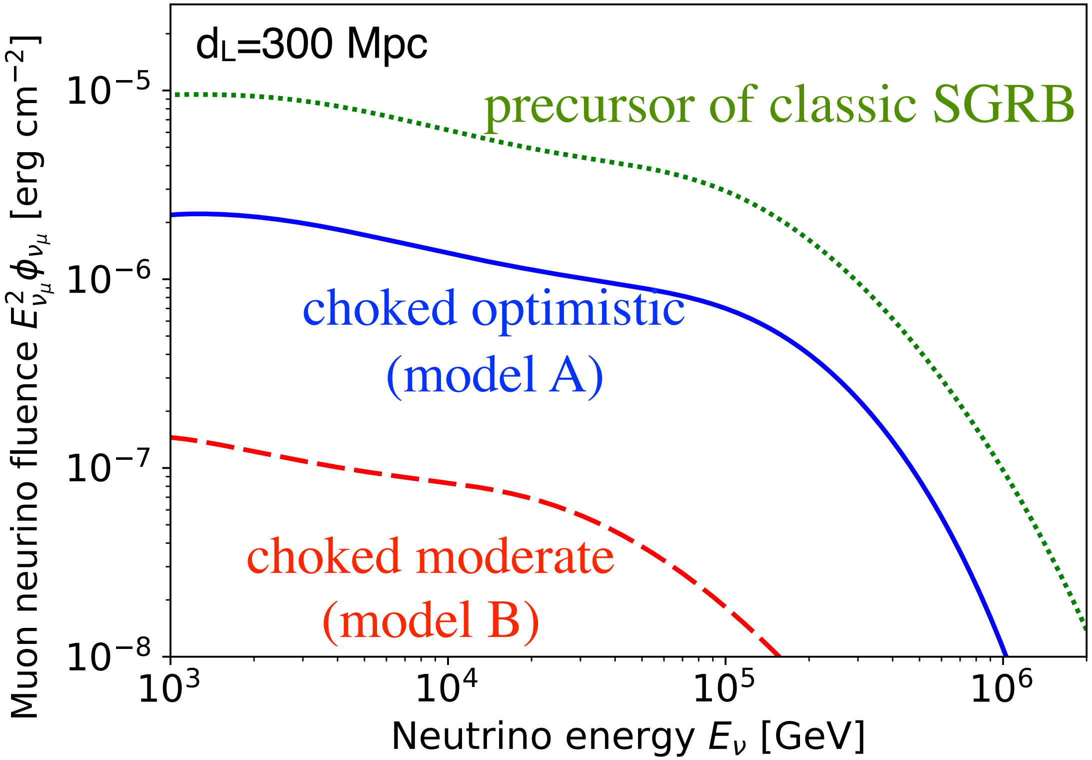
Critical Energies

- High-photon density —> Calorimetric system
- Both shock can accelerate CRs up to a few PeV
- Collimation shock: pion synchrotron + low Γ (~3)
  $E_{\pi,syn} \sim 0.2$ TeV —> Eν < TeV
- Internal Shock: adiabatic cooling + high Γ (~300)
  $E_{\pi,ad} \sim 1$ PeV —> Eν ~ 100 TeV
- We focus on Internal Shock neutrinos with E > TeV



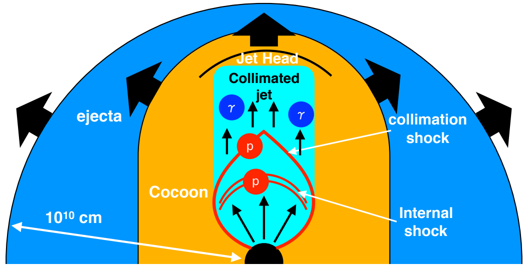
Neutrino Fluence from Choked Jets





- Neutrino spectrum is flat for ~1-100 TeV
- Bethe-Heitler process suppresses νs for GeV-TeV

Detection Probability Coincident with GWs

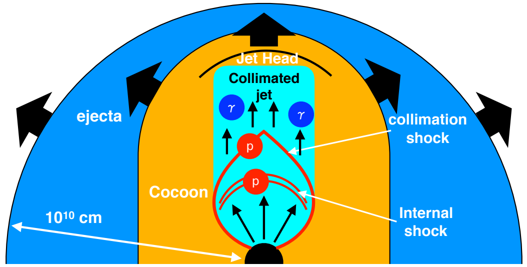


Number of detected neutrinos from single event at 40 Mpc			
model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A (Optimistic)	$\boxed{2.0}$	0.16	$\boxed{8.7}$
B (Moderate)	0.11	7.0×10^{-3}	0.46

Number of detected neutrinos from single event at 300 Mpc			
model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A (Optimistic)	$\boxed{0.035}$	2.9×10^{-3}	$\boxed{0.15}$
B (Moderate)	1.9×10^{-3}	1.3×10^{-4}	8.1×10^{-3}

- At 40 Mpc, detection is possible even with IceCube
  —> **neutrino obs. can put a limit on physical quantities**
- At 300 Mpc, detection is challenging even with Gen2
  —> stacking technic is important

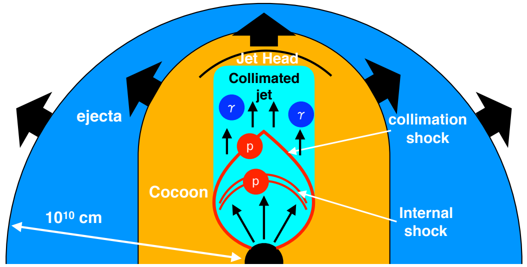
Detection Probability Coincident with GWs



- Merger rate: R~1500 Gpc^{-3} 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)	$\boxed{0.38}$	1.2
B (Moderate)	0.024	$\boxed{0.091}$

Detection Probability Coincident with GWs



- Merger rate: $R \sim 1500\ \mathrm{Gpc^{-3}\ yr^{-1}}$
- Beaming factor: $f_b \sim 0.045$
  —> on axis event rate $R_{on} \sim 4\ \mathrm{yr^{-1}}$

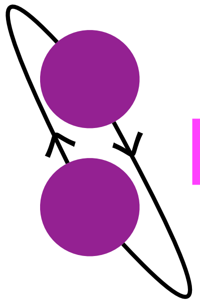
Choked system
—> faint prompt γ-rays
—> multi-messenger with ν & GW without EM counterpart

model	IceCube (up+hor+down)	Gen2 (up+hor)
A (Optimistic)	$\boxed{0.38}$	1.2
B (Moderate)	0.024	$\boxed{0.091}$

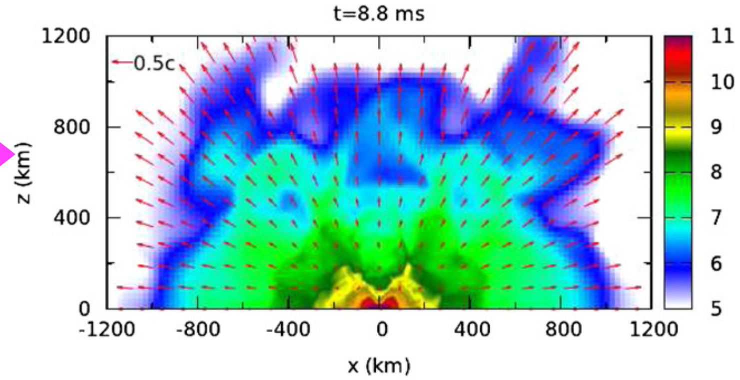
CR production at NS Merger Remnants

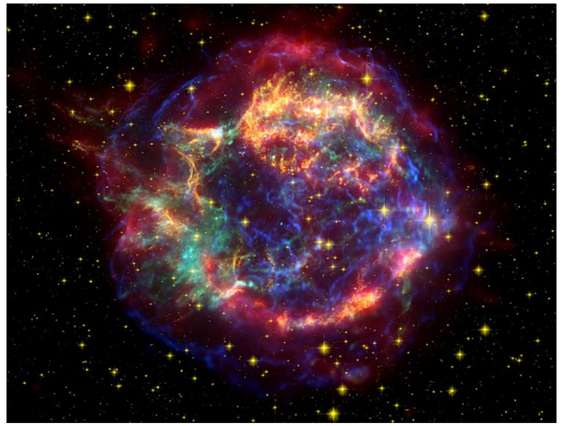
SSK, Murase, Meszaros, ApJ accepted (arXiv:1807.03290)

