Potential Neutrino Sources associated to Gravitational Waves

Tohoku University

Shigeo S. Kimura

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.

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Dialog at Dream Field 2024@Guiyang

May 13, 2024

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- 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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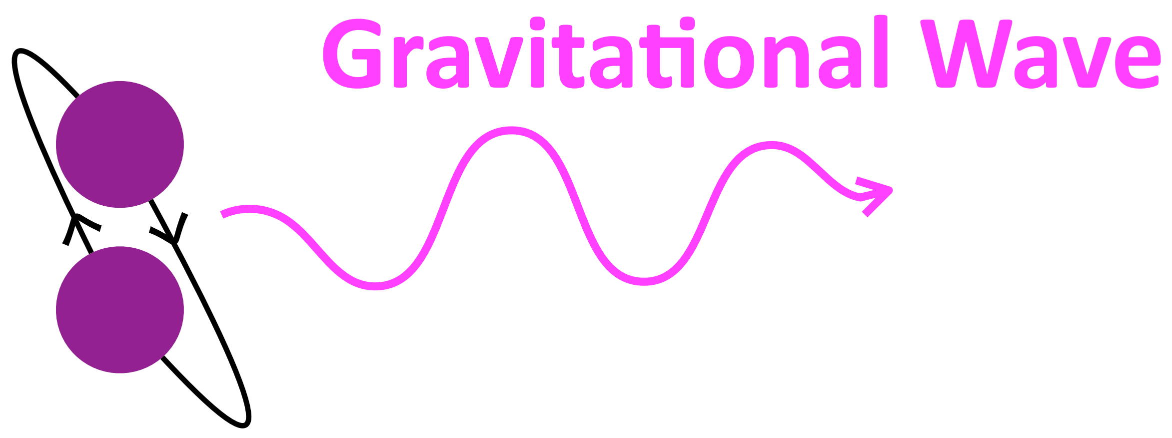
BNS mergers as Multi-messenger sources



- Binary inspiral

—> GW (~min)

- GRB jets

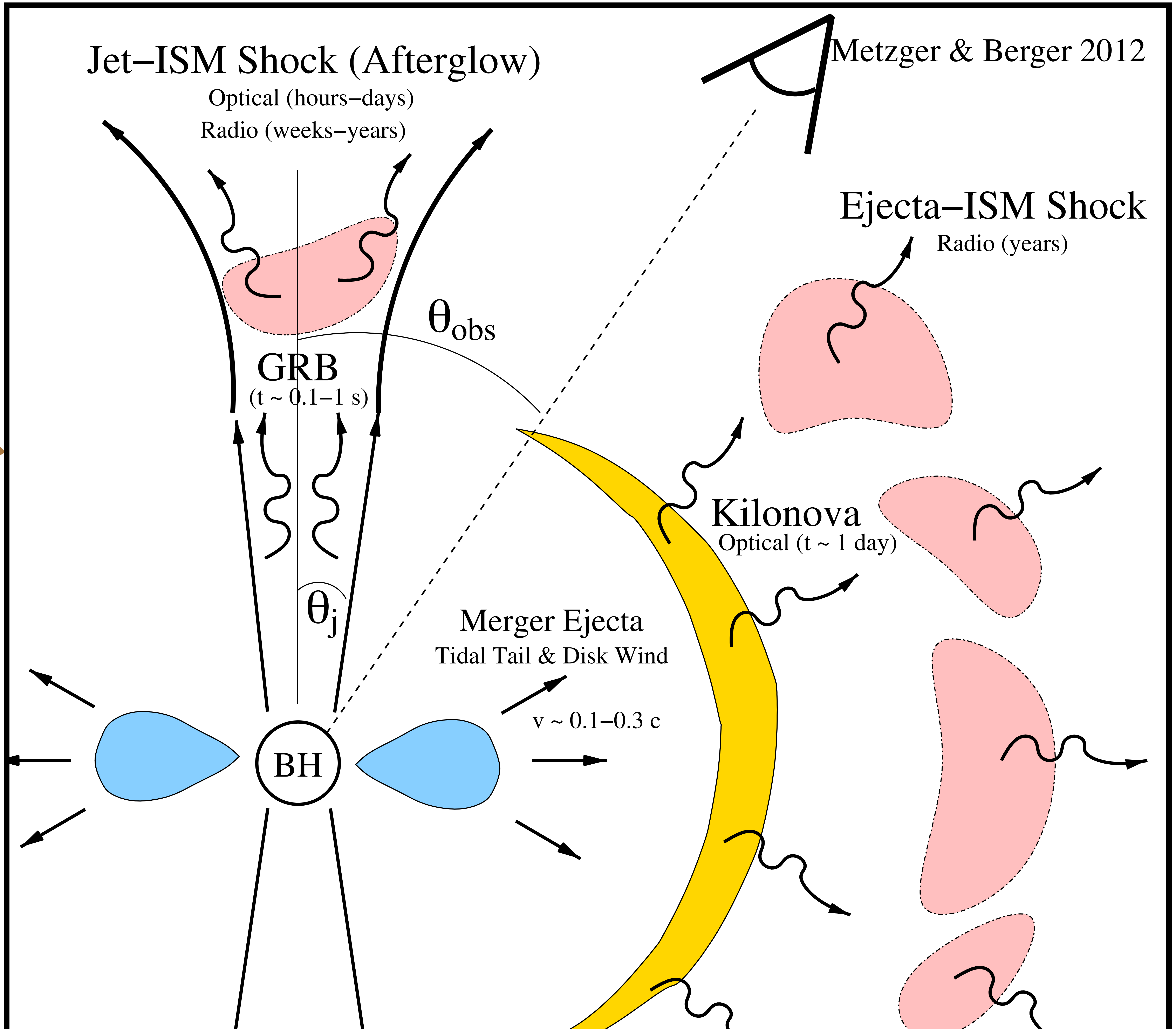
—> gamma-ray (~ sec)

- Jet-ISM interaction

→ radio, optical, X-ray (~ hour - day)

- Merger Ejecta

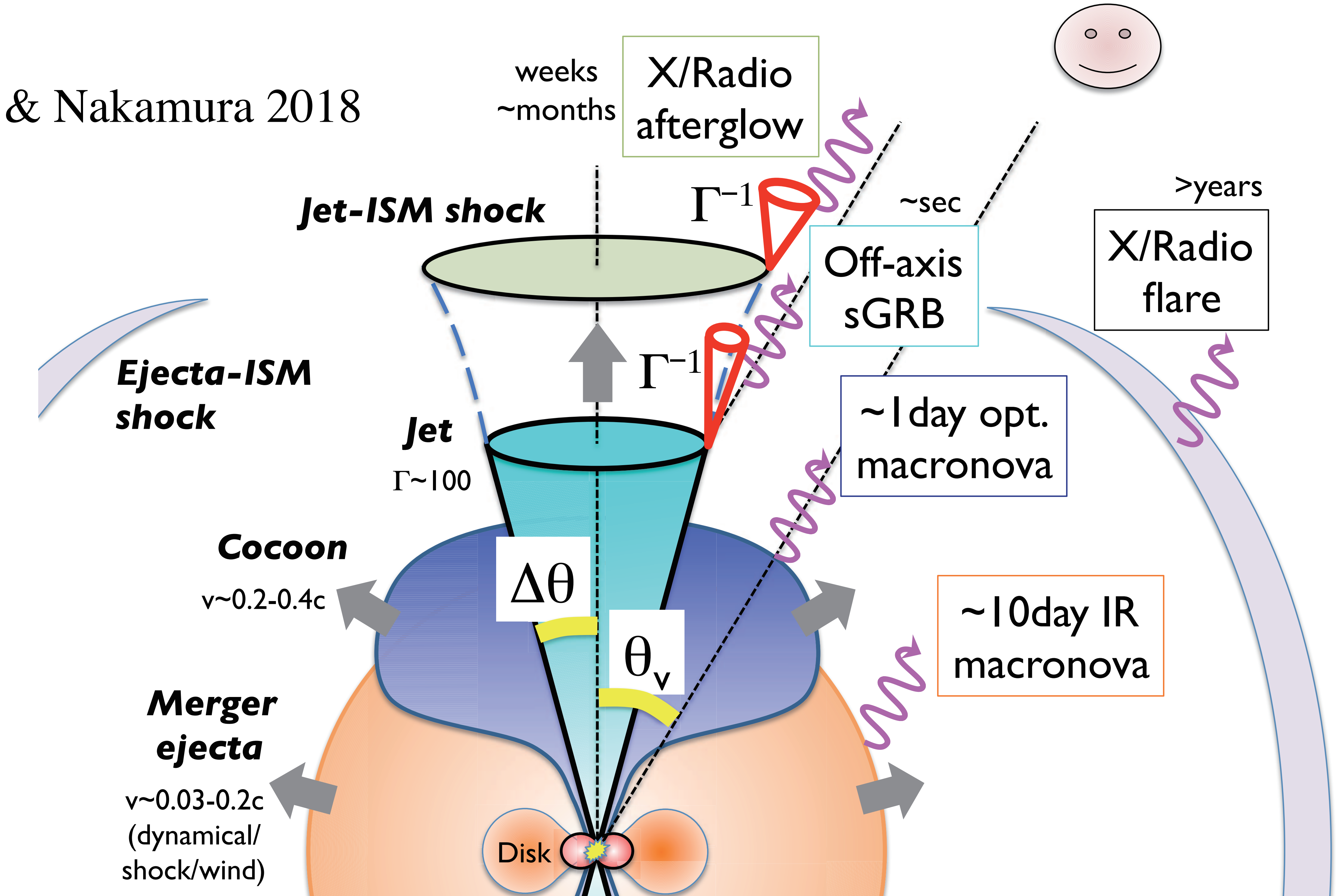
—> optical (~ day)



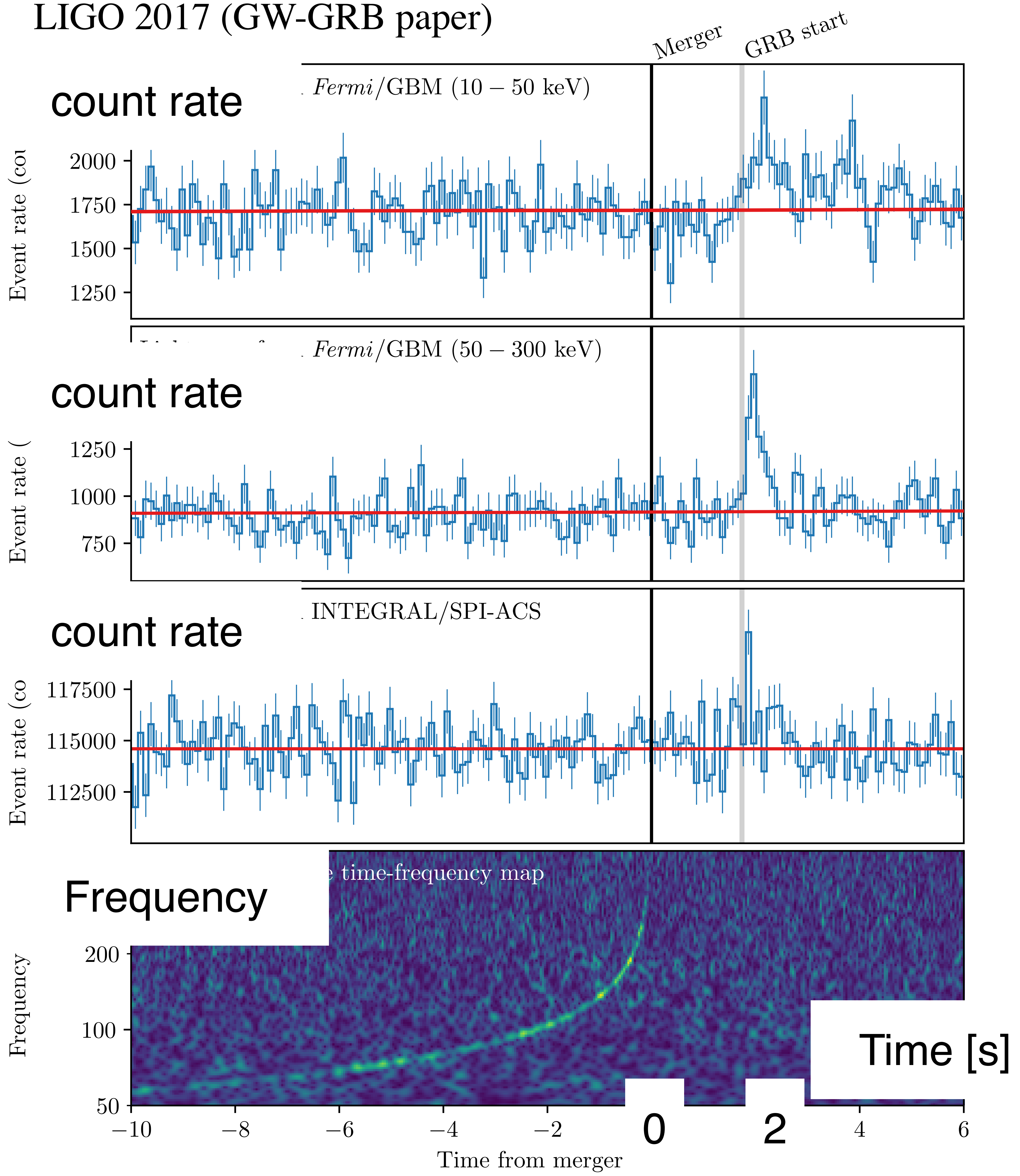
GW170817: Multi-messenger event

- 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**

Ioka & Nakamura 2018



LIGO 2017 (GW-GRB paper)



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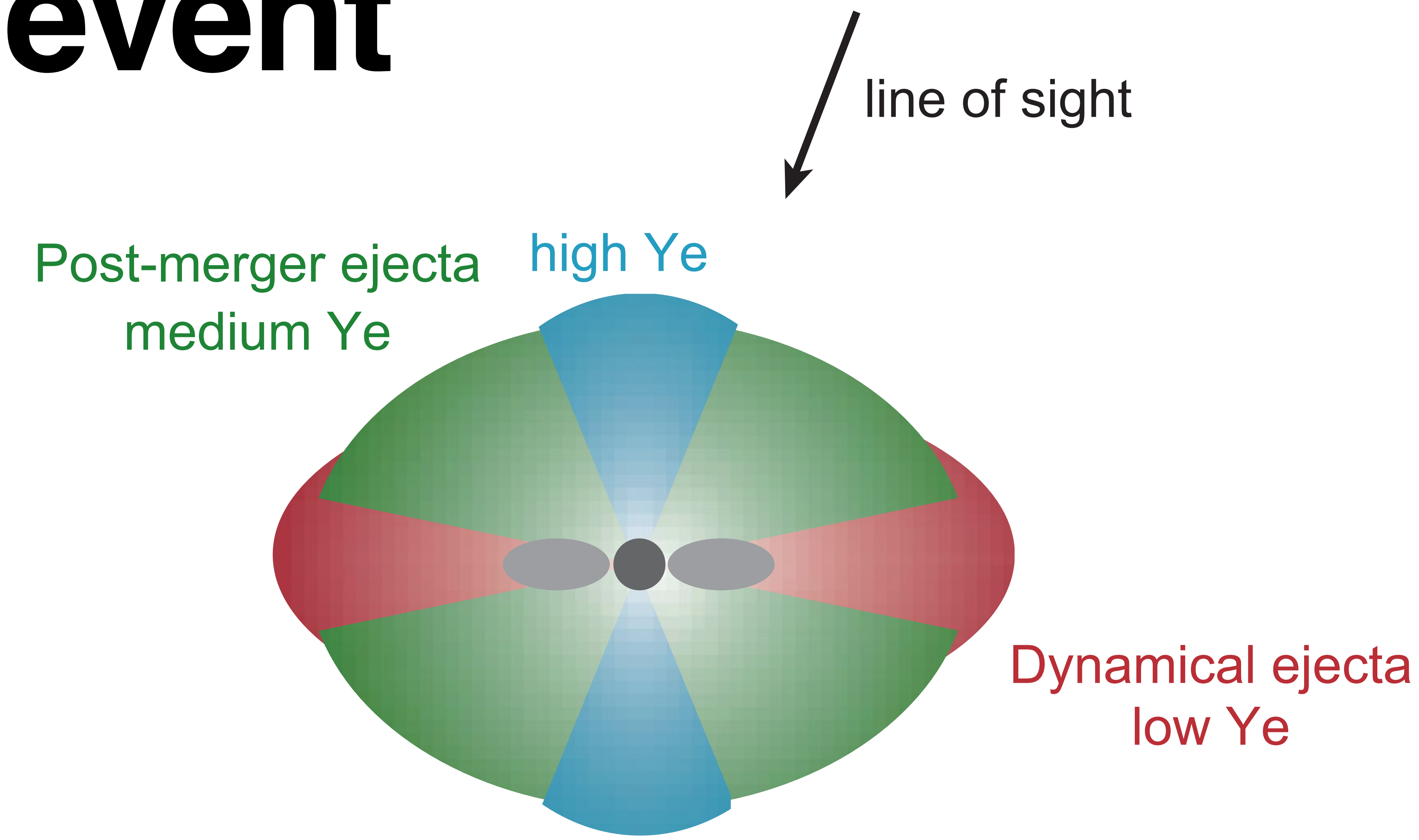
- GW signal from BNS merger
  —> short GRB just 2 sec after the merger
- **Optical signal from ejecta**
  —> outflows with r-process elements