NS Merger Remnants (NSMRs)



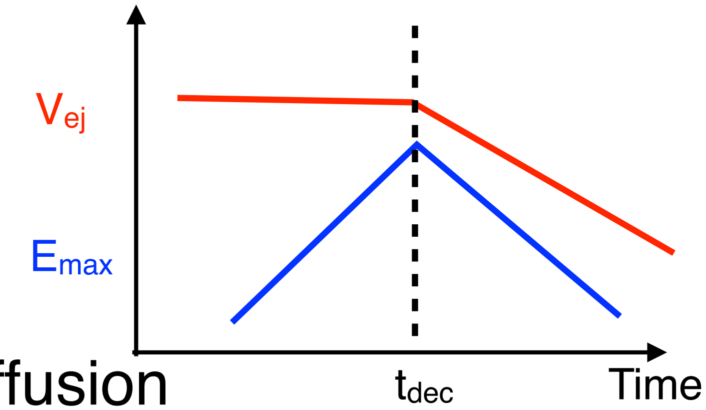
Hotokezaka et a. 2013





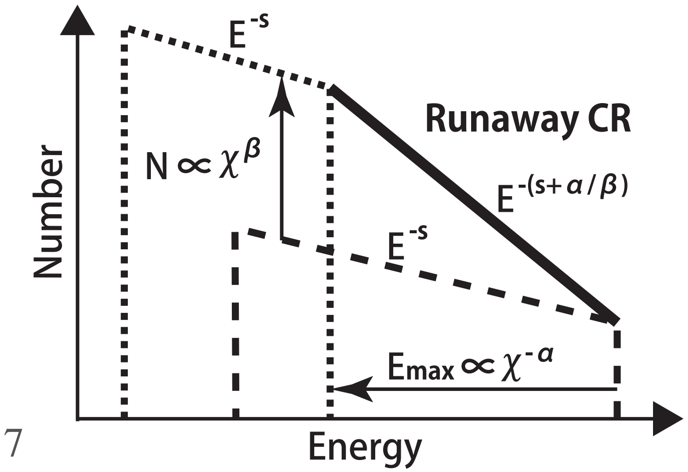
- Interaction between NS merger ejecta and ISM
  —> forward shock produces CRs analogous to SNRs
- NS mergers produce faster ejecta (~0.3c) than SNRs (~0.03c)
  —> Between "knee" and "ankle" e.g. Tanaka et al. 2017
- NS merger rate: R~1500 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ LIGO (Multi-messenger) 2017
  —> CR production rate in the Galaxy: ~ 1% of SNR
  —> **enough to explain CRs above "knee"**

Model

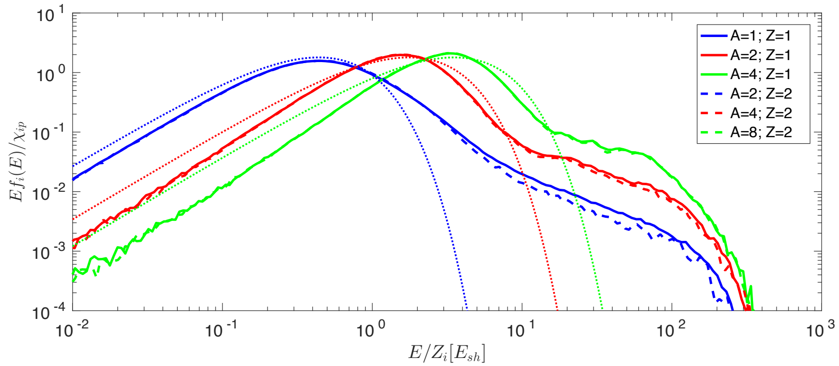


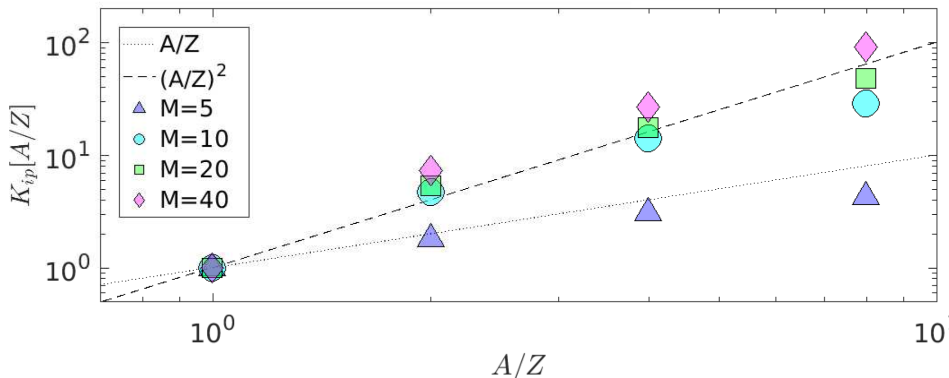
- Maximum energy: $t_{acc} = t_{age}$ with Bohm diffusion
  E_{max} increases in ballistic phase and decreases in Sedov phase
  E_{max} ~ **20 PeV for protons, 500 PeV for iron nuclei at $t=t_{dec}$**

- Escape limited model: Ohira et al 2010
  CRs with E~E_{max} can escape from NSMRs
  low energy CRs cannot escape
  Time integration gives power-law spectrum



- mass-charge ratio dependent injection:
  injection efficiency K_{ip}~ $(A_i/Z_i)^2$ Caprioli et al. 2017





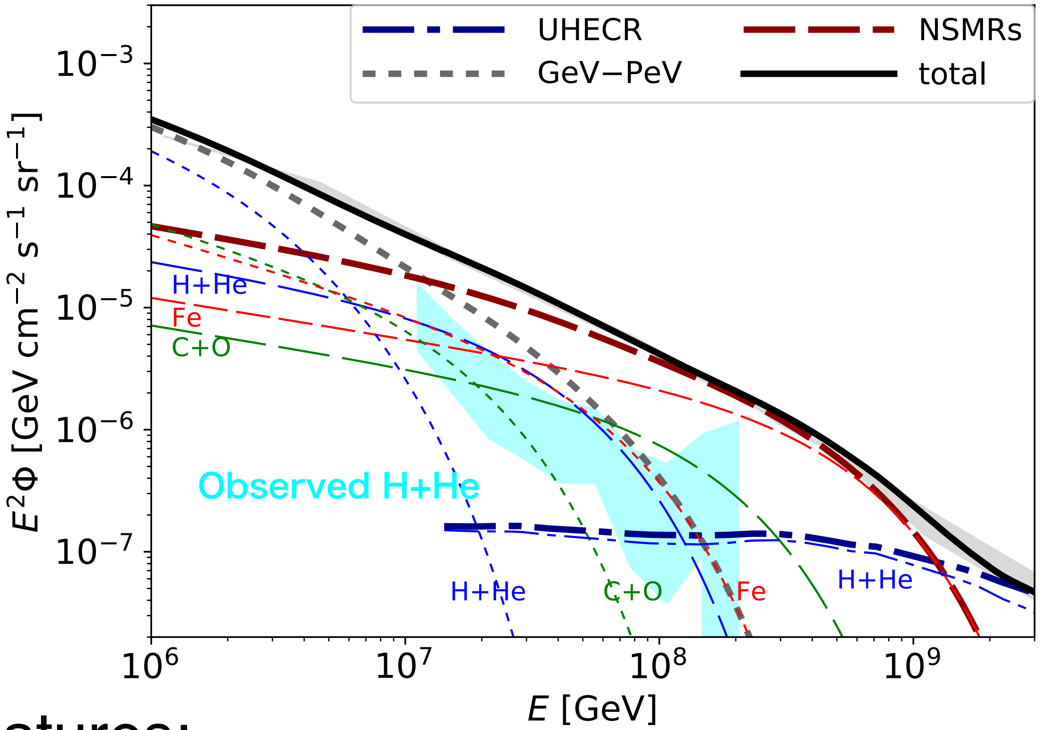
Spectrum on Earth

- One-zone diffusion model with steady state

$$(E^2\Phi)_i \approx \frac{(EQ_{E,\mathrm{inj}})_i X_{\mathrm{esc}}}{4\pi M_{\mathrm{gas}}}$$

- **NSMRs can be dominant source of CRs for 10 - 10³ PeV**
- E < 10 PeV: GeV-PeV (SNR?)
- E>1EeV: UHECR (ANG?)

talk by Fang, Bell, Matthews, Eichmann



- Consistent with observational features:
  - Slight hardening of total spectrum at E~10 PeV
  - Light element spectrum at E~10—100 PeV
- If NS mergers leave magnetars as a central remnant, the magnetar injects energies to ejecta by magnetar winds —> UHE CR production might be possible

Fang & Metzger 2017
(talk by Decoene for deferent scenario)

Summary

Summary

- **NS mergers are interesting multi-messenger sources**
- Neutrino observations associated with SGRBs can be detected or put some limit with IceCube-Gen2
- Neutrinos observation from choked jet system may put some constraint on physical parameters without EM
- Galactic NSMRs are suitable CR sources between knee and ankle

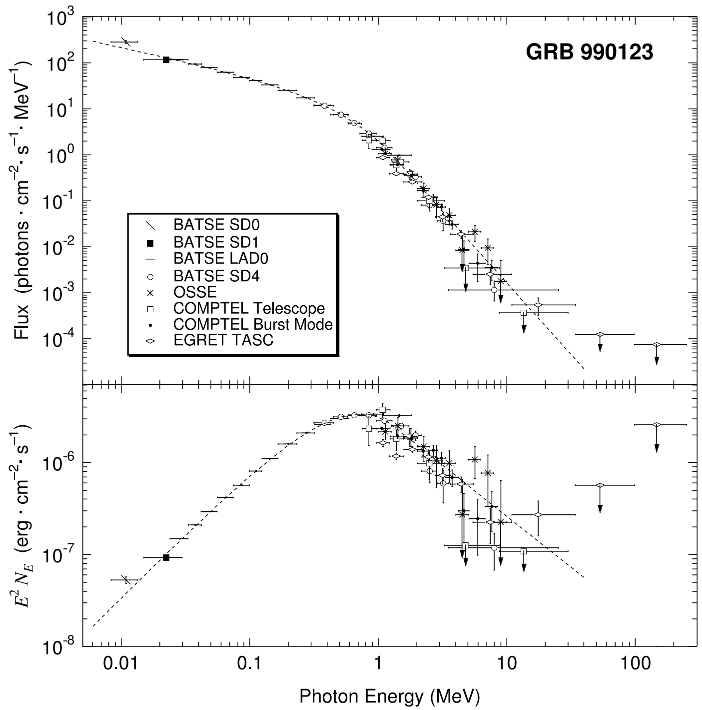
Thank you
for your attention

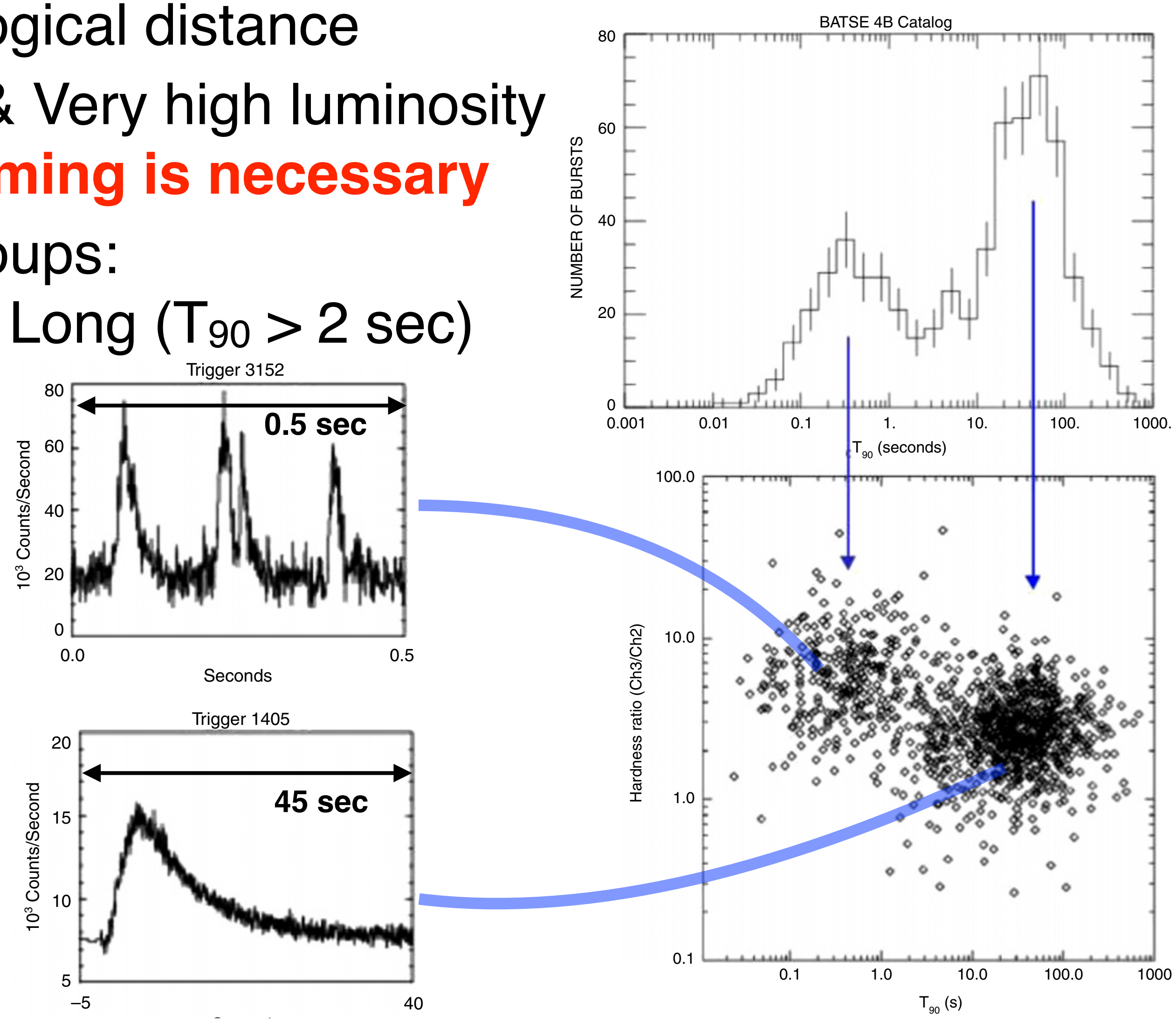
Backup

Gamma-ray Bursts

see e.g. Kumar & Zhang 2015

- The brightest explosion in the Universe:
  $L_{iso} \sim 10^{50}$—10^{52} erg/s, $E_{iso} \sim 10^{50}$–10^{53} erg, $E_{pk} \sim 0.1$–1 MeV
- Events in the cosmological distance
- Very short variability & Very high luminosity
  —> **Relativistic beaming is necessary**
- Classified into two groups:
  Short ($T_{90} < 2$ sec) & Long ($T_{90} > 2$ sec)





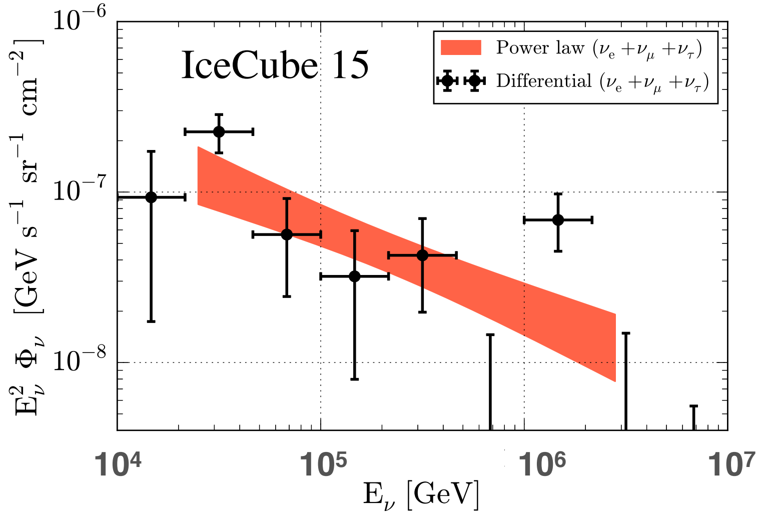
Why Neutrinos?