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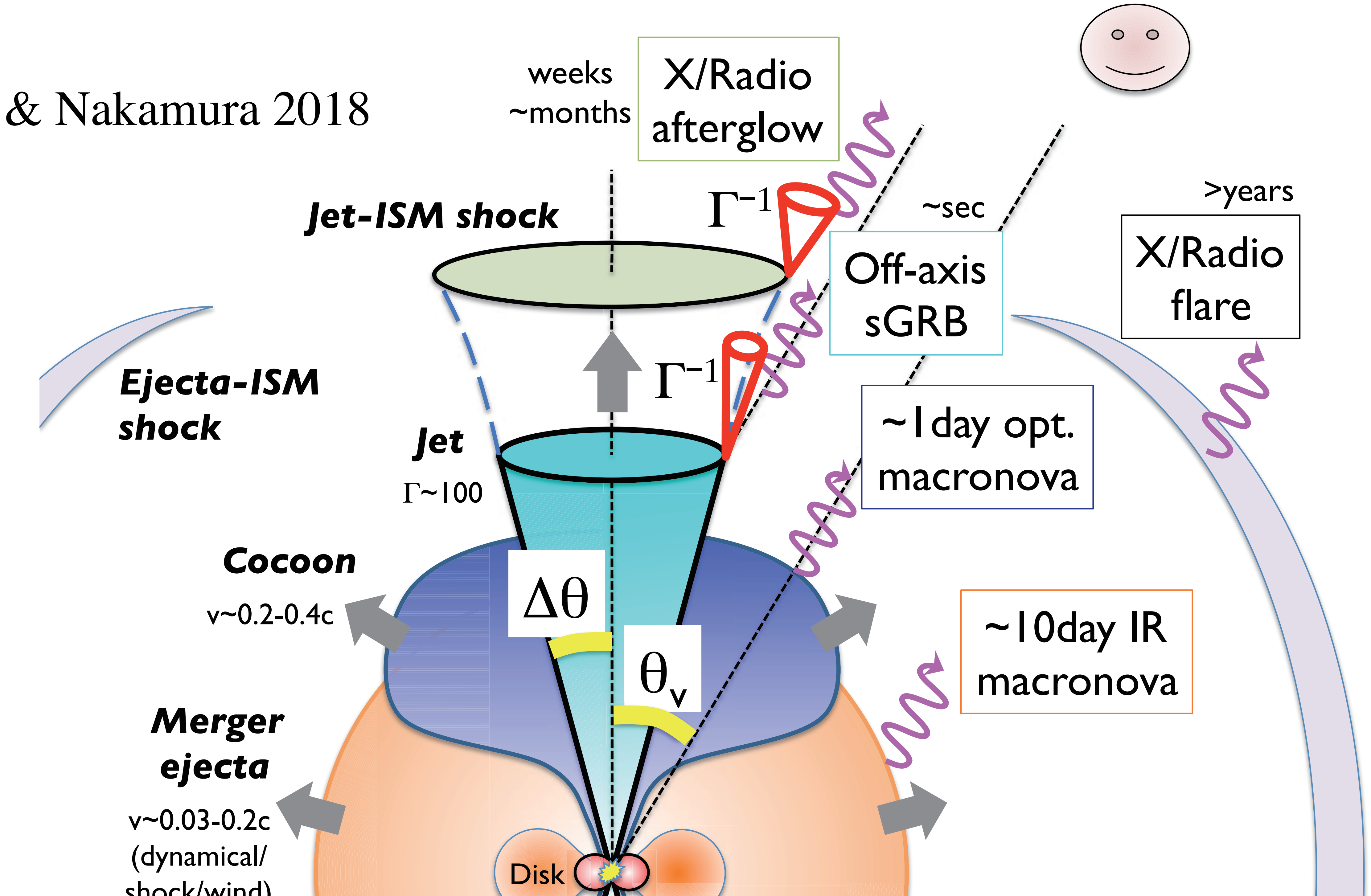
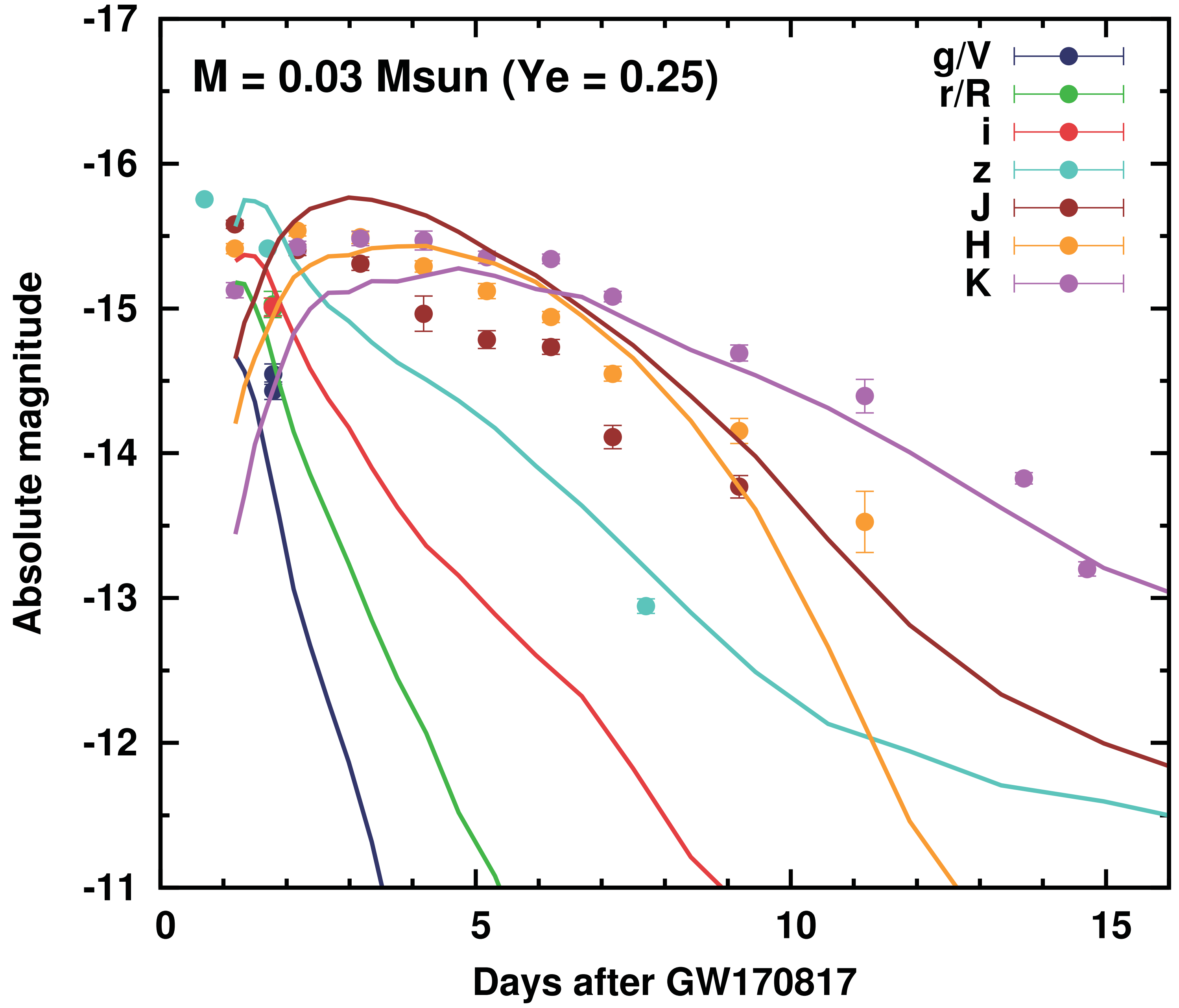


Tanaka et al. 2017 ; Utsumi et al. 2017



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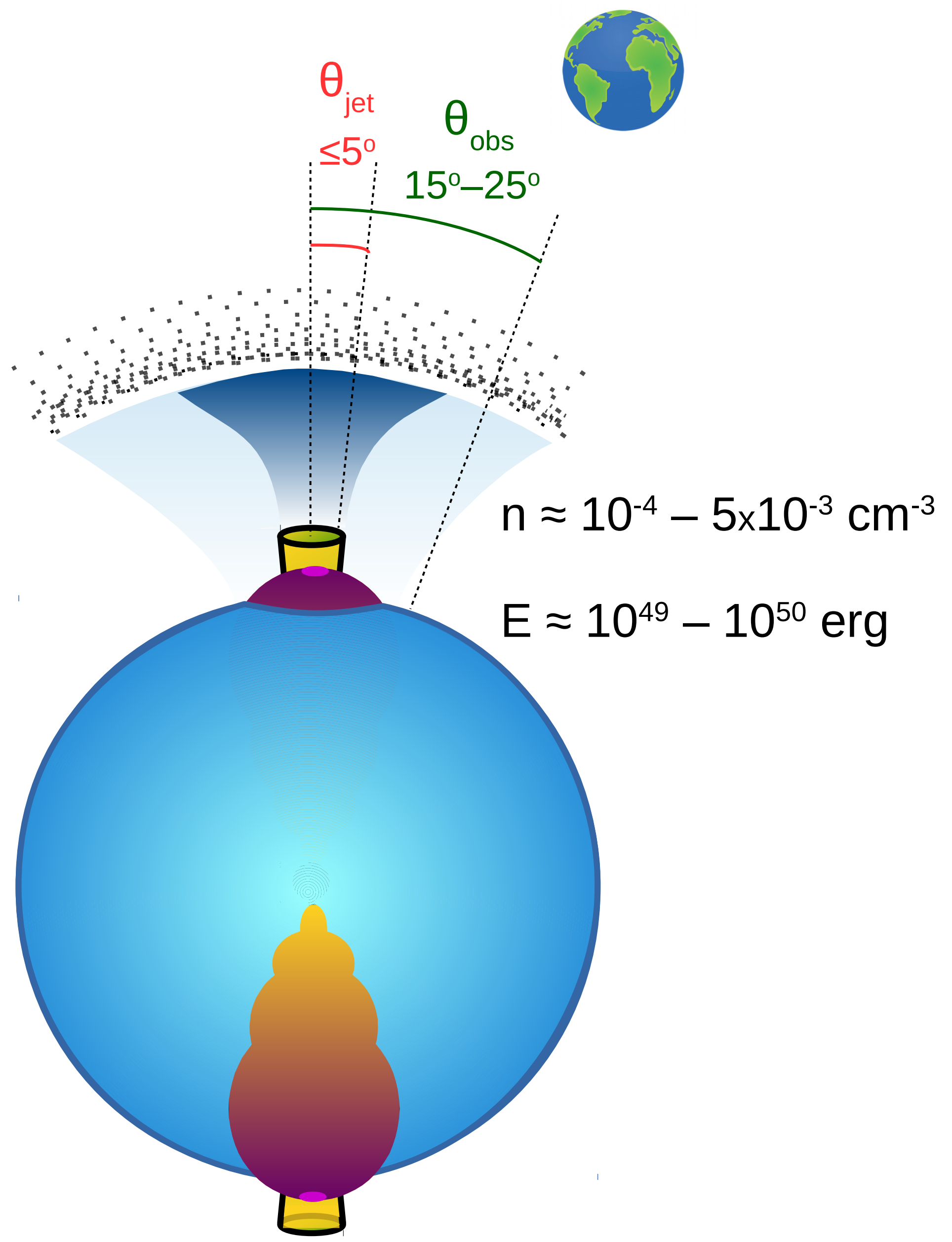
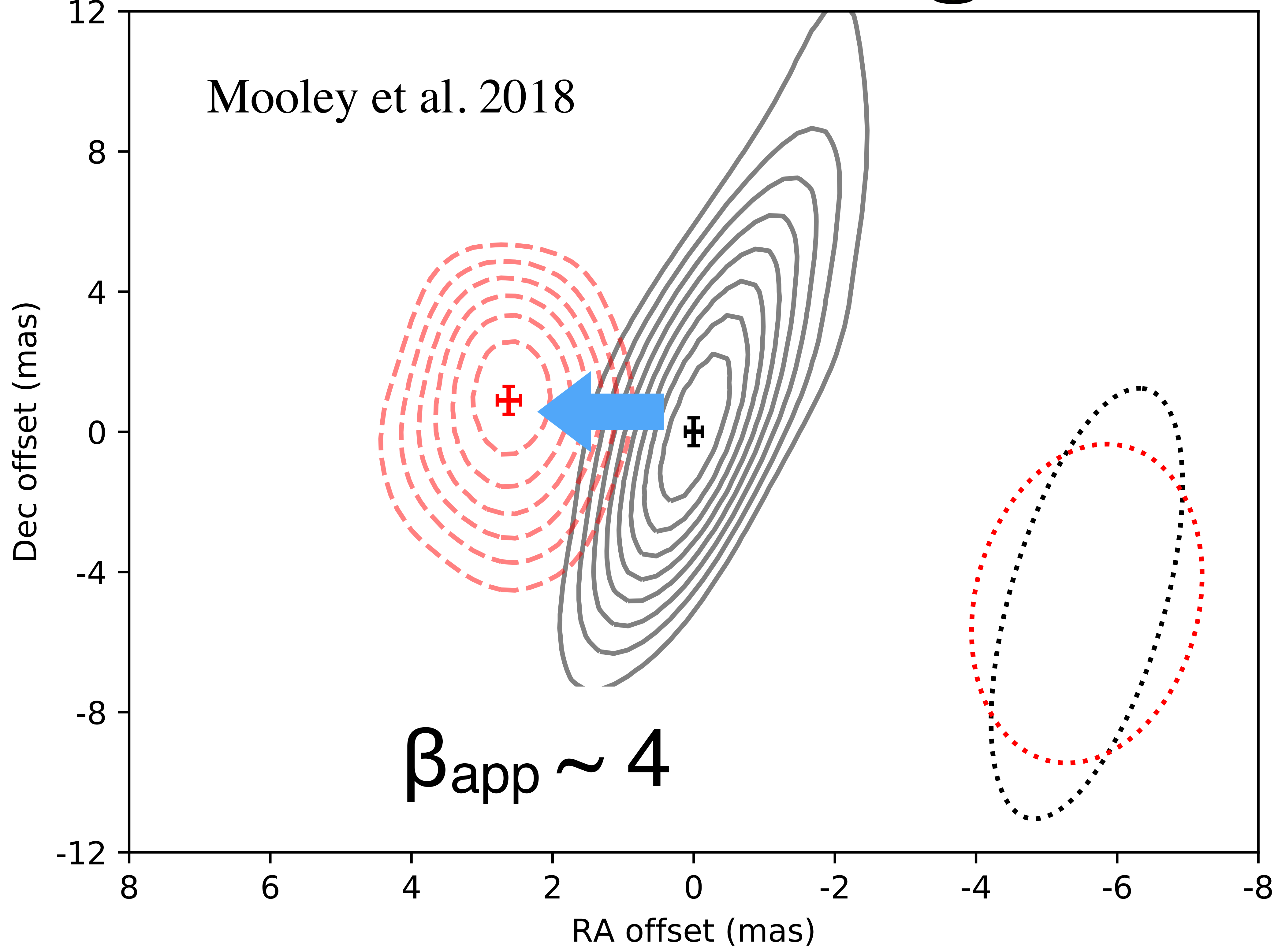
- The first detection of BNS merger event by GW, radio, IR/opt/UV, X-ray, MeV γ-ray
- GW signal from BNS merger —> short GRB just 2 sec after the merger
- Optical signal from ejecta

  —> outflows with r-process elements
- **Superluminal motion by VLBI observation —> existence of powerful relativistic jets**

Mooley et al. 2018





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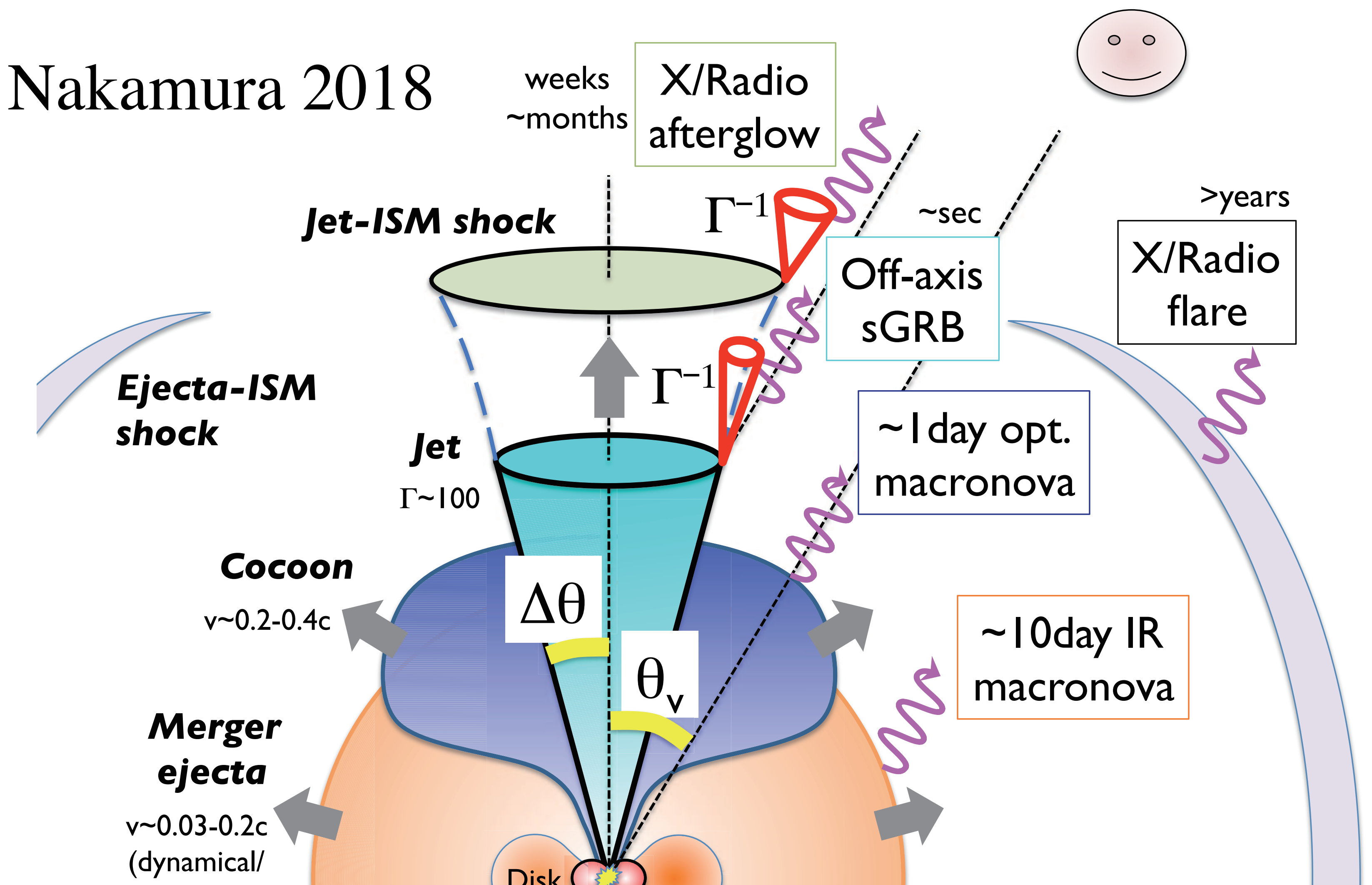