	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

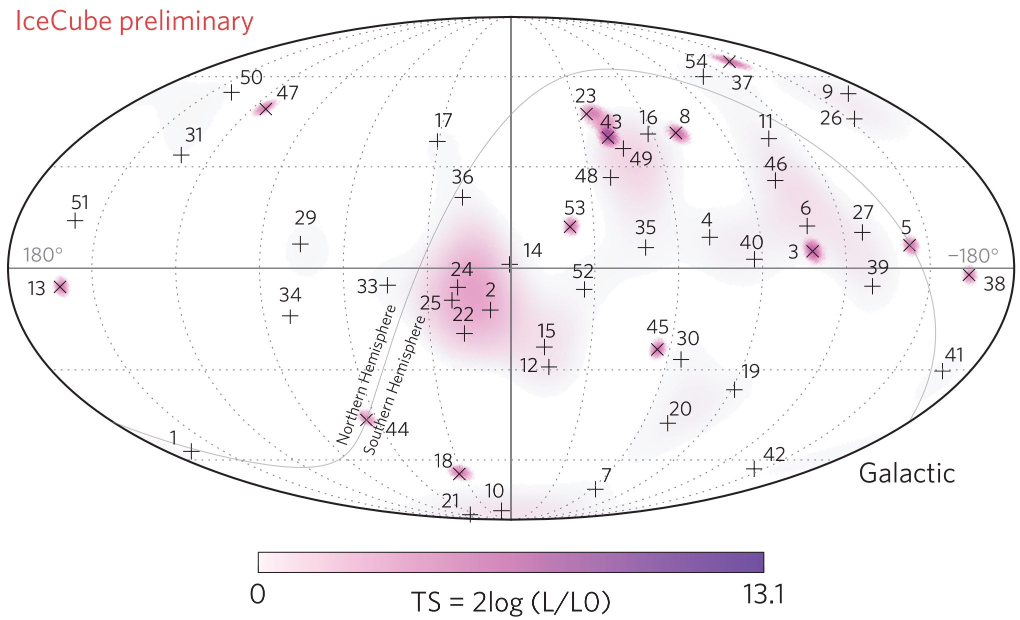
Difficulty for Neutrino Astronomy

- 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)

Astrophysical Neutrinos

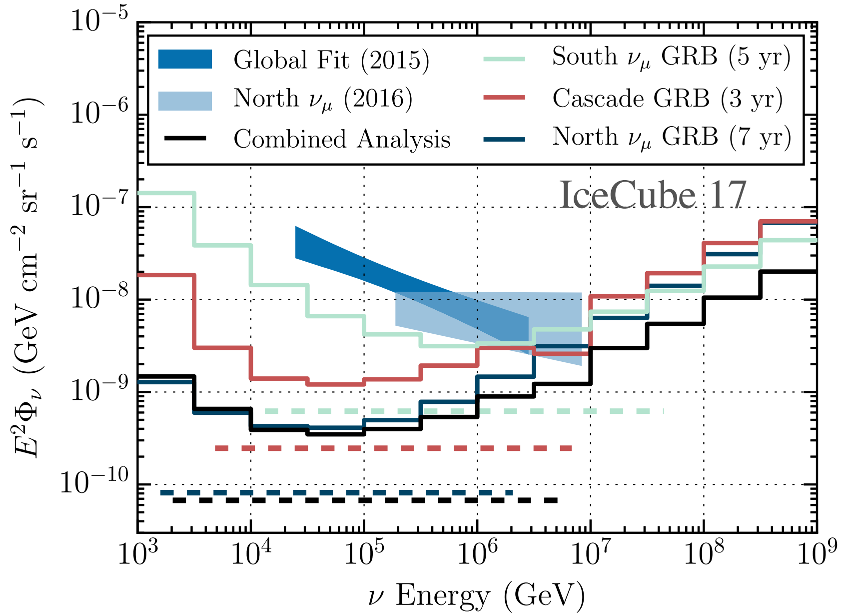


Halzen+ 17



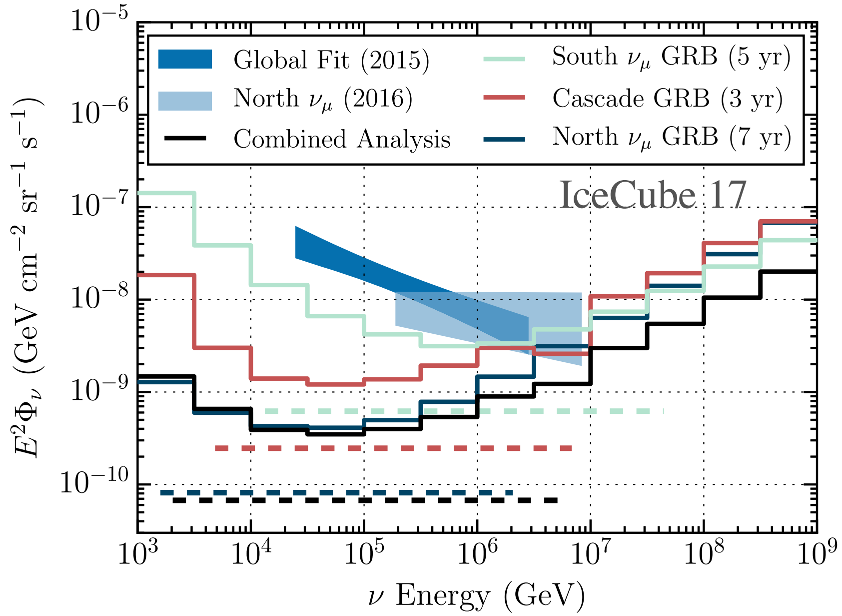
- IceCube reported TeV-PeV astrophysical neutrinos
- Isotropic arrival direction —> extragalactic origin

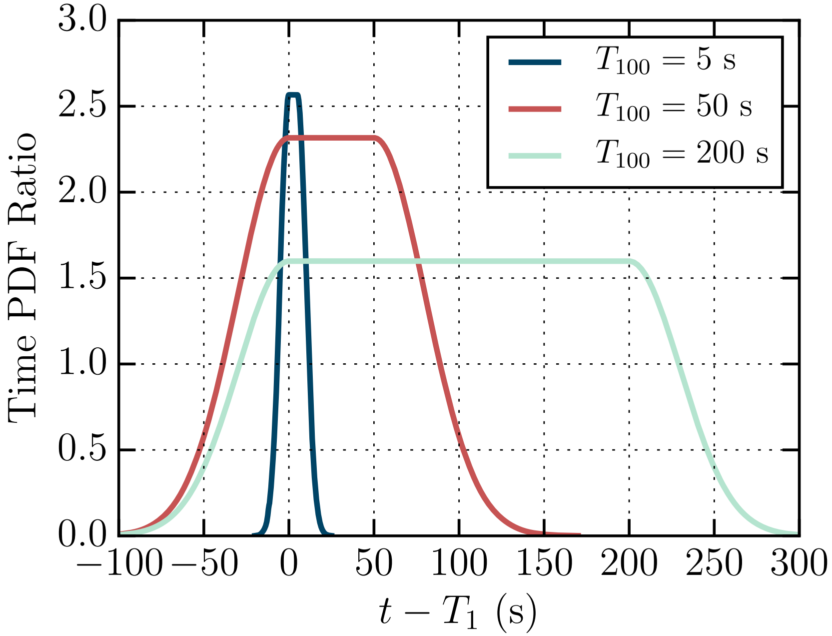
IceCube GRB Analysis



- Using the timing and position information of each GRB, IceCube put the limit on GRB associated neutrinos —> **GRB cannot be a source of observed neutrinos**

IceCube GRB Analysis





These analyses focus on the prompt phase

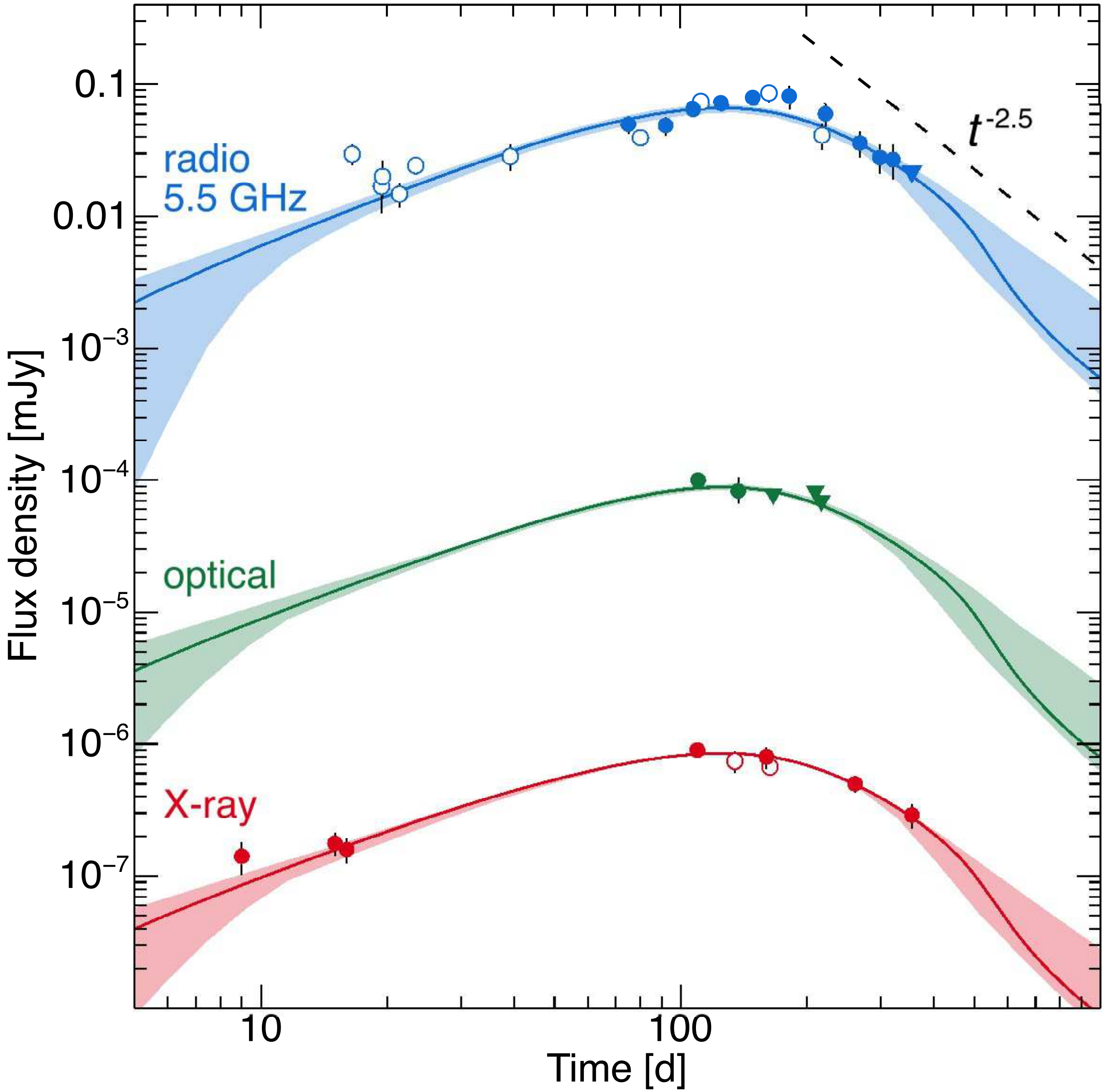
afterglow phase is not constrained

SGRBs are minority

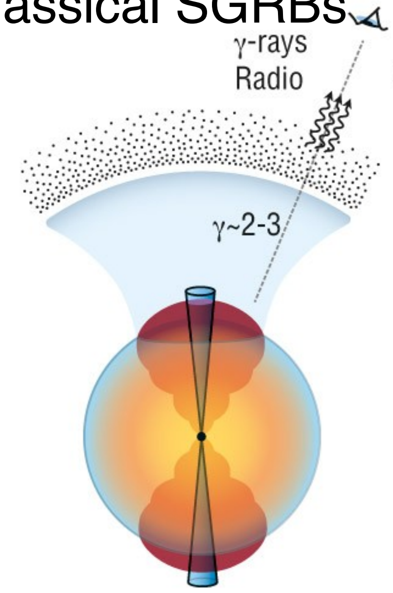
—> constraint is not strong

Afterglow

slowly brightening emission requires structure



Successful Jet:
classical SGRBs



Mooley+17

- Long-term monitoring
  —> F ~ $t^{-2.5}$
  —> successful jet model is favored

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:

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

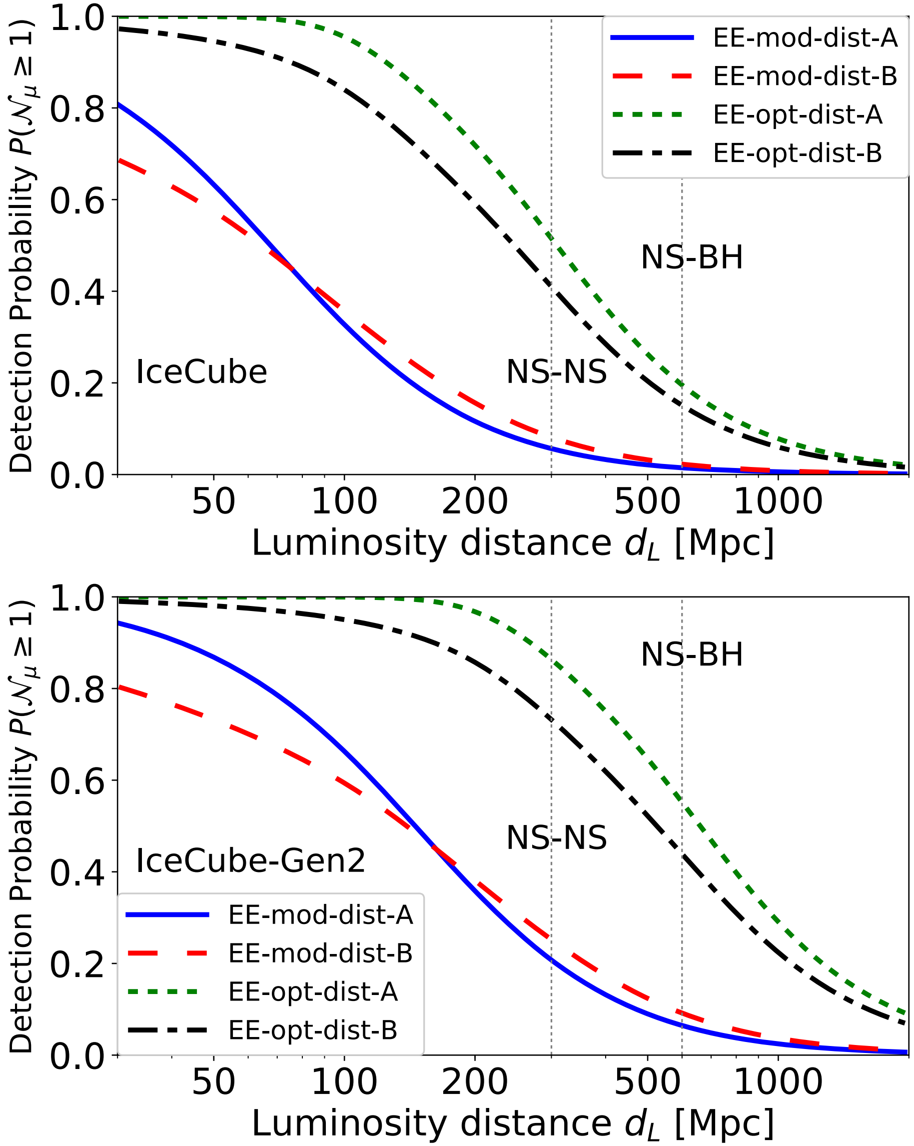
- Assume distribution of Γ

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

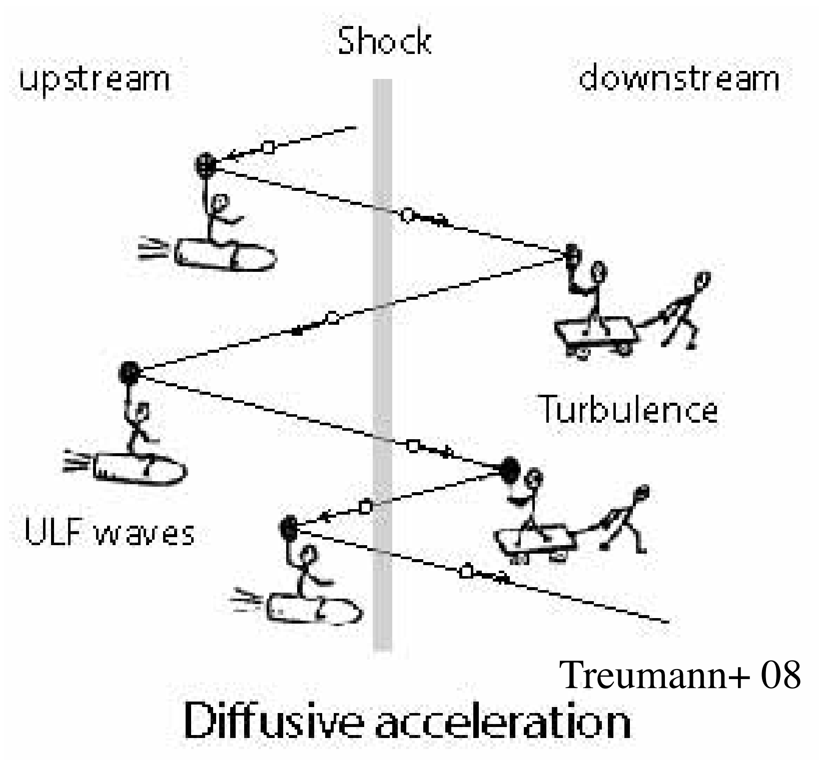
- Estimate the detection probabilities

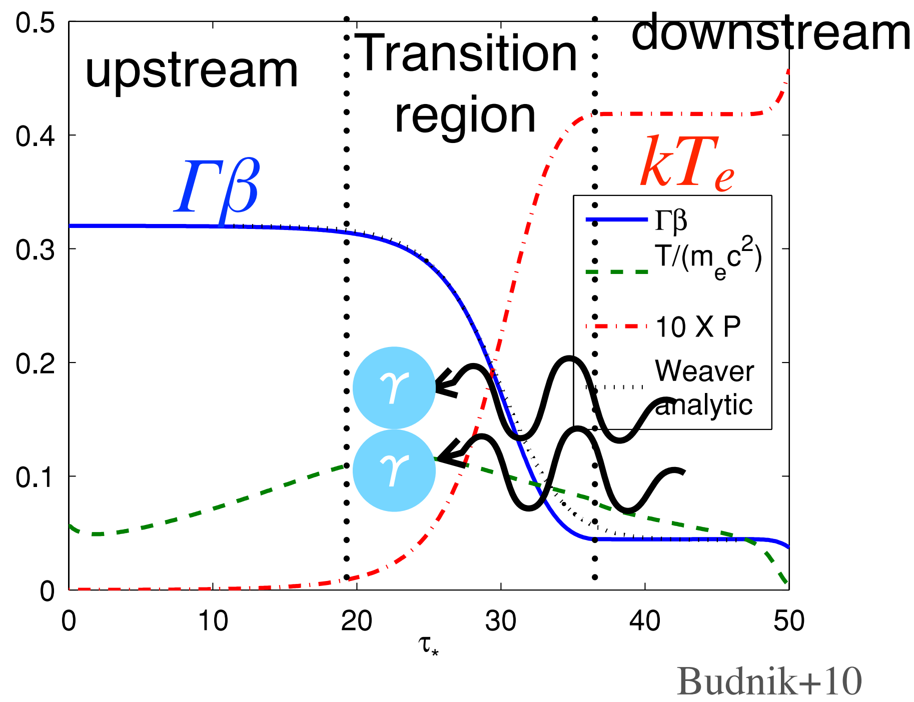
$$P_k = \int d\Gamma F_\Gamma p_k$$

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



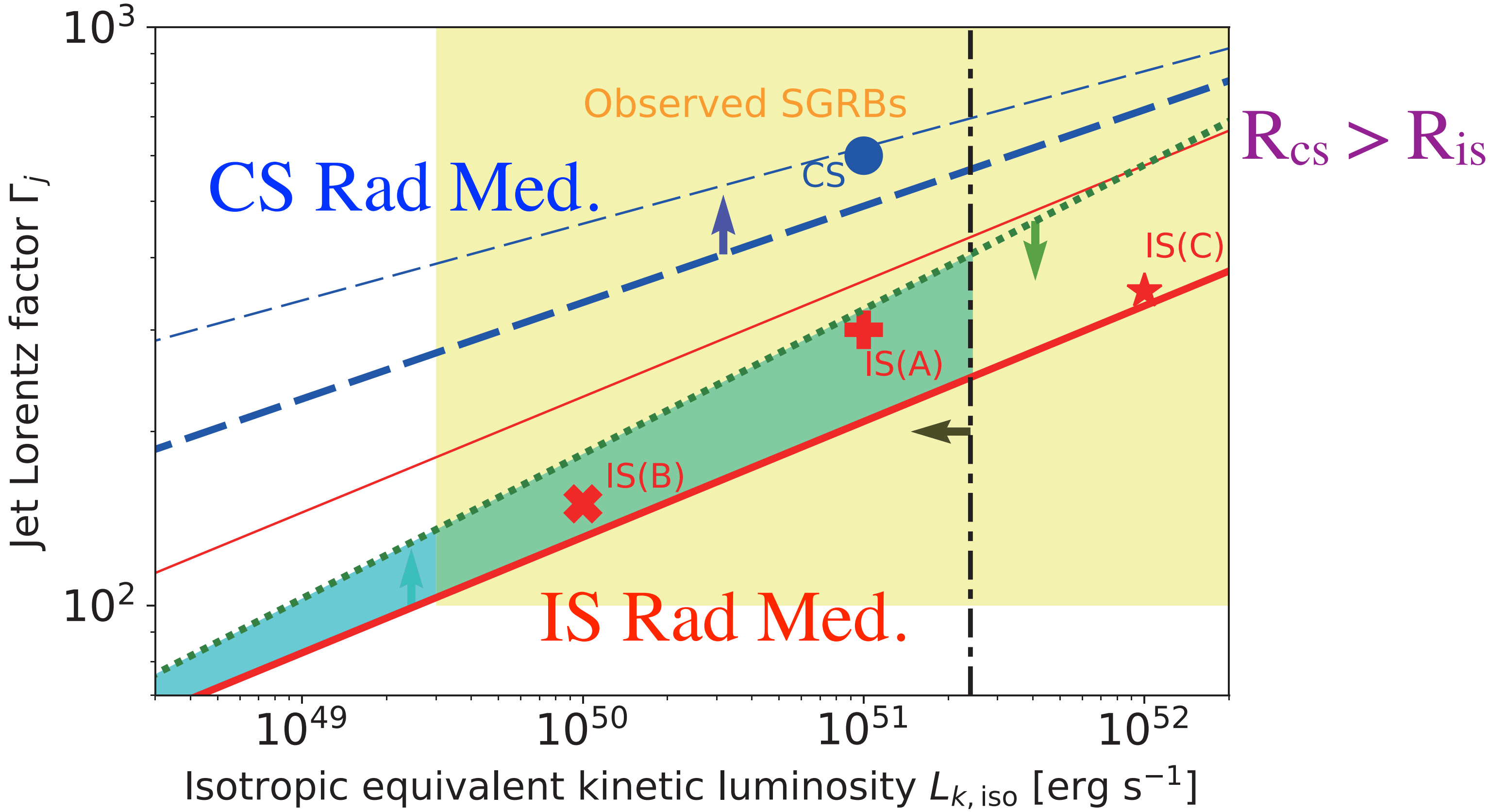
Particle Acceleration





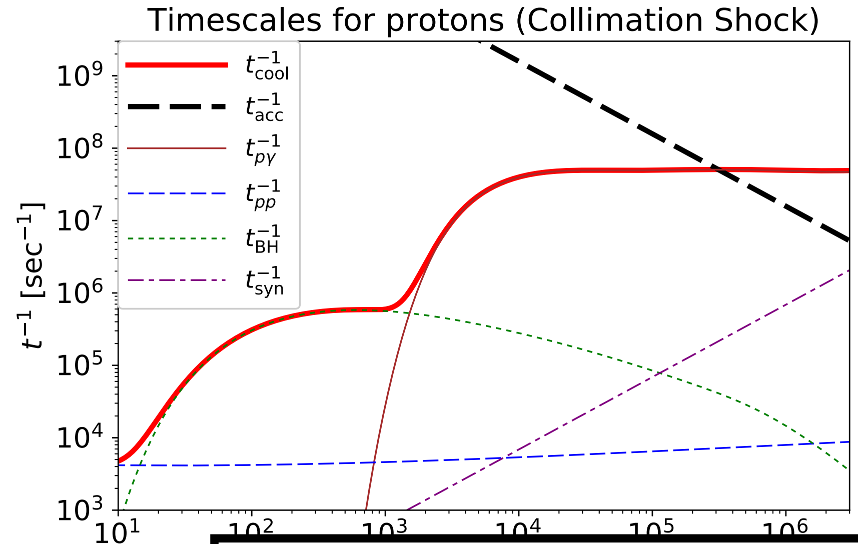
- Particle acceleration requires **sharp velocity jump** in λ_{mfp}
- **High upstream density** —> **no particle acceleration**
  high density —> radiation pressure dominant @ down stream
  —> photons diffuse to upstream —> decelerate the upstream fluid
  —> gradual velocity change (Radiation Mediated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