Things confirmed by GW170817

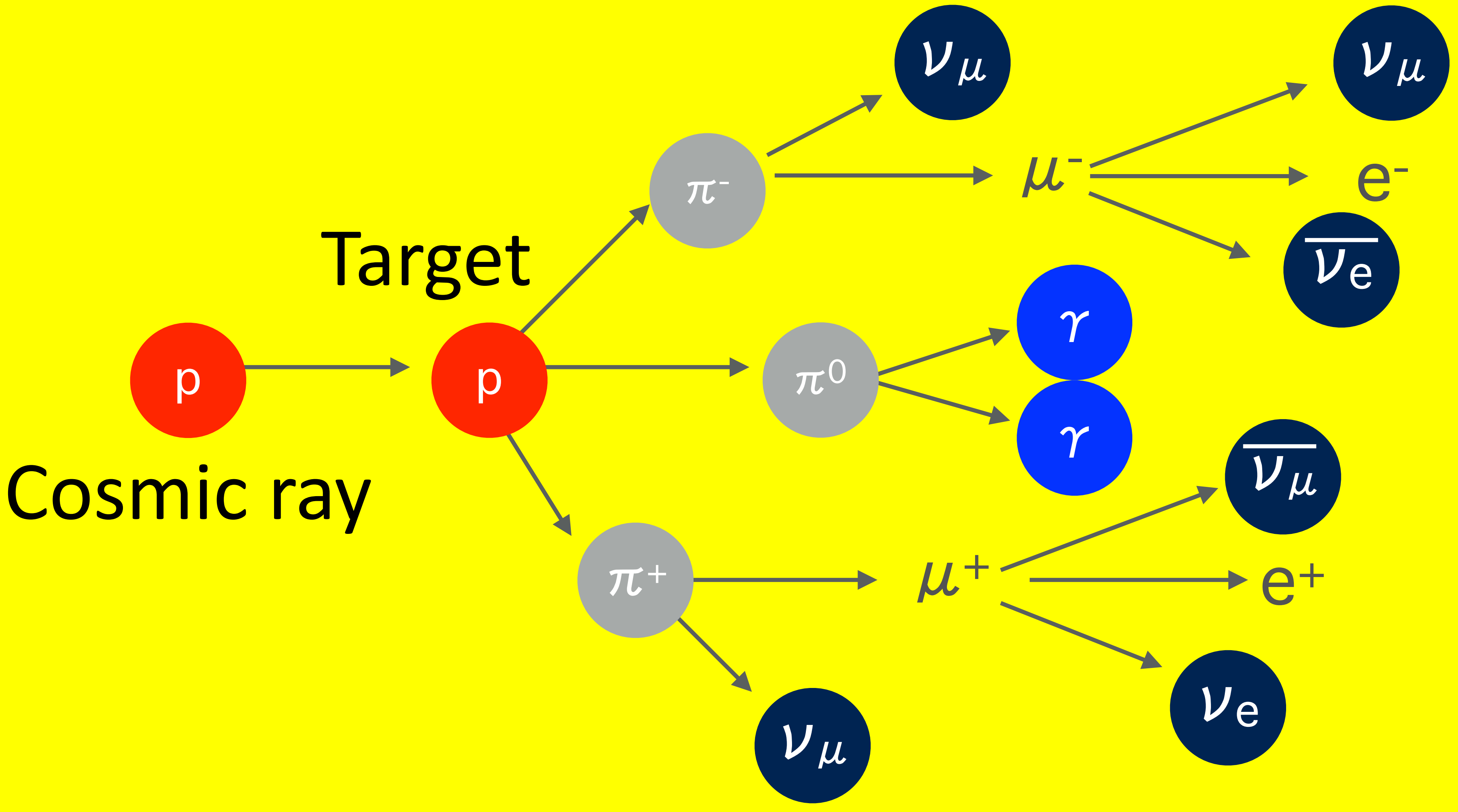
- Gamma-ray counterparts
  —> Some fraction of GRBs should be produced by BNS mergers
- UV/Optical/IR counterparts
  —> Existence of merger ejecta with r-process heavy elements
- Radio & X-ray afterglows
  —> BNS mergers create relativistic jets

High-energy neutrinos are not detected

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

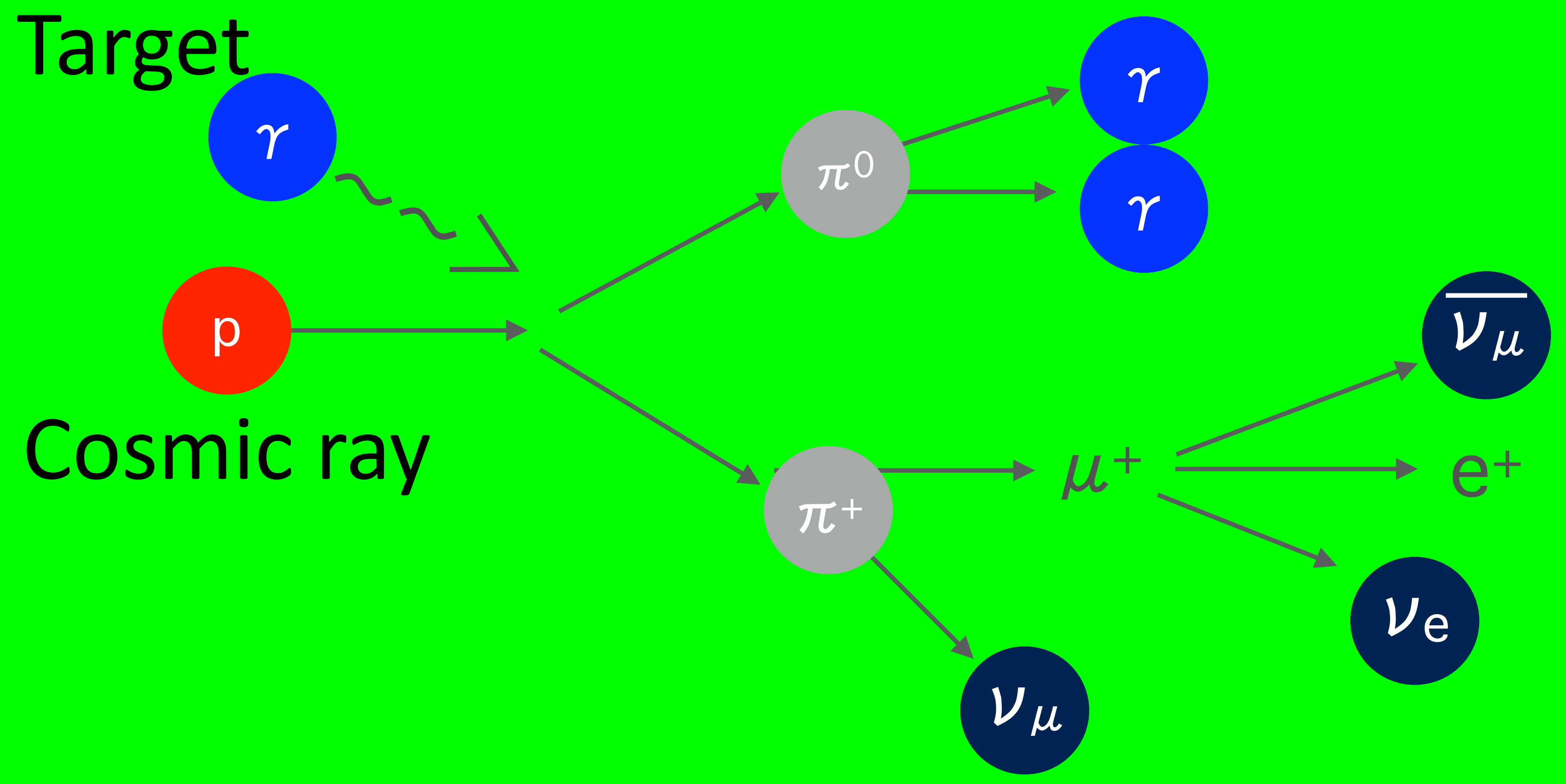
High-energy neutrino production

- pp inelastic collision



- $p+p \rightarrow p+p+\pi$
- $\pi^{\pm} \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

- Photomeson production ($p\gamma$)

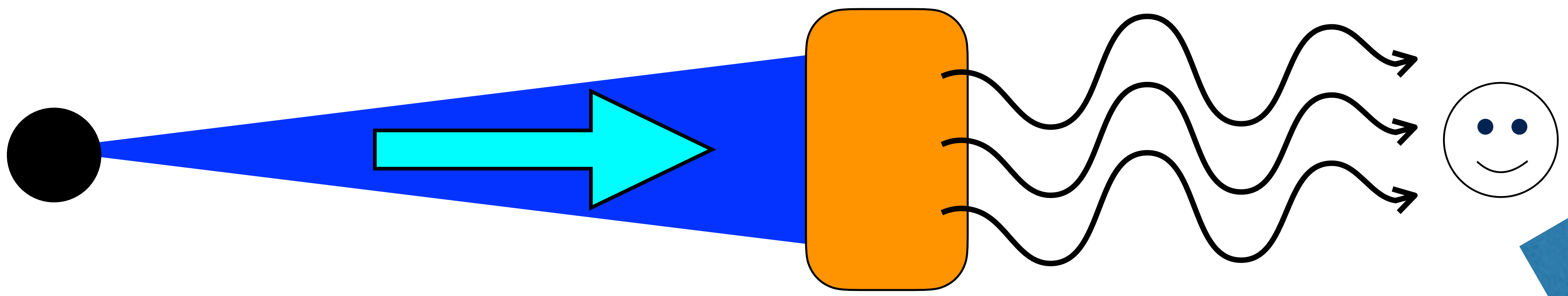


- $p+\gamma \rightarrow p+\pi$
- $\pi^{\pm} \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

Interaction between CRs & photons/nuclei → Neutrino production

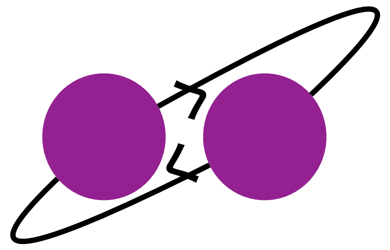
Gamma-rays inevitably accompanied with neutrinos

Neutrino Emission Sites for BNS mergers



SSK et al. 2017; Biehl et al. 2018
Matsui, SSK, et al. 2023;
Matusi, SSK et al. in prep.

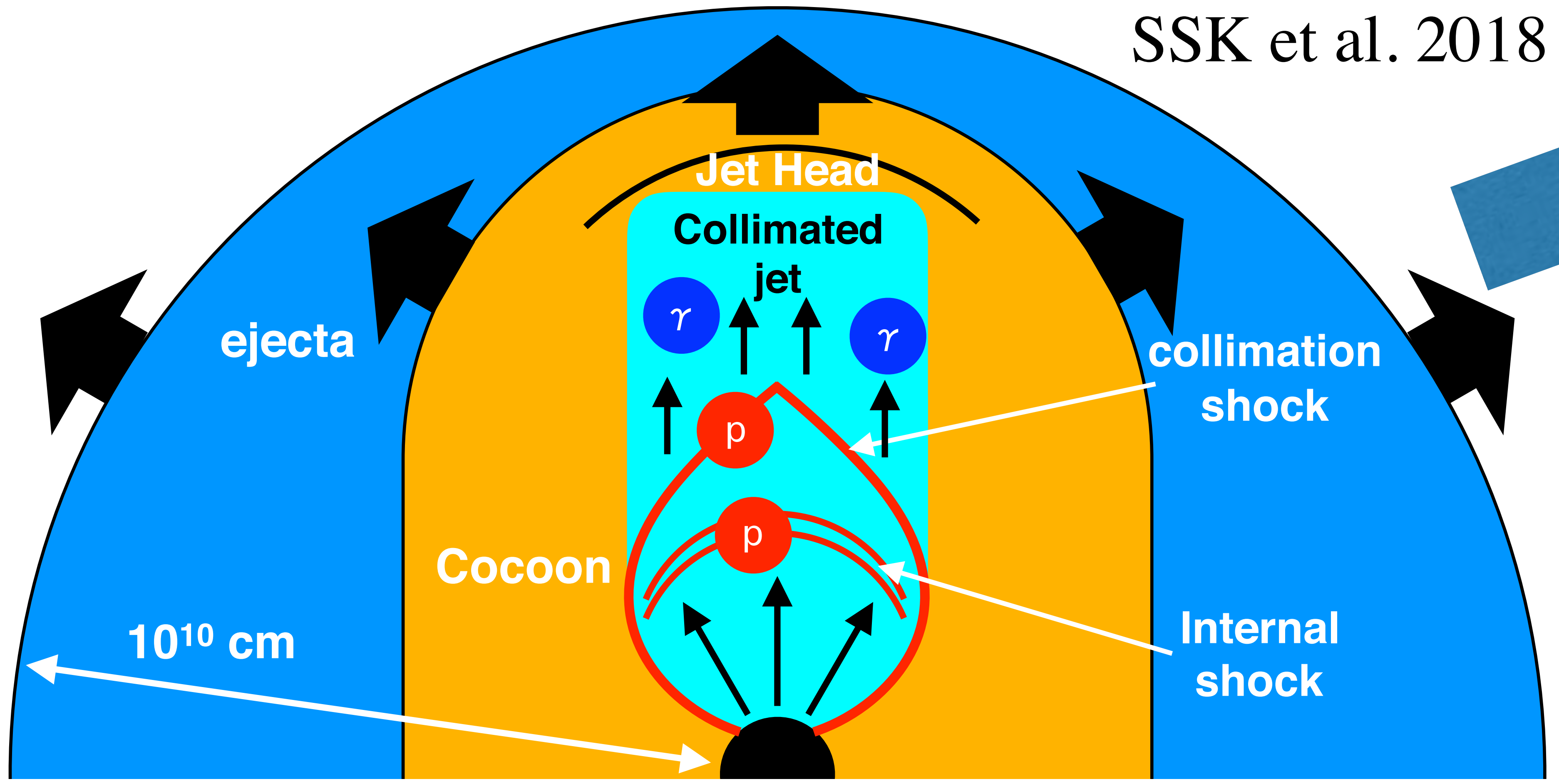
Successful jets
(sGRBs)

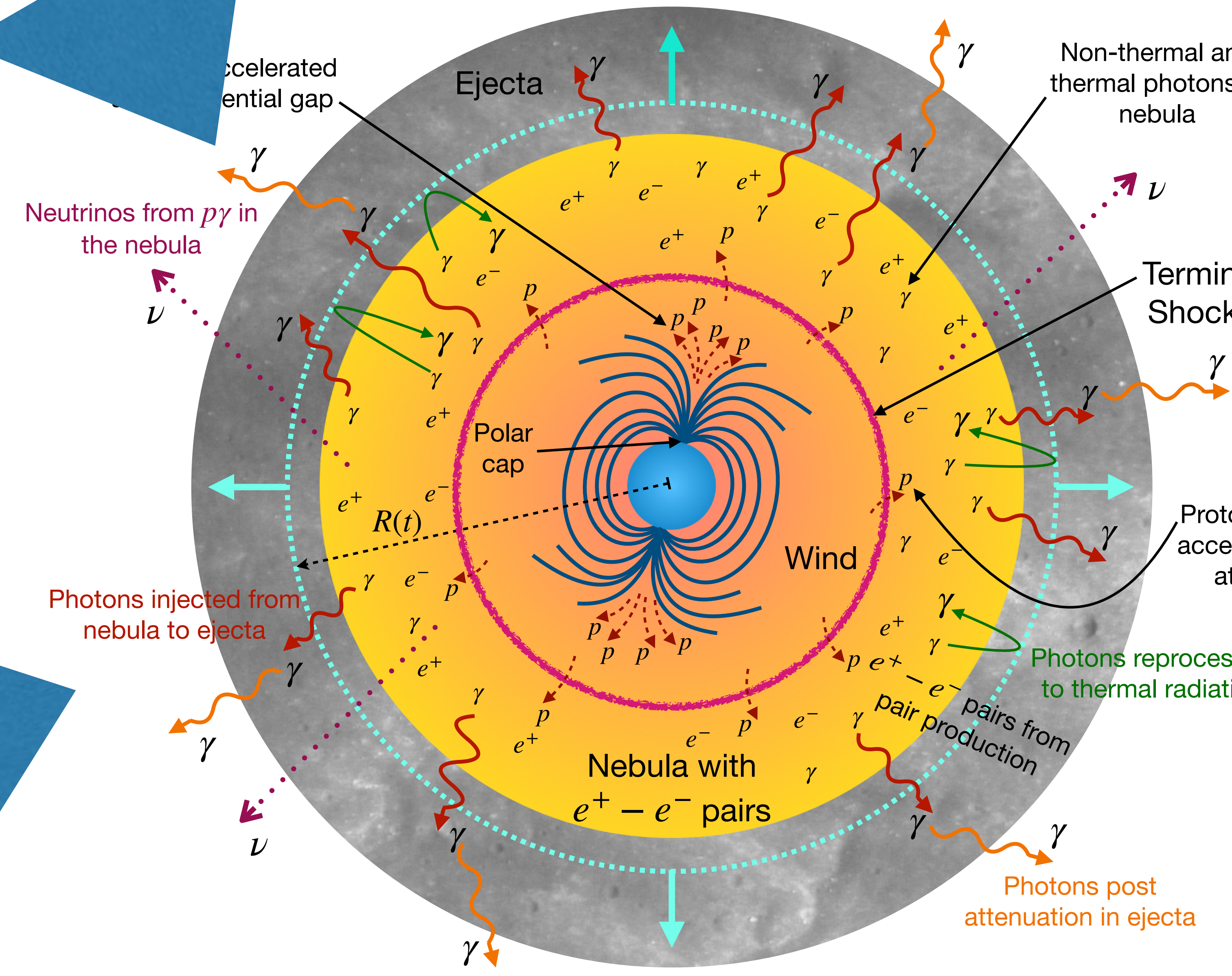


NS-NS merger

Choked jets

SSK et al. 2018





Merger remnants

Gao et al. 2013; Fang & Metzger 2017
Mukhopadyay & SSK in prep.

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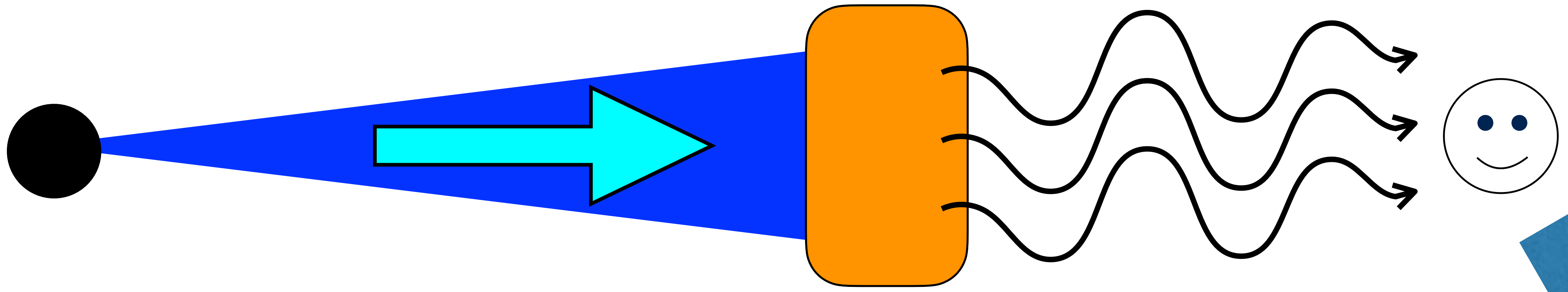

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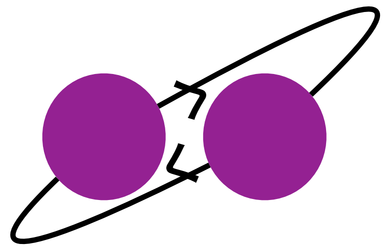

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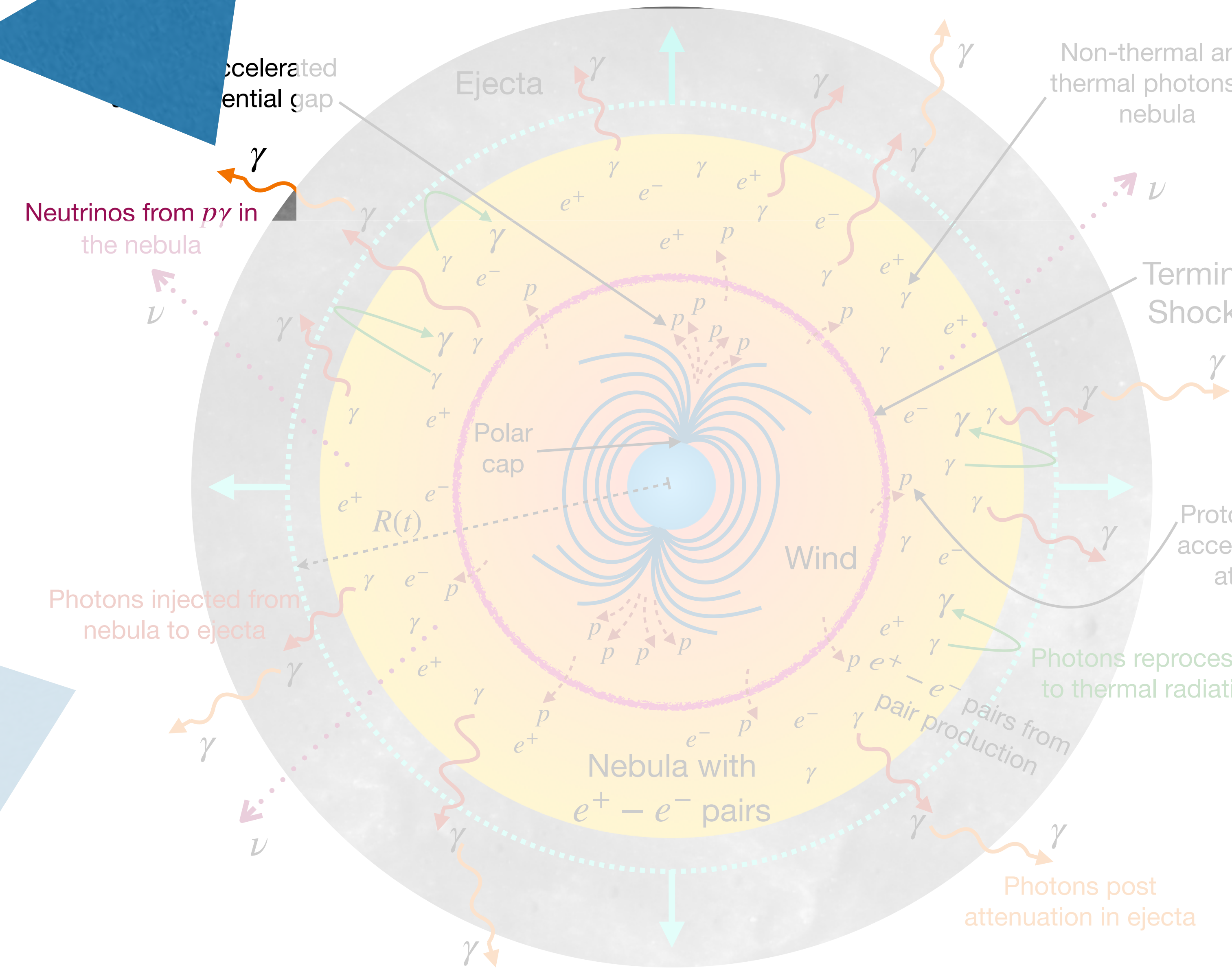

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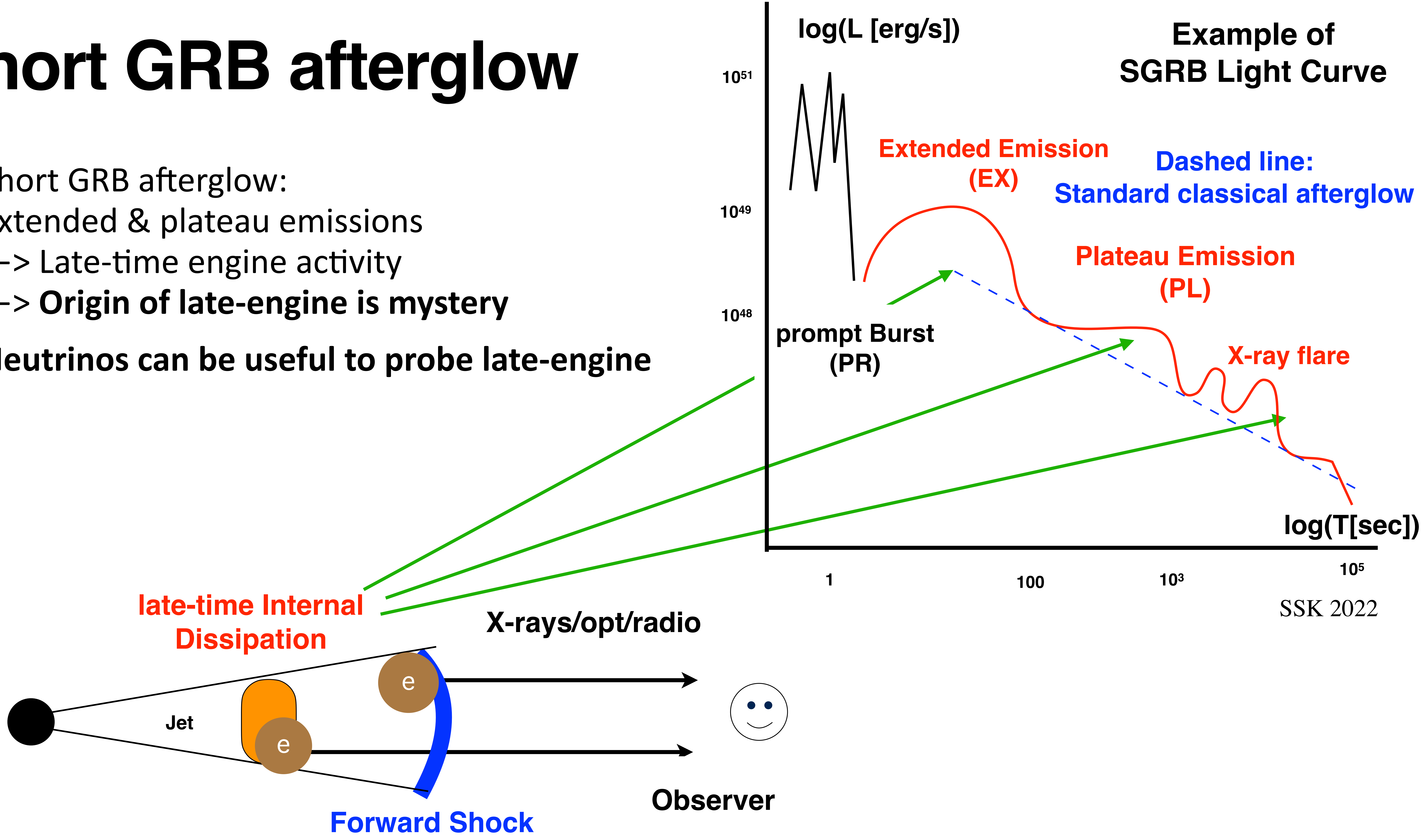
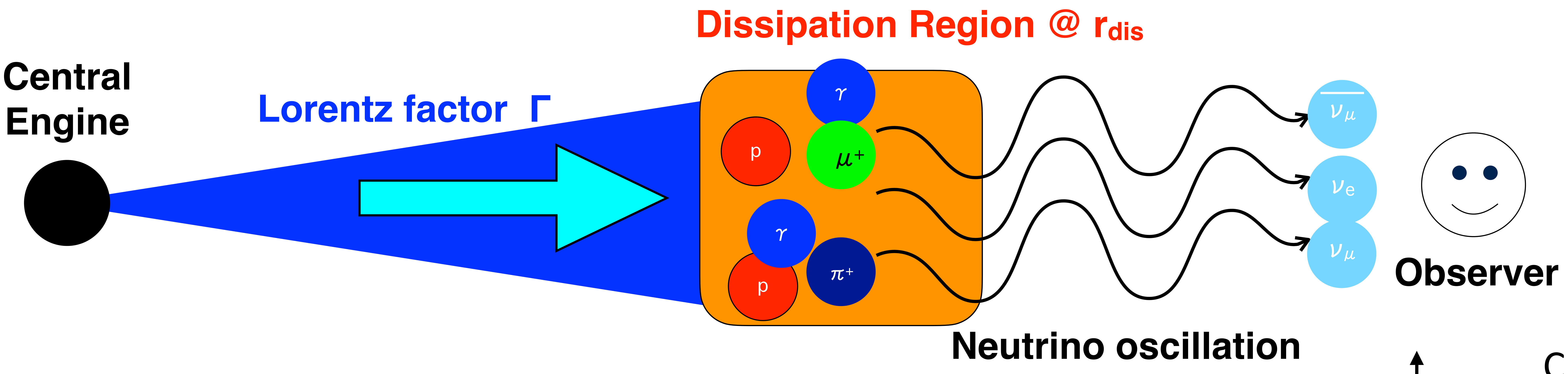
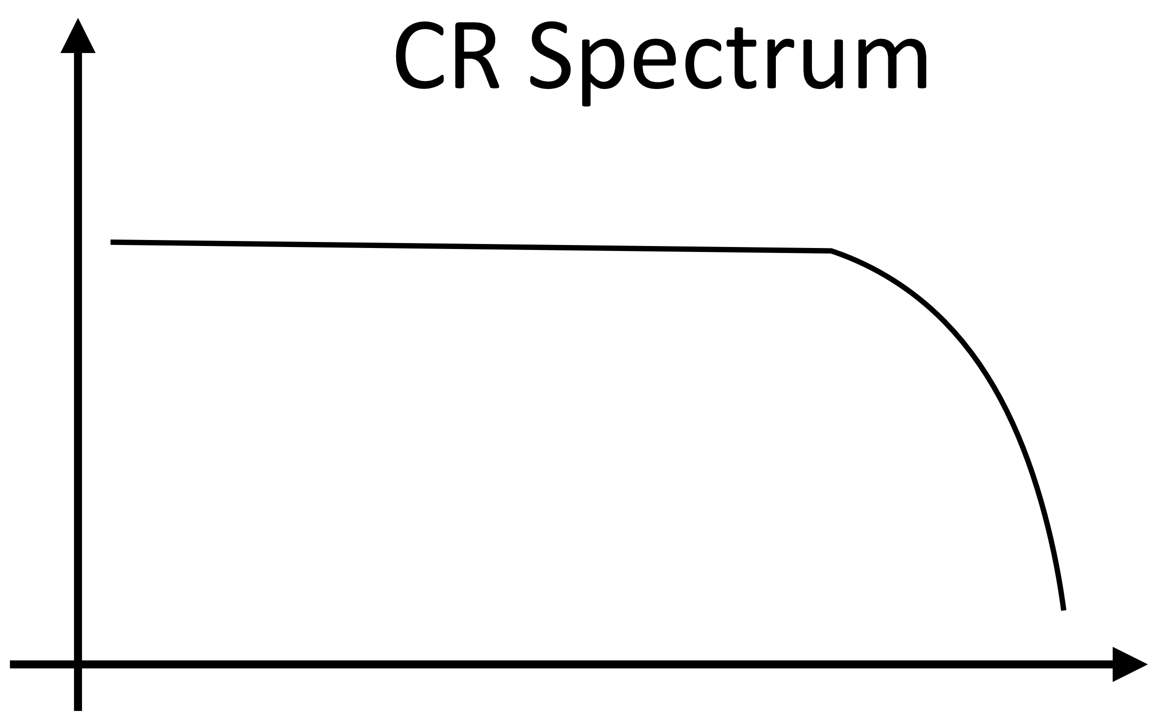
short GRB afterglow

- Short GRB afterglow:
  Extended & plateau emissions
  —> Late-time engine activity
  —> **Origin of late-engine is mystery**
- **Neutrinos can be useful to probe late-engine**



Multi-component One-zone Model



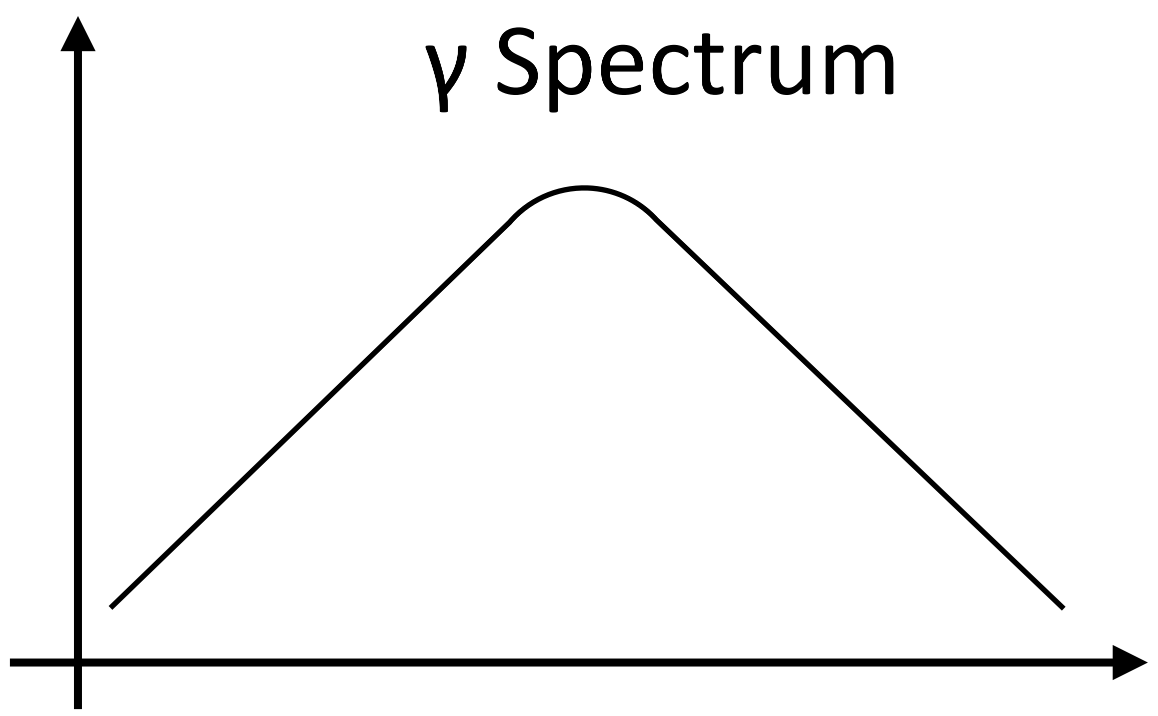


- Calculate ν fluence from each component by one-zone model
- Power-law proton injection: $E_p^2 \frac{dN}{dE} = \frac{\xi_p E_{\gamma,\mathrm{iso}}}{\ln(E_{p,\max}/E_{p,\min})}$

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

$$f_{p\gamma} = t_{p\gamma}^{-1} / t_{p,\mathrm{cl}}^{-1}$$

$$f_{\sup\pi} = 1 - \exp(-t_{\pi,\mathrm{cool}}/t_{\pi,\mathrm{dec}})$$



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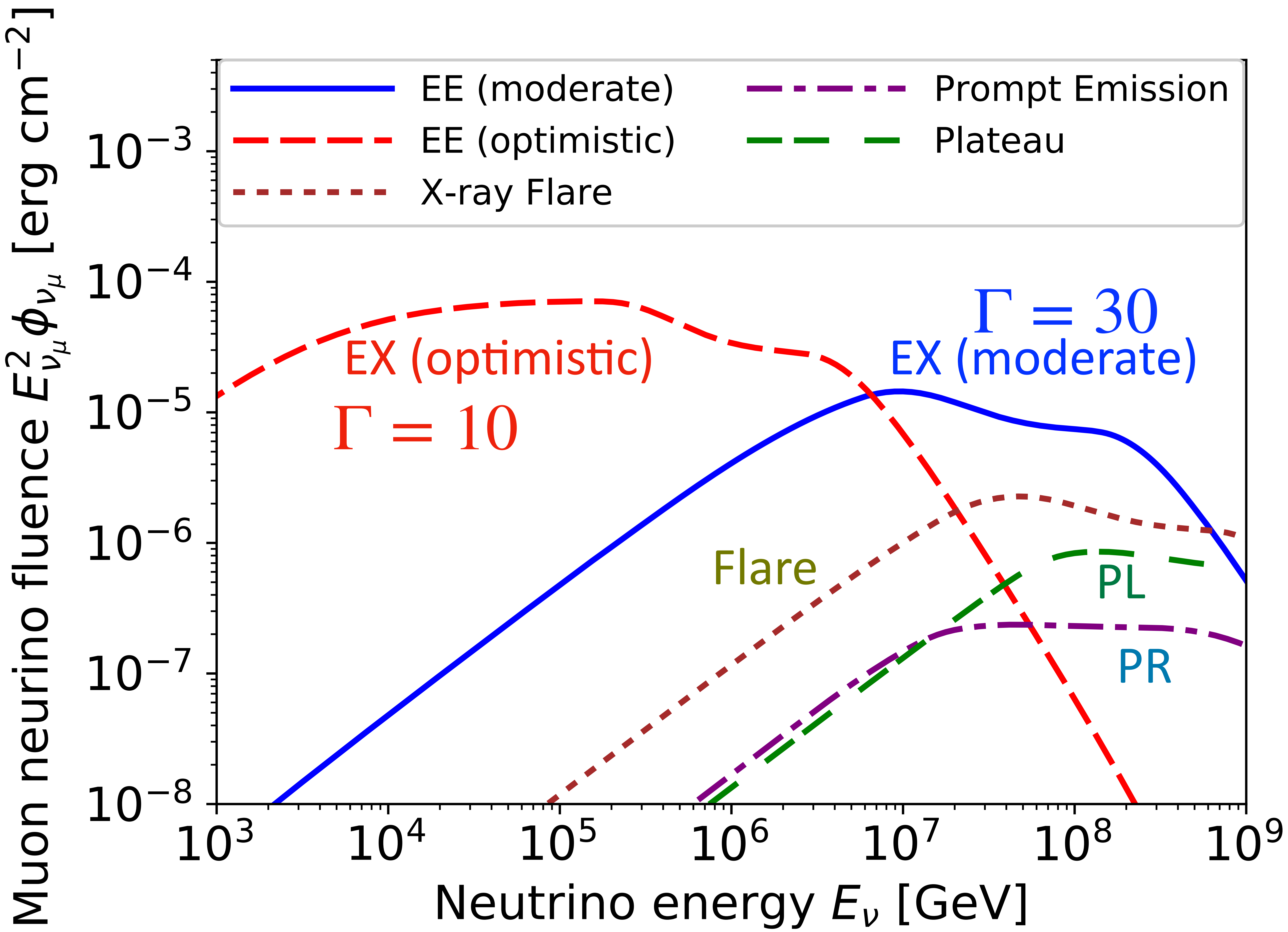


SSK et al. 2017

Model	EX	PL	PR	Flare
Γ	10–30	30	1000	30
r_{diss} [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}

- Extended emission (EE): highest neutrino production efficiency
- Low Γ_j or low $r_{\rm diss}$
  → high photon density
  → high fluence ϕ

Prospects for GW-Neutrino association

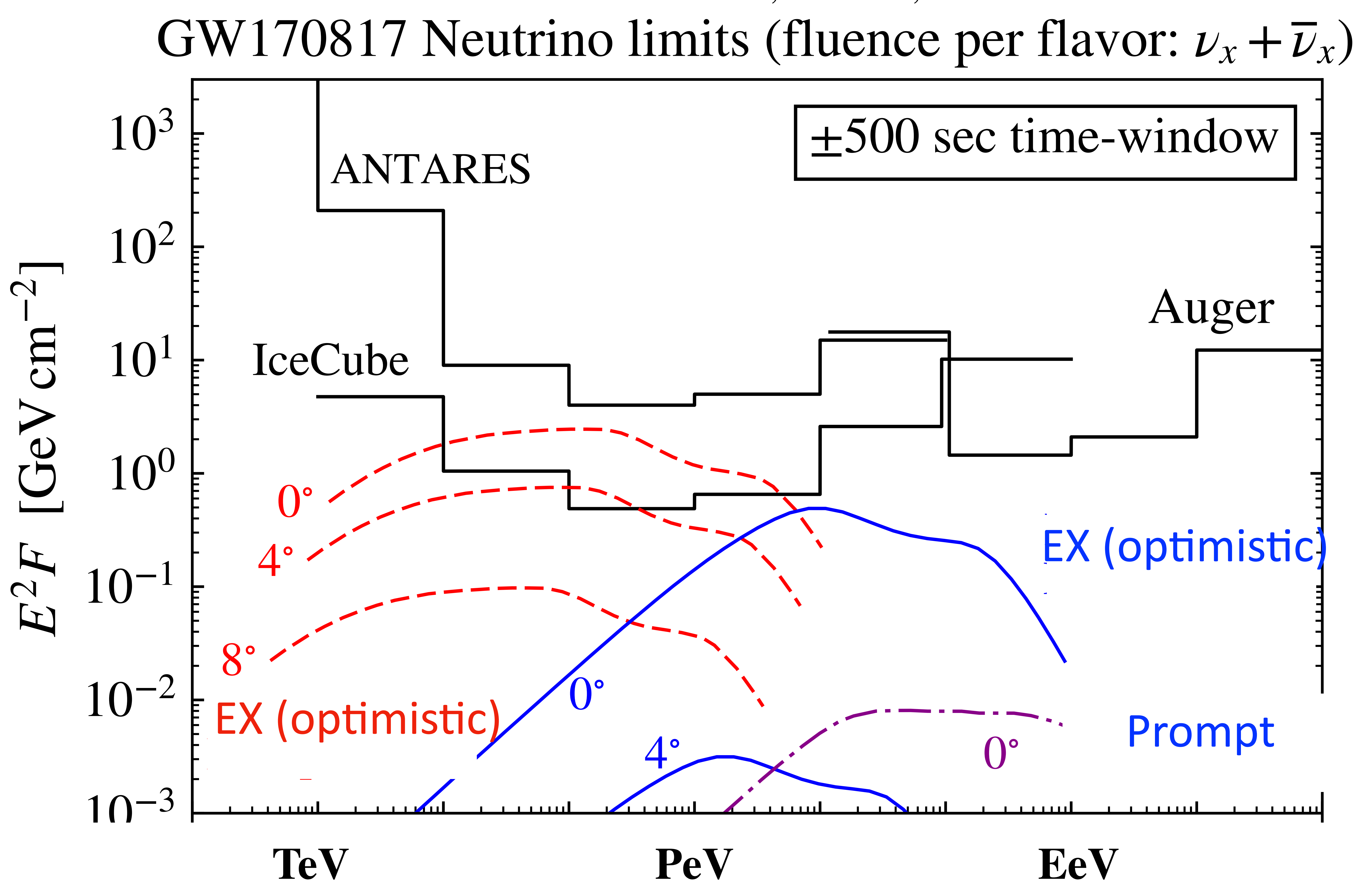
NS–NS (ΔT = 10 years)	IC (all)	Gen2 (all)
EE-mod-dist-A	0.11–0.25	0.37–0.69
EE-mod-dist-B	0.16–0.35	0.44–0.77
EE-opt-dist-A	0.76–0.97	0.98–1.00
EE-opt-dist-B	0.65–0.93	0.93–1.00

SSK et al. 2017

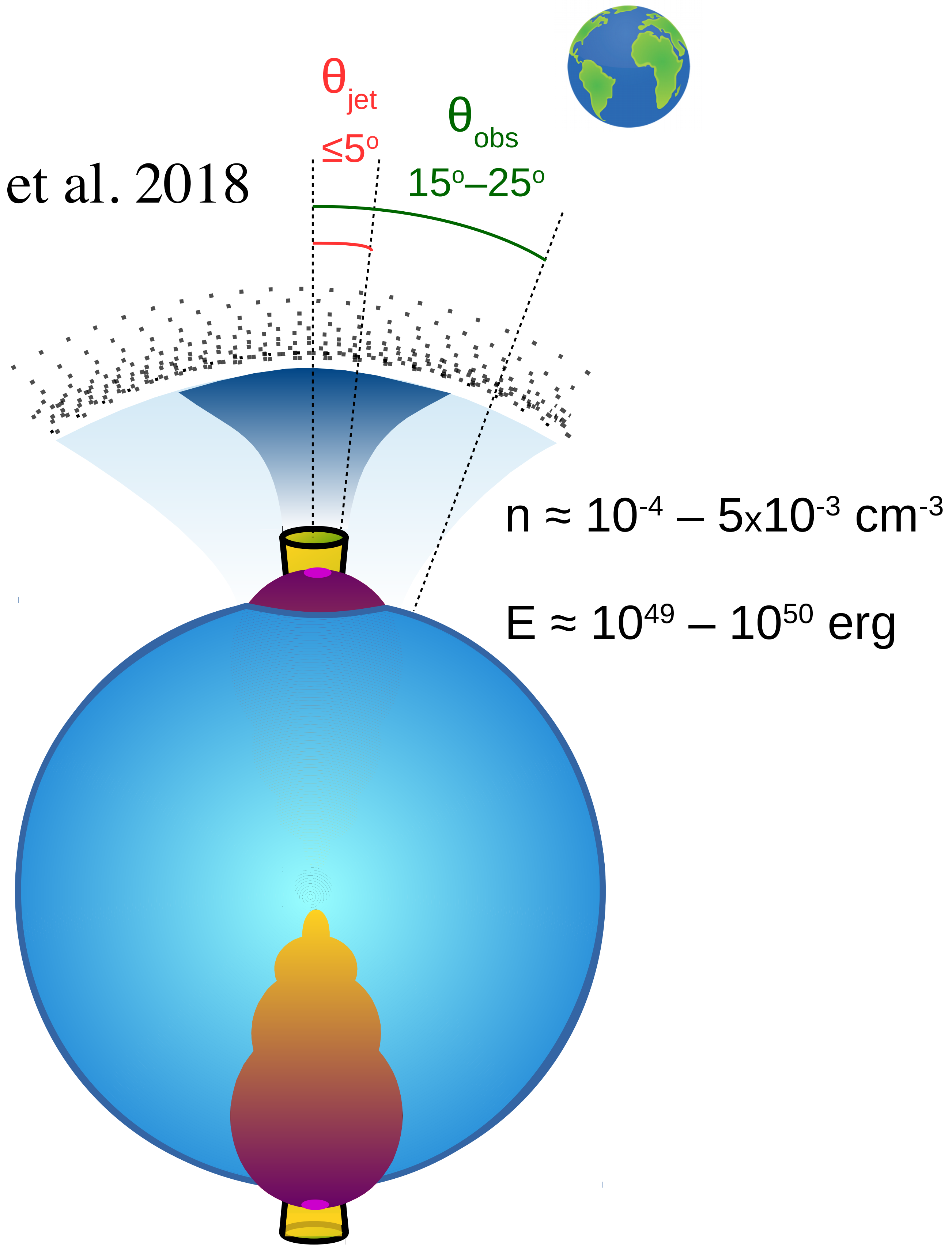
- Assume that all the NS mergers within 300 Mpc are detected by GW
- $\dot{\rho}_{\rm sGRB} \sim 4-10\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ & half of SGRBs have EE Wanderman & Piran 15, Nakar + 06
  → 2-5 EEs (10 yr) within GW horizon (300 Mpc)
- For optimistic case, **simultaneous detection of GWs and vs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

IceCube Constraint on GW170817

Antares, IceCube, PAO 2017

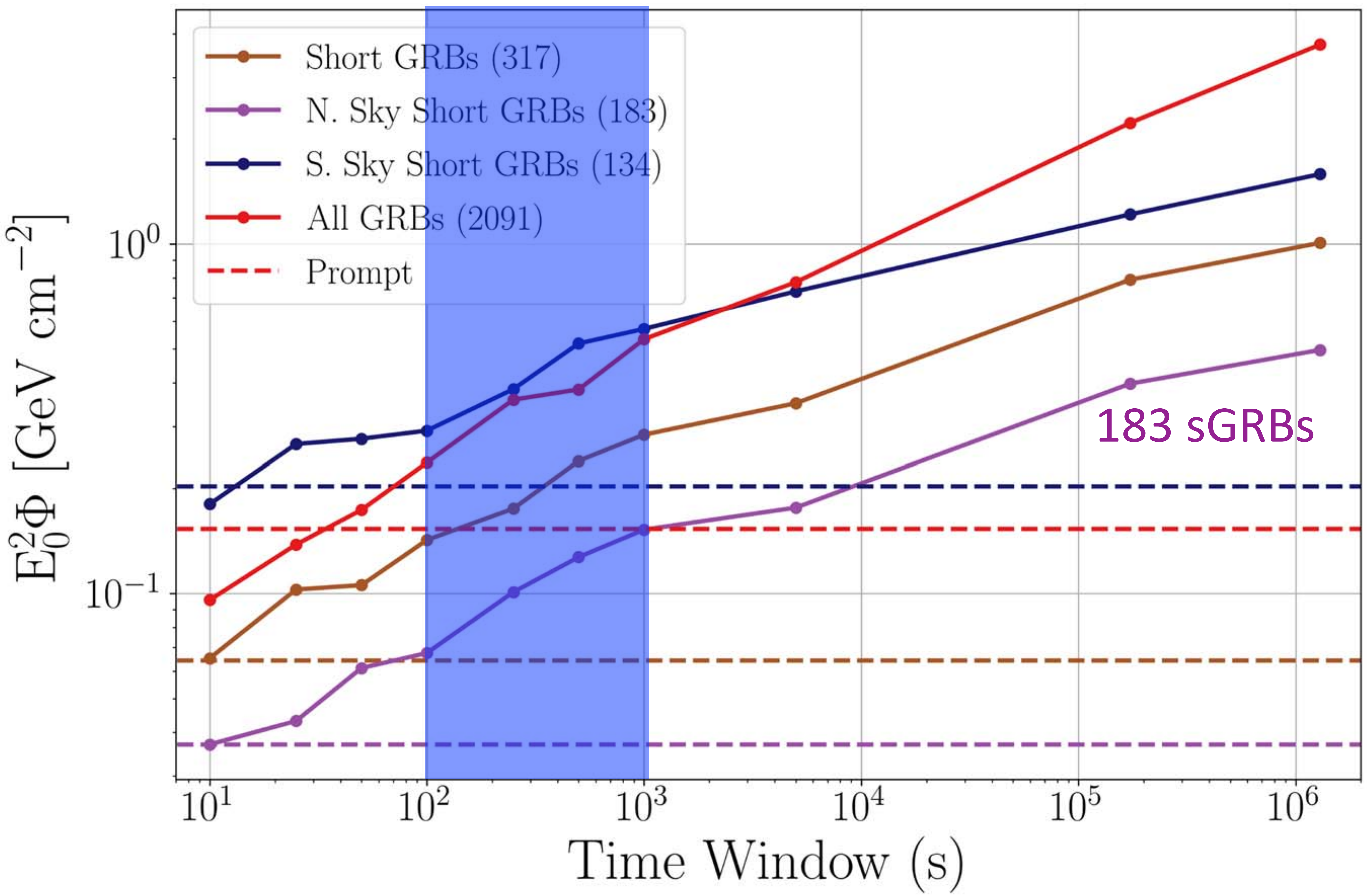


Mooley et al. 2018

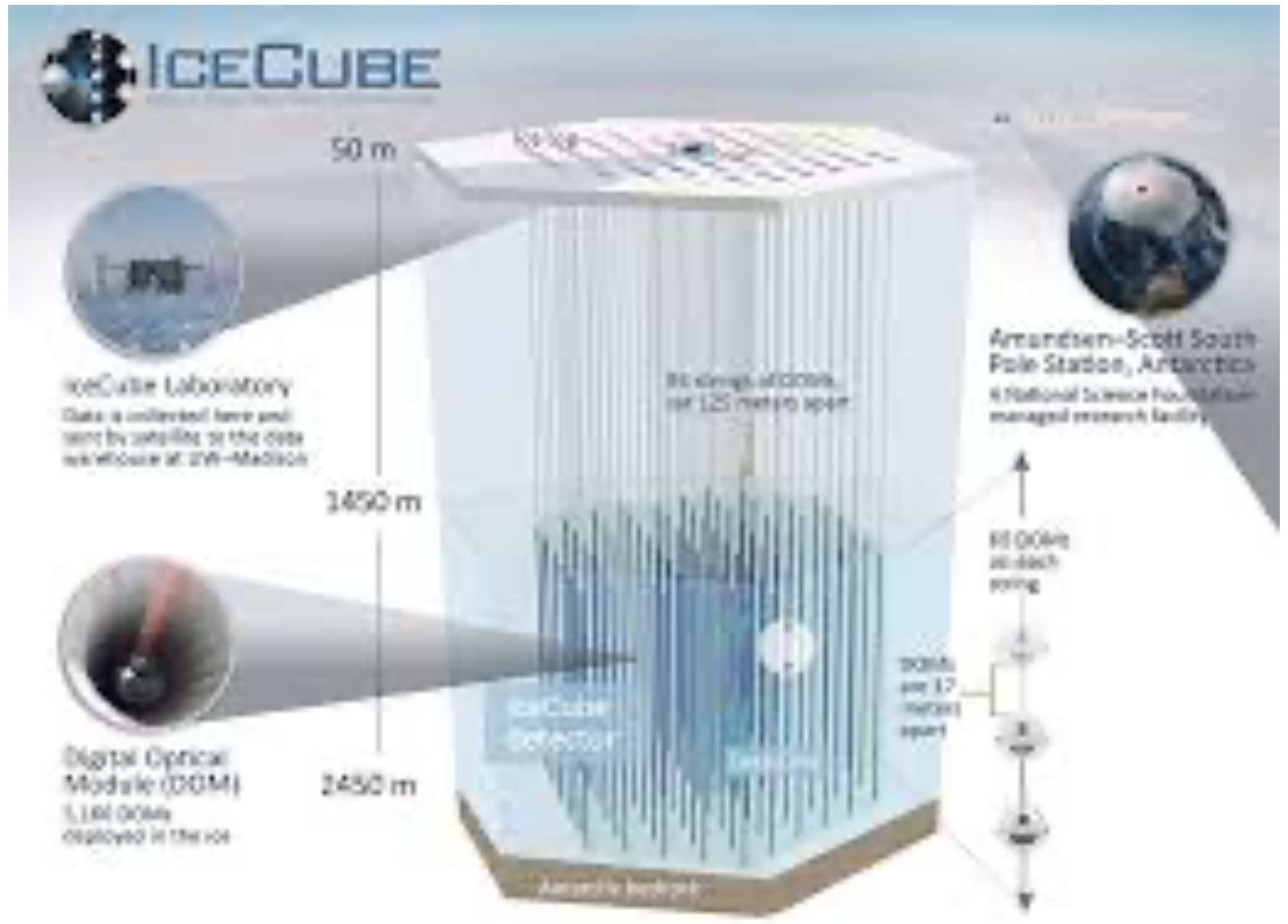


- GW170817 is slightly off-axis event —> $F \propto (\Gamma\theta)^{-3}$
- Optimistic model was consistent with IceCube upper limit for GW170817

IceCube Constraints on late-time emission



IceCube 2023



- For EX, stacked fluence should be 0.03 - 0. 2 GeV/cm^2 for 200 sGRB
- Typical distance (d_L=3 Gpc; z=0.5) —> $\mathscr{E}_\nu^{\rm iso} \lesssim 10^{50} - 10^{51}$ erg per burst
- **Optimistic EX model is constrained**

Multi-component One-zone Model

SSK et al. 2017

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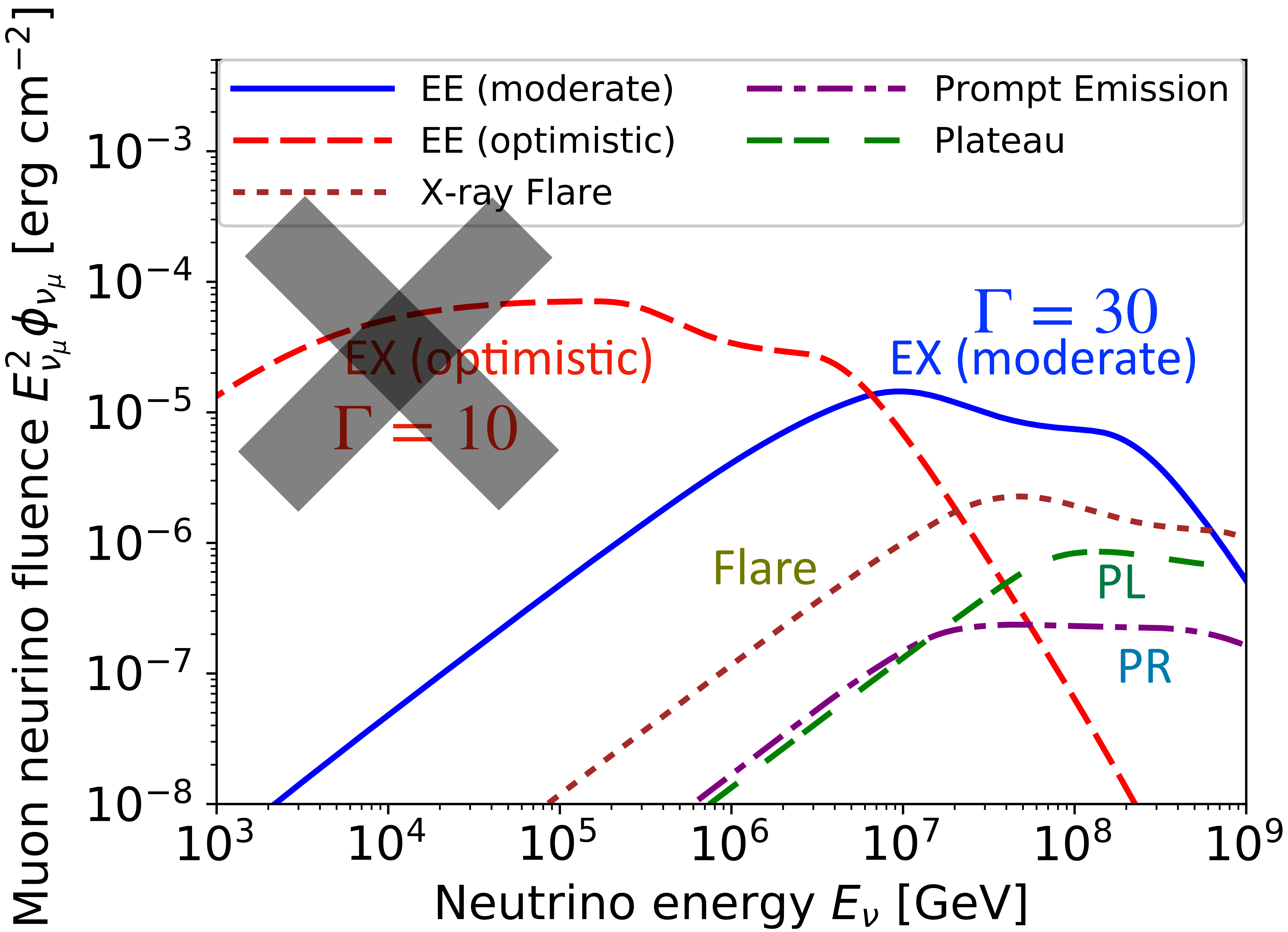

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Formation of Cocoon

- Optical counterpart detection in GW170817

—> outflow/ejecta at BNS merger

- 2-sec delay time between GW & γ-ray

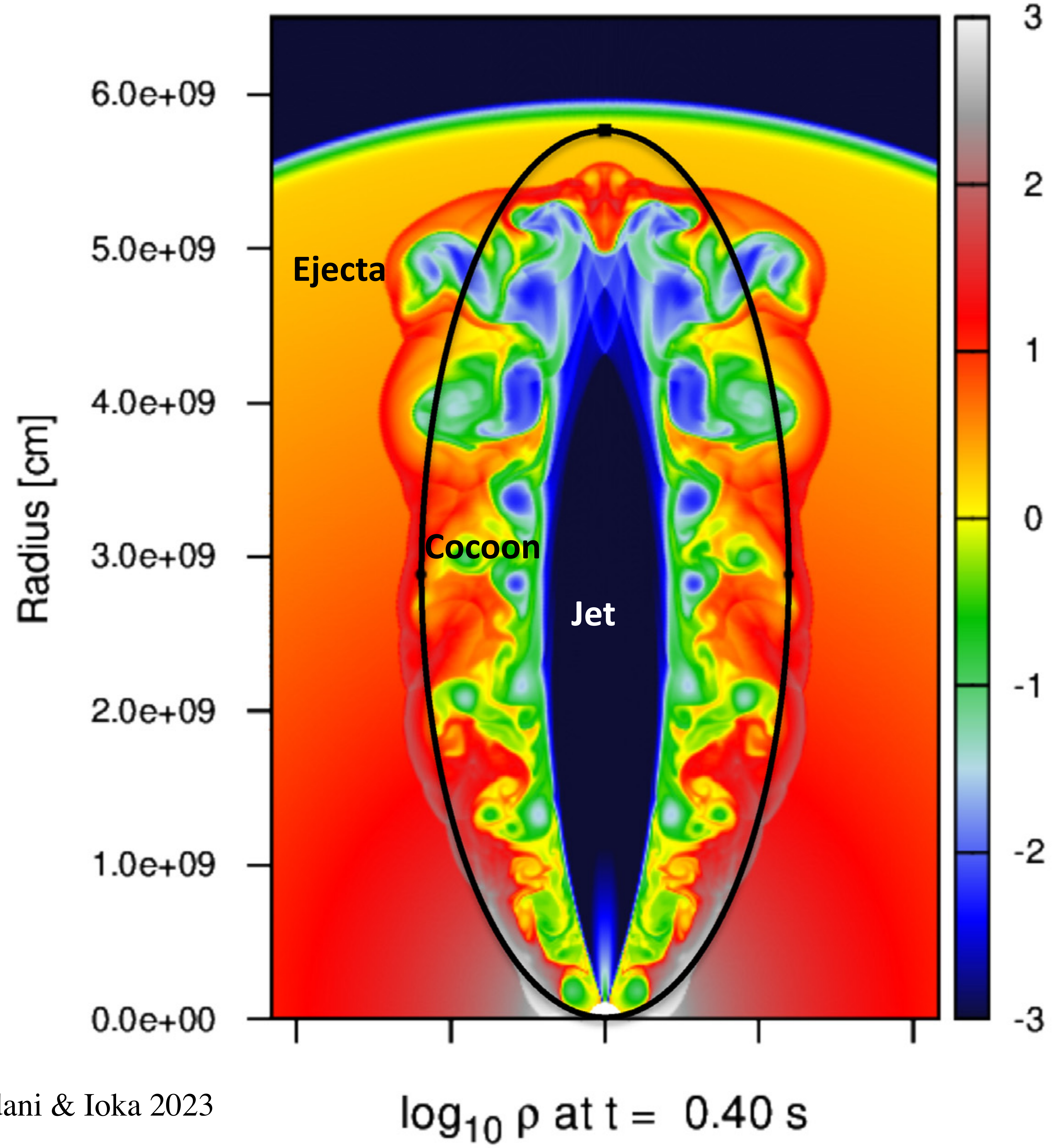
—> jet is launched sometime after merger

- Jets need to propagate in ejecta

—> Jet-ejecta interaction form shocks

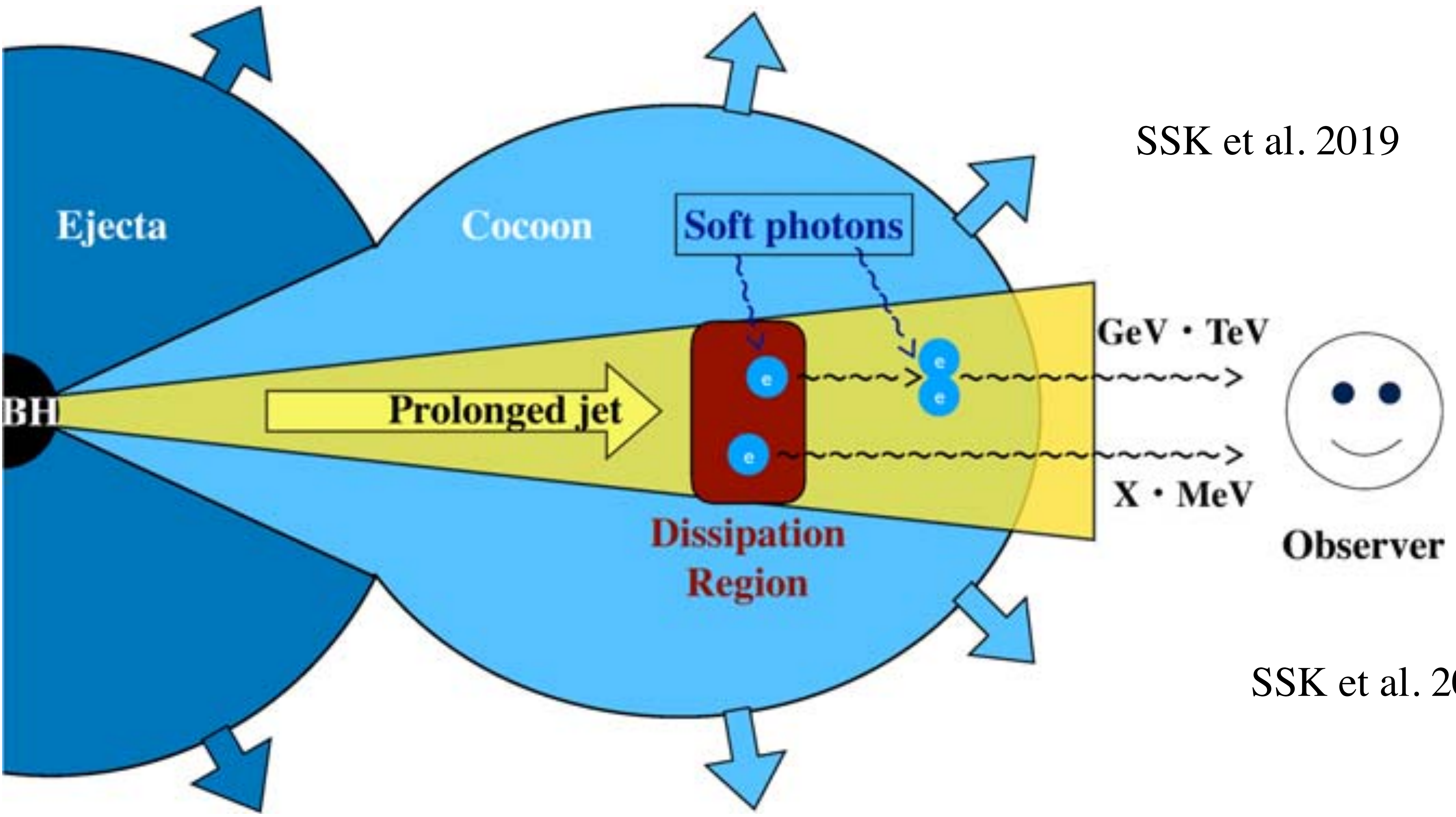
- Shock heated material surrounds jets

—> Formation of cocoon



Hamidani & Ioka 2023

Gamma-ray counterparts to GWs



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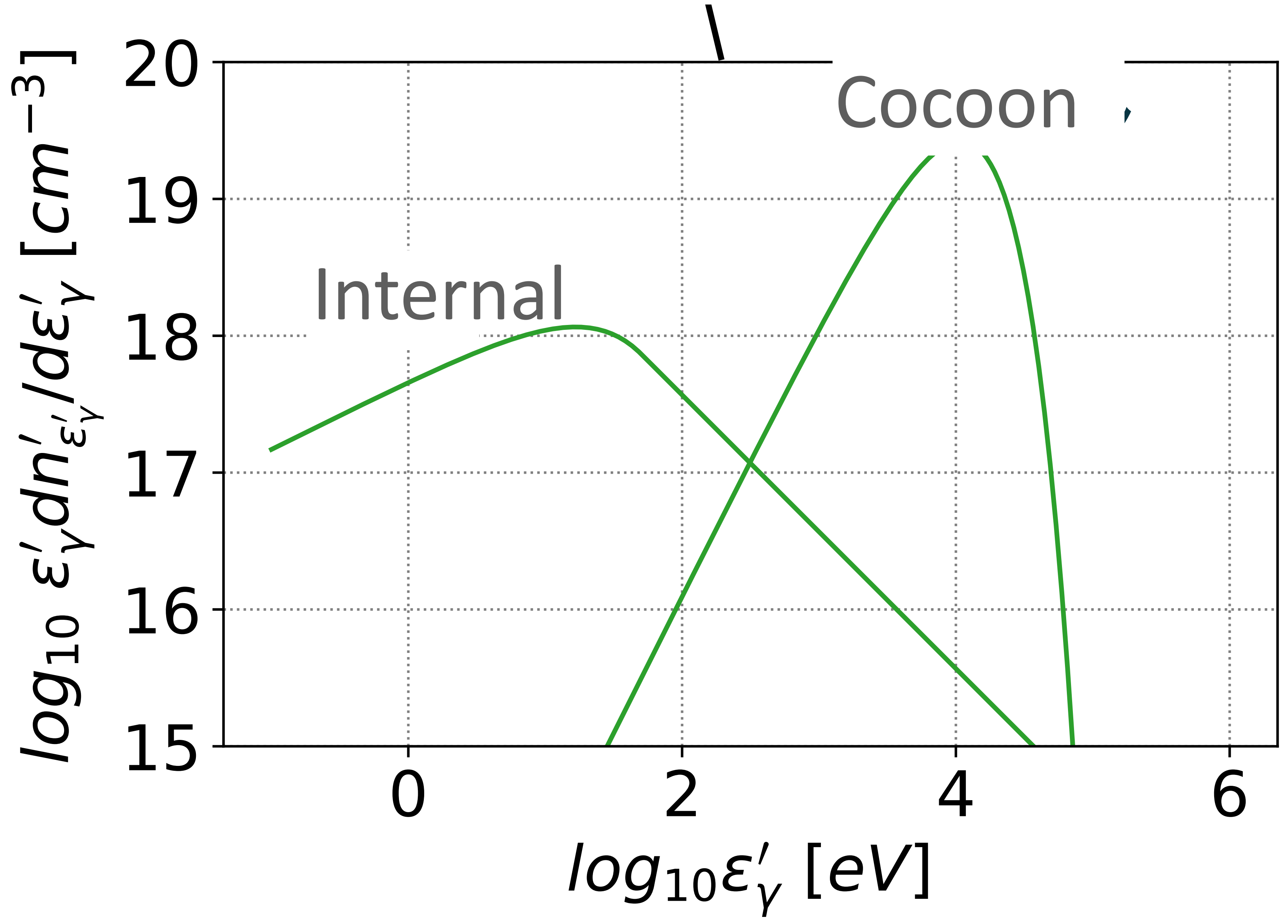


SSK et al. 2019

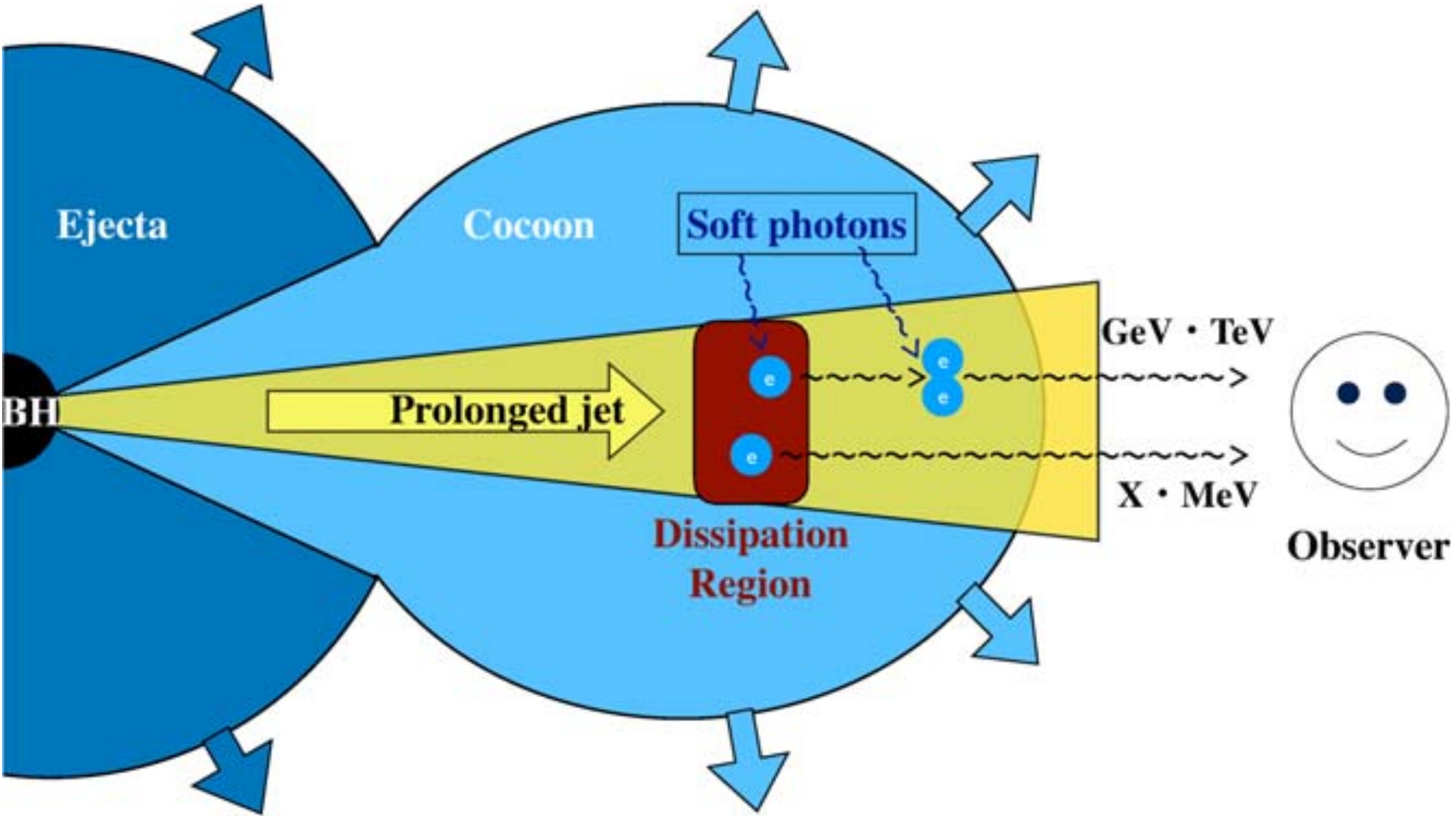
$$t_{p\gamma}^{-1} = \frac{c}{2\gamma_p^2}\int_{\varepsilon_{\rm th}}^{\infty} d\bar{\varepsilon}_\gamma \sigma_{p\gamma}\kappa_{p\gamma}\bar{\varepsilon}_\gamma \int_{\bar{\varepsilon}_\gamma/(2\gamma_p)}^{\infty} \frac{d\varepsilon_\gamma}{\varepsilon_\gamma^2} n_{\varepsilon_\gamma},$$

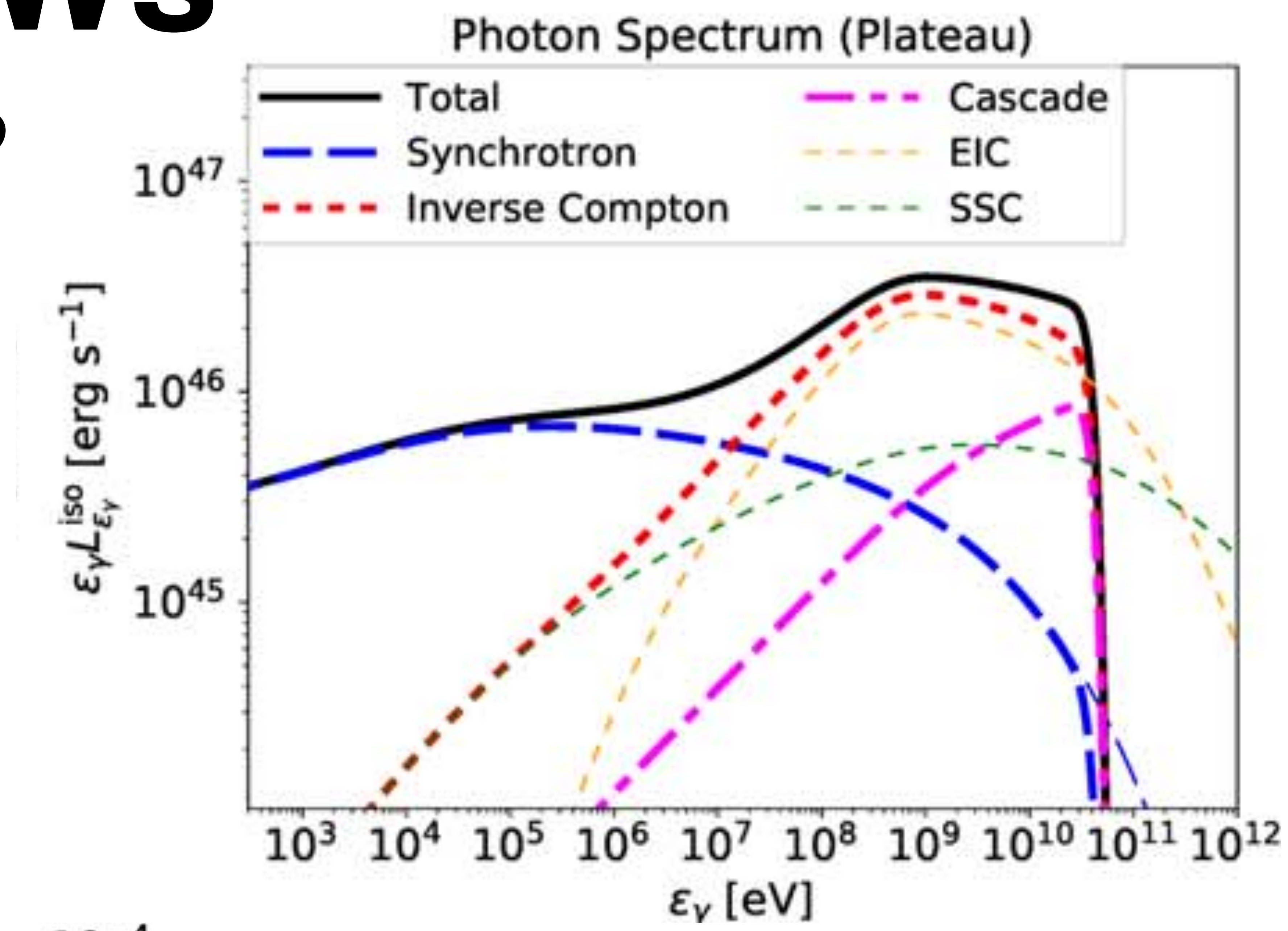
- Cocoon breaks out from the ejecta with jets
- Cocoon is dense & filled with photons (thermal distribution with $T \sim 10^4 - 10^5$ K)
- Cocoon can provide photons to prolonged jets

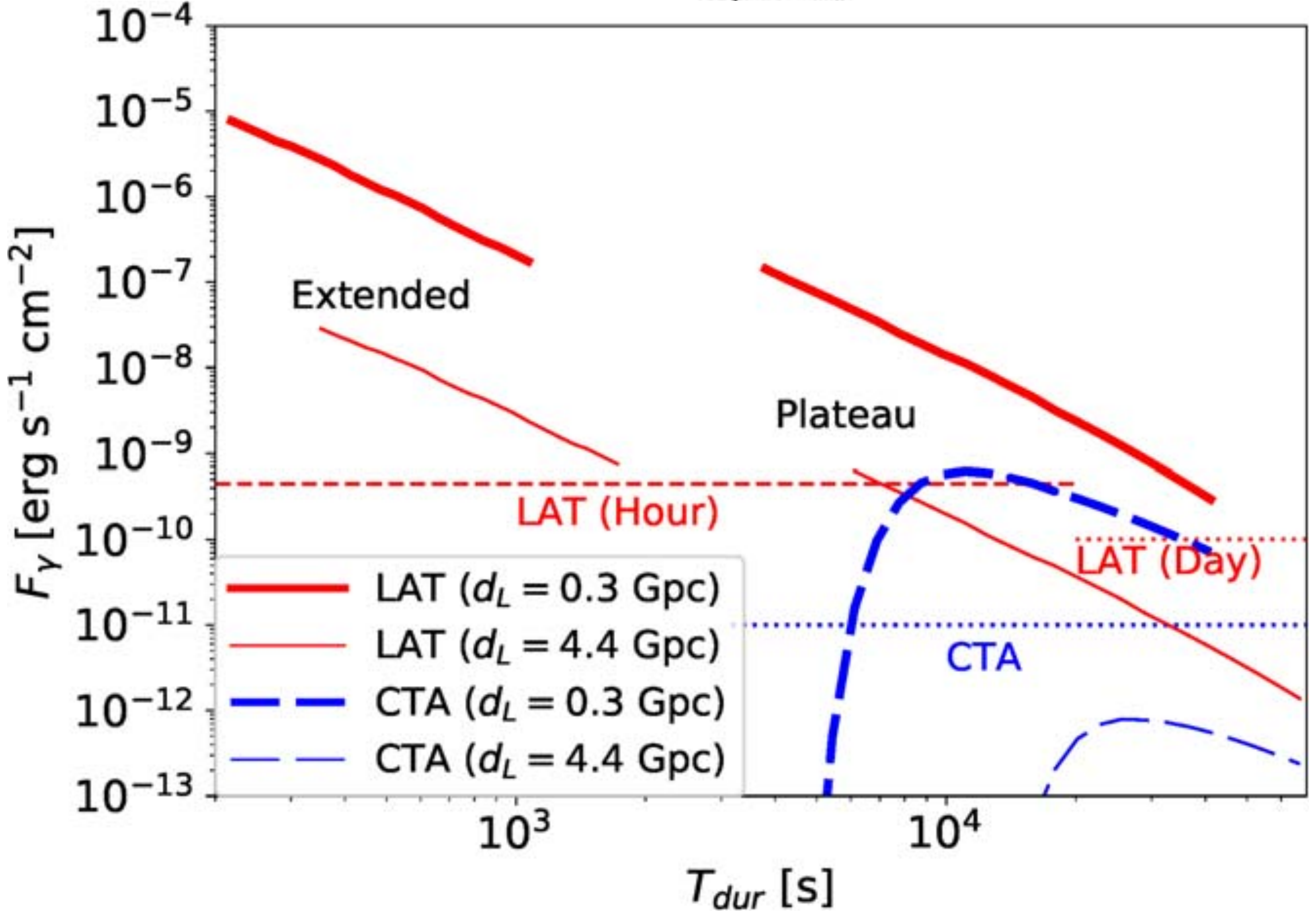
—> enhances pγ interaction & inverse Compton scattering

Gamma-ray counterparts to GWs

SSK et al. 2019

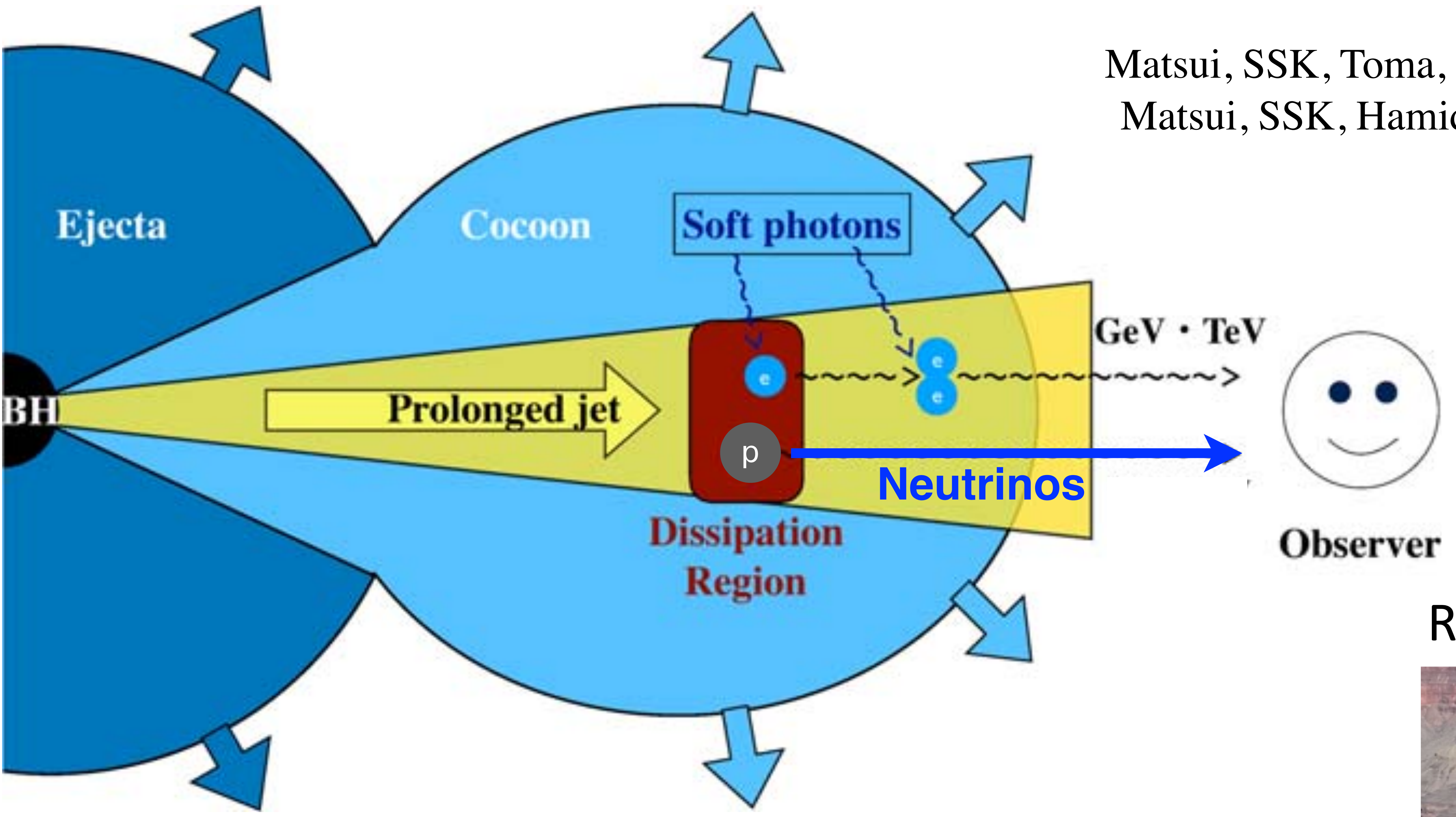






- Up-scattered kilonova (or cocoon) model produces GeV-TeV gamma-rays for 10^2 - 10^4 sec
- Leptonic process emit strong γ-rays
  —> **γ-ray counterpart of GW event should be detected**

Neutrino Counterparts to GWs



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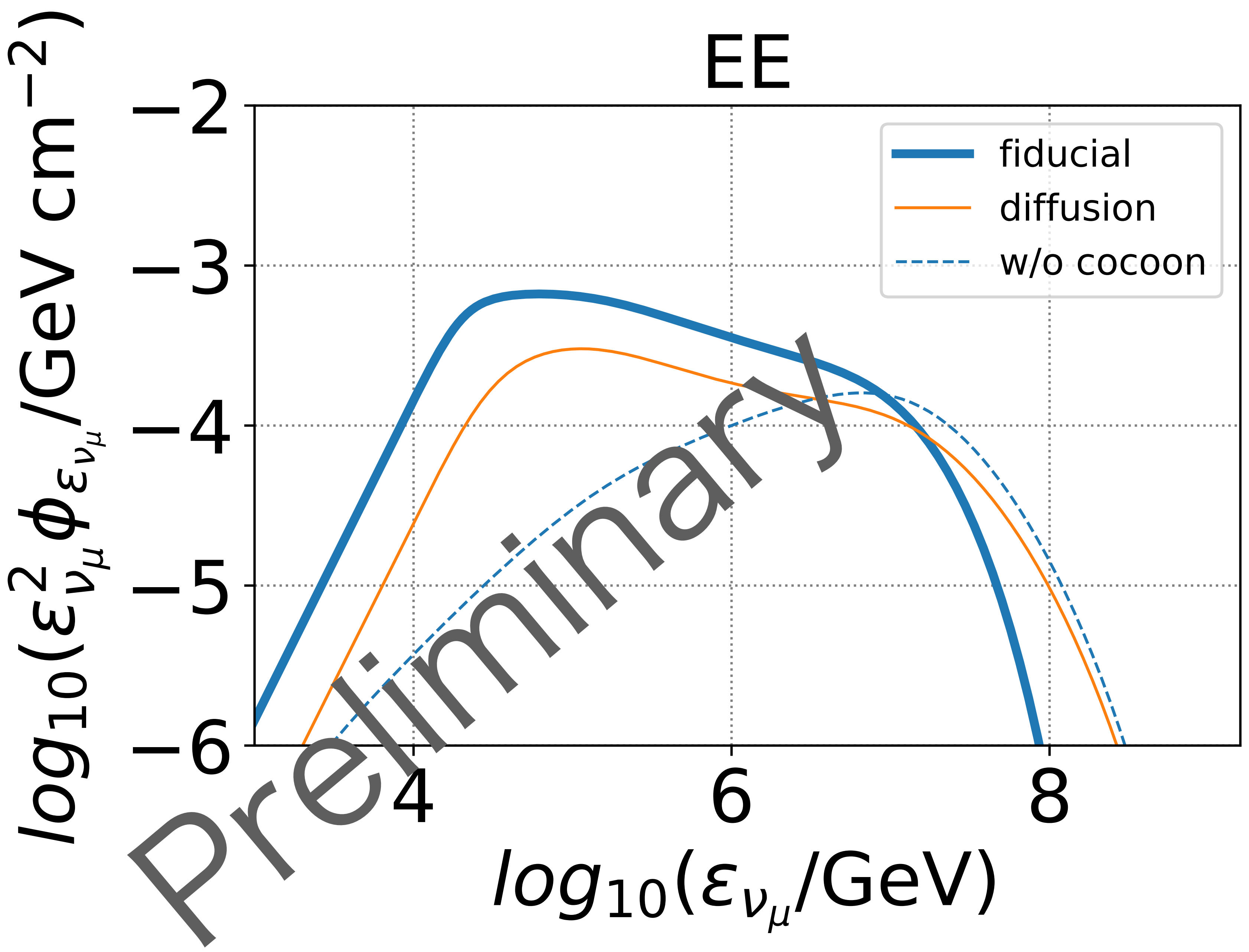
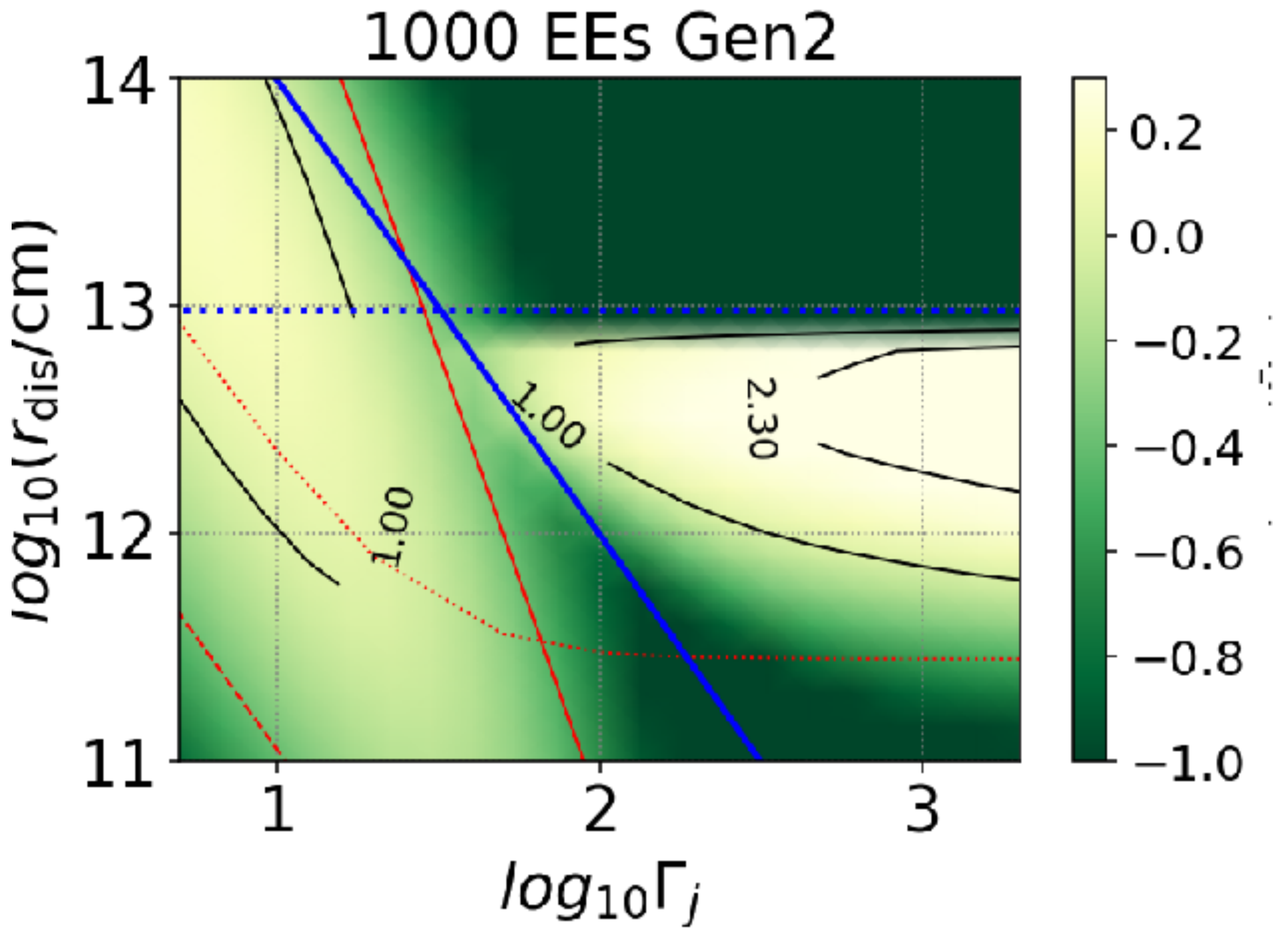
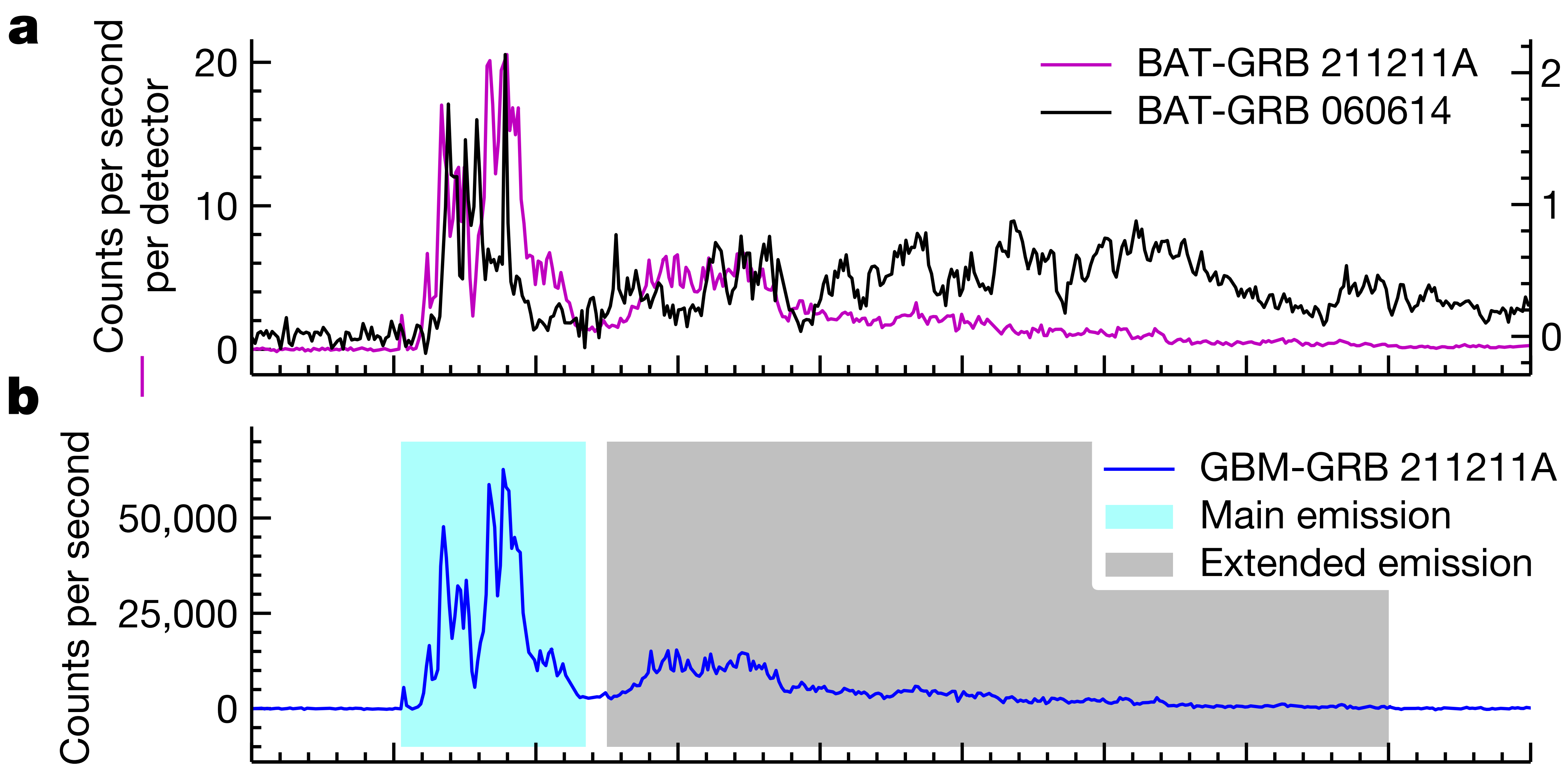


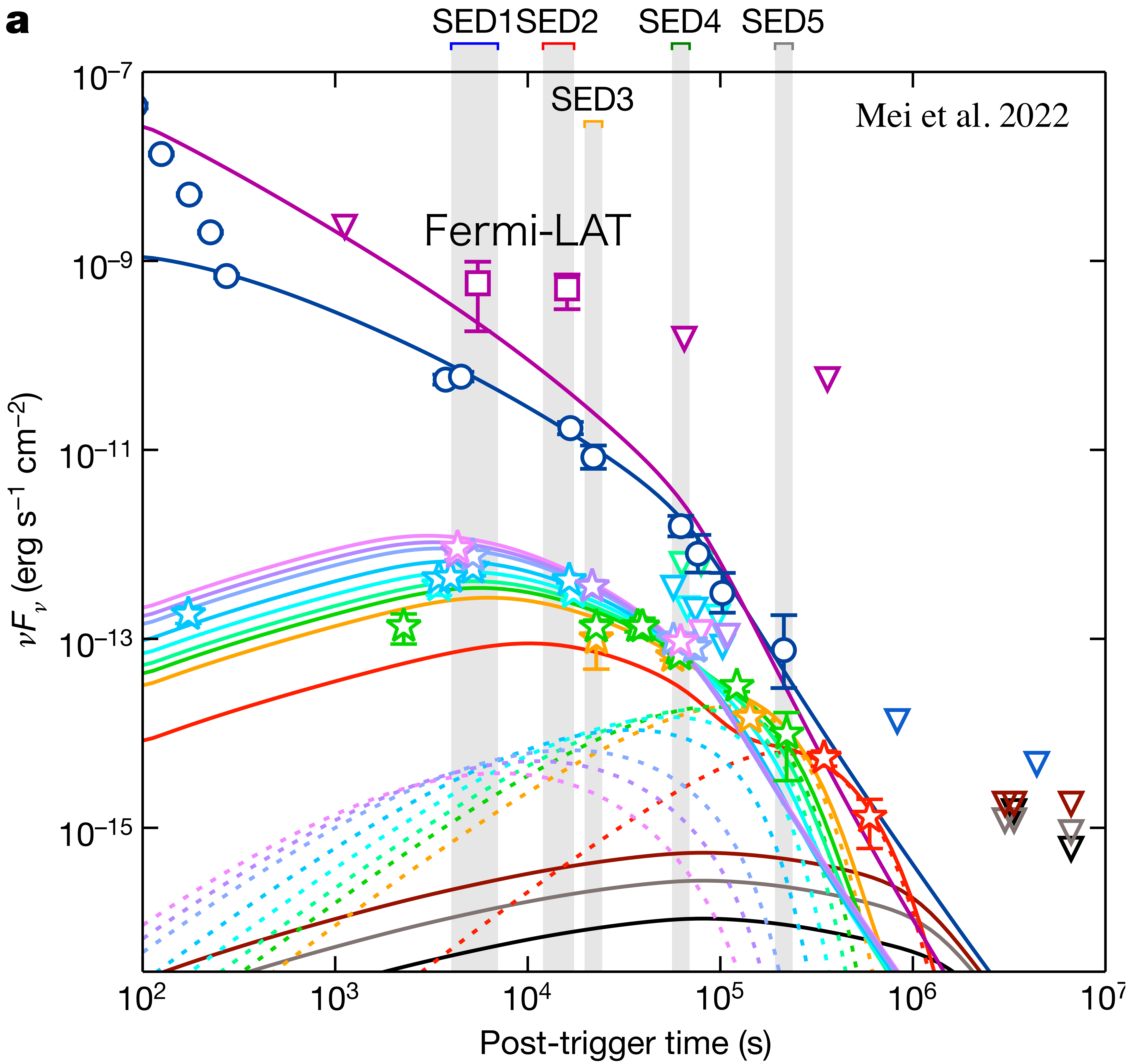
Riki MATSUI



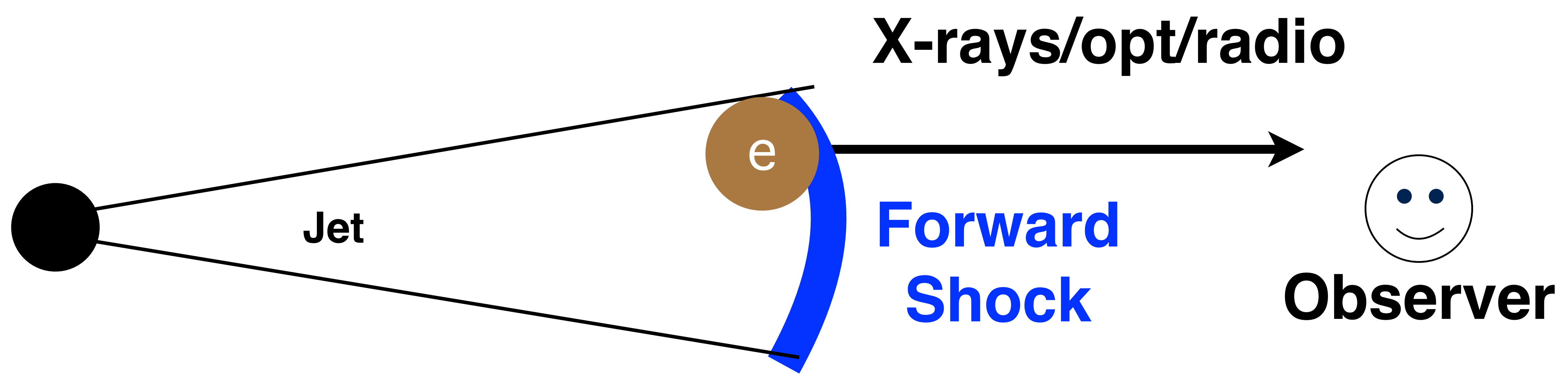
- Protons interact with cocoon photons
  —> neutrinos @ $E_\nu \sim 10^5 - 10^7$ GeV
- **Detectable with 10-yr operation with 10-km³ detector**
  —> Non-detection will put constraint

GeV gamma-rays from GRB 211211A





- GeV gamma-ray detection ($T \sim 10^3$-10^4 sec)
- **Standard forward shock model cannot emit observed gamma-ray flux**
  (but, see Liu et al. 2022 for an alternative)



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- GeV gamma-ray detection ($T \sim 10^3$-10^4 sec)
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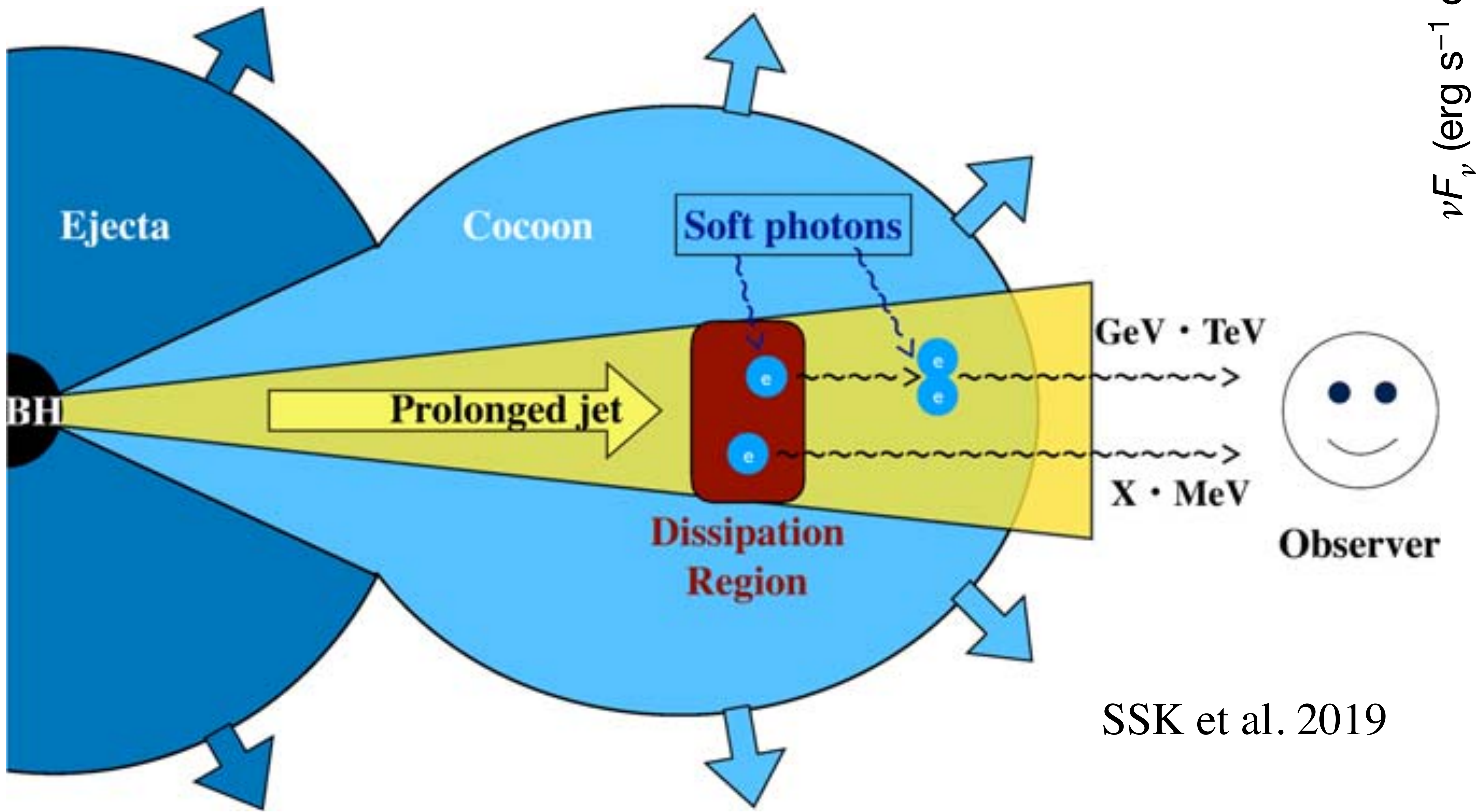