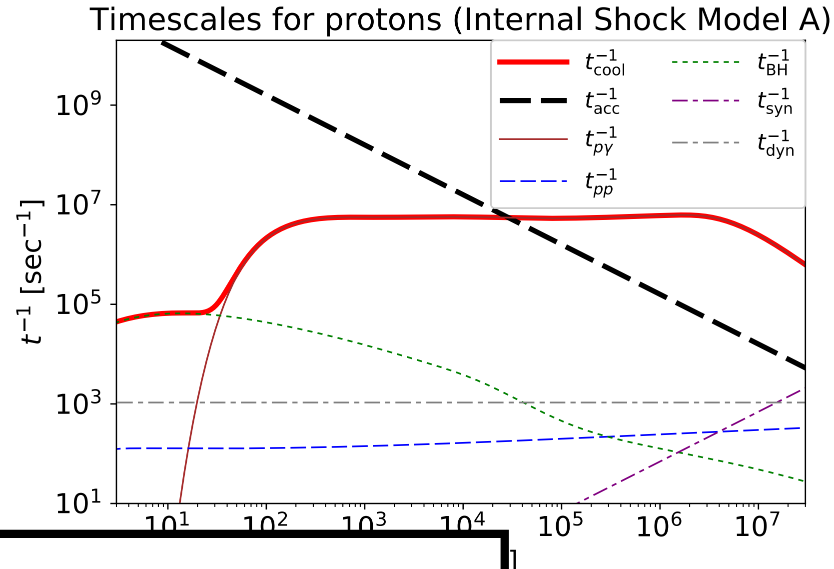
Particle Acceleration



- 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

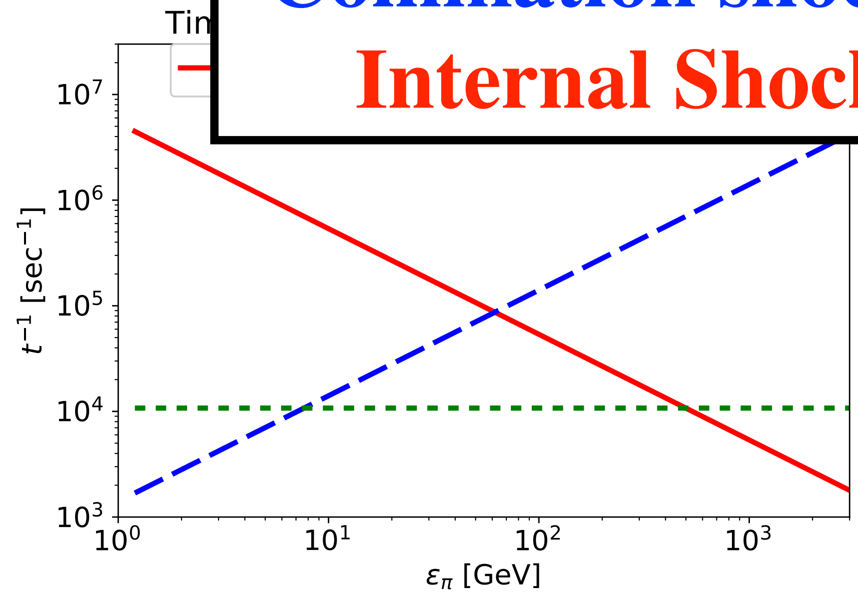
Critical Energies

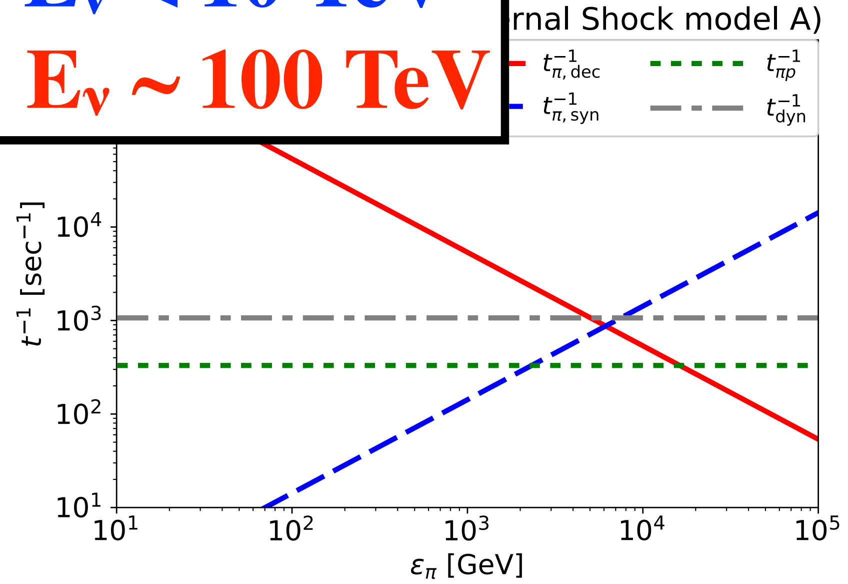


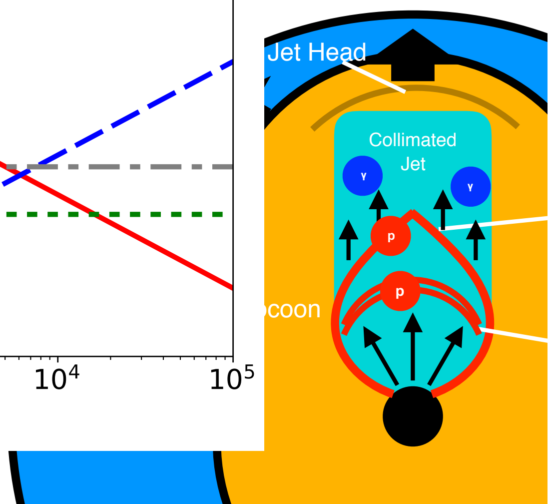


Collimation shock: E_ν < 10 TeV

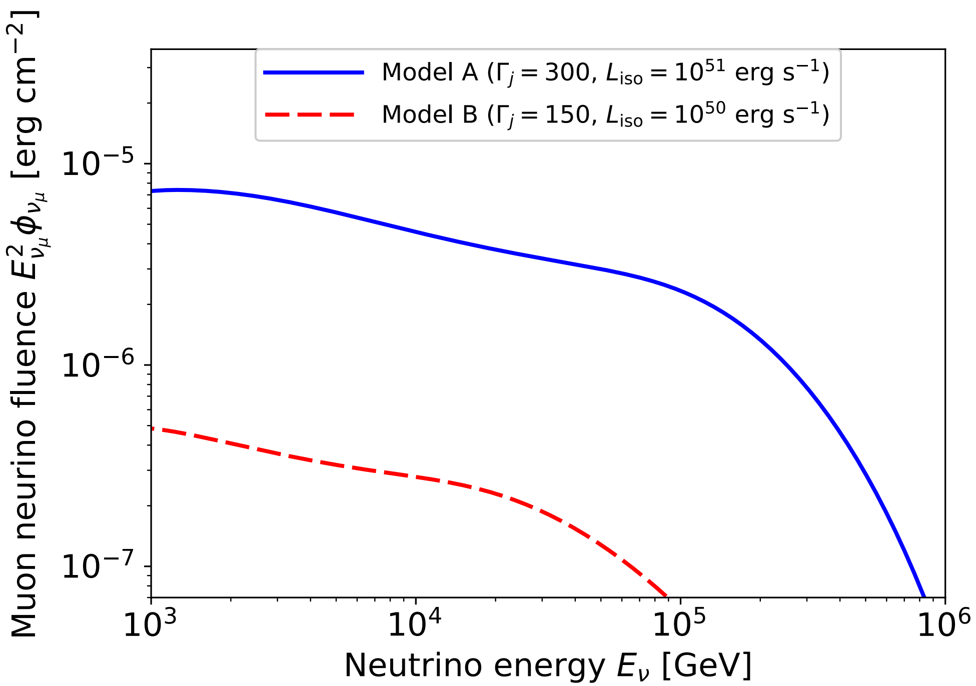
Internal Shocks: E_ν ~ 100 TeV

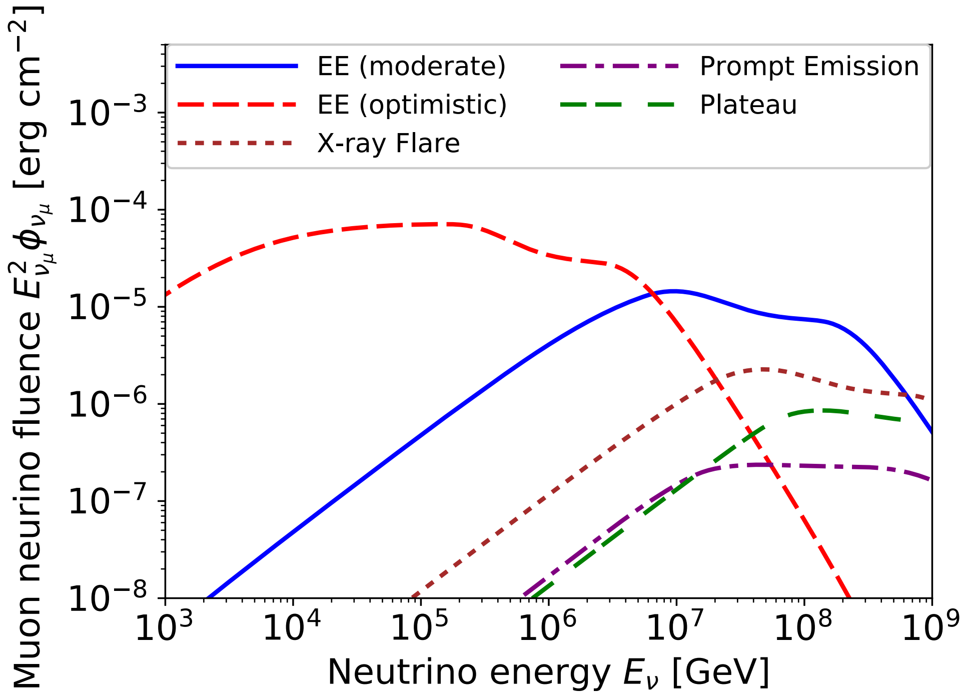




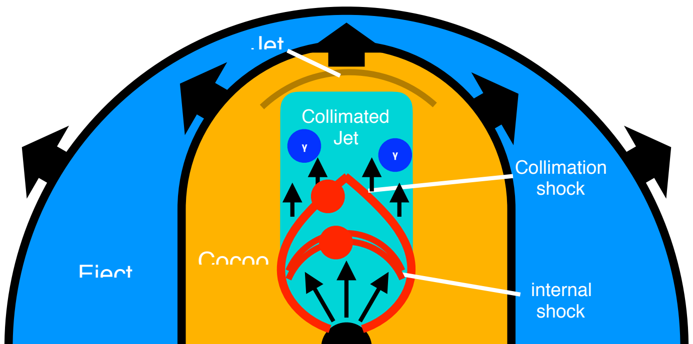


Choked or Successful?

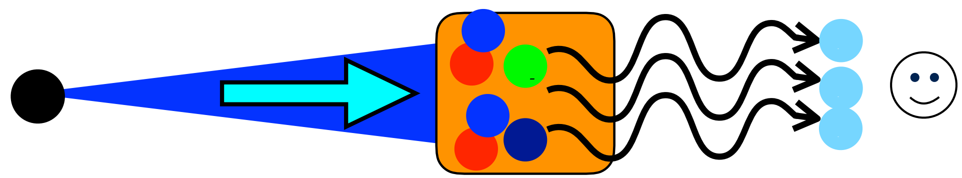




- E < 300 TeV

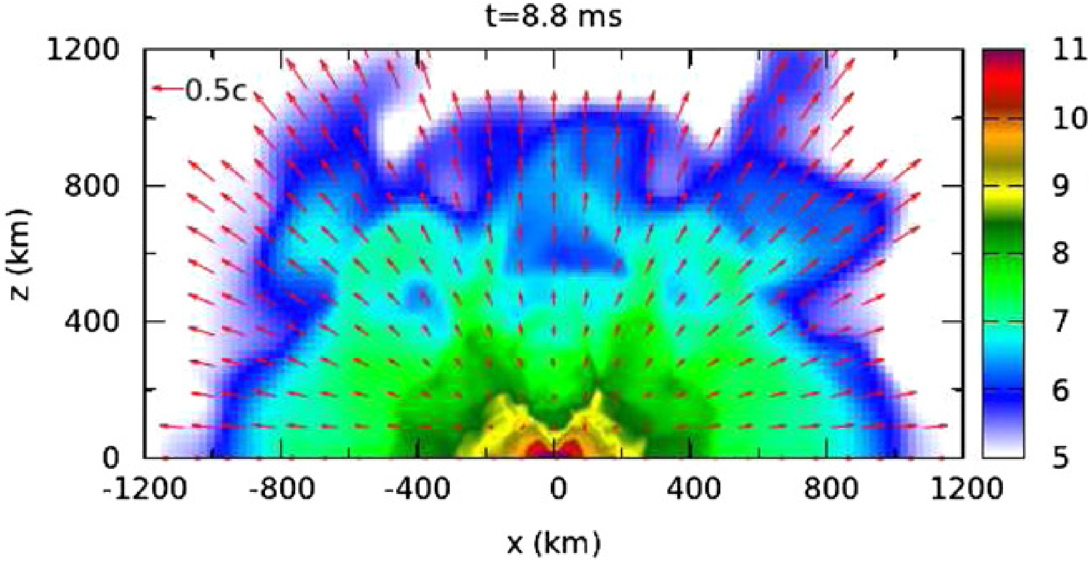


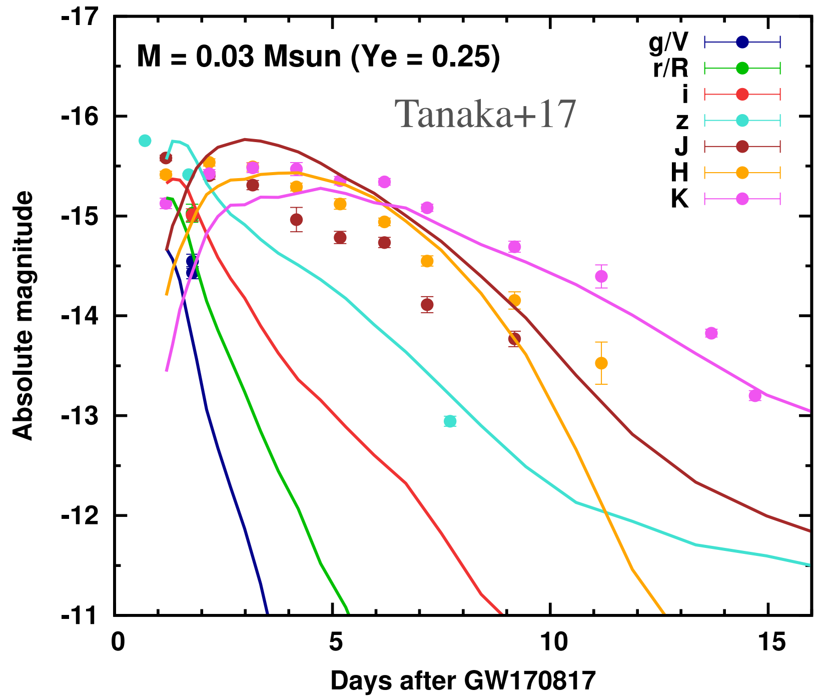
- E > PeV



Ejecta of NS Merger

Hotokezaka+13





- NS mergers creates fast & massive outflows
- Modelings of kilonova/macronova for 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

e.g. LIGO+17

- **comparable kinetic energy to SNe**
- **higher velocity than SNe,**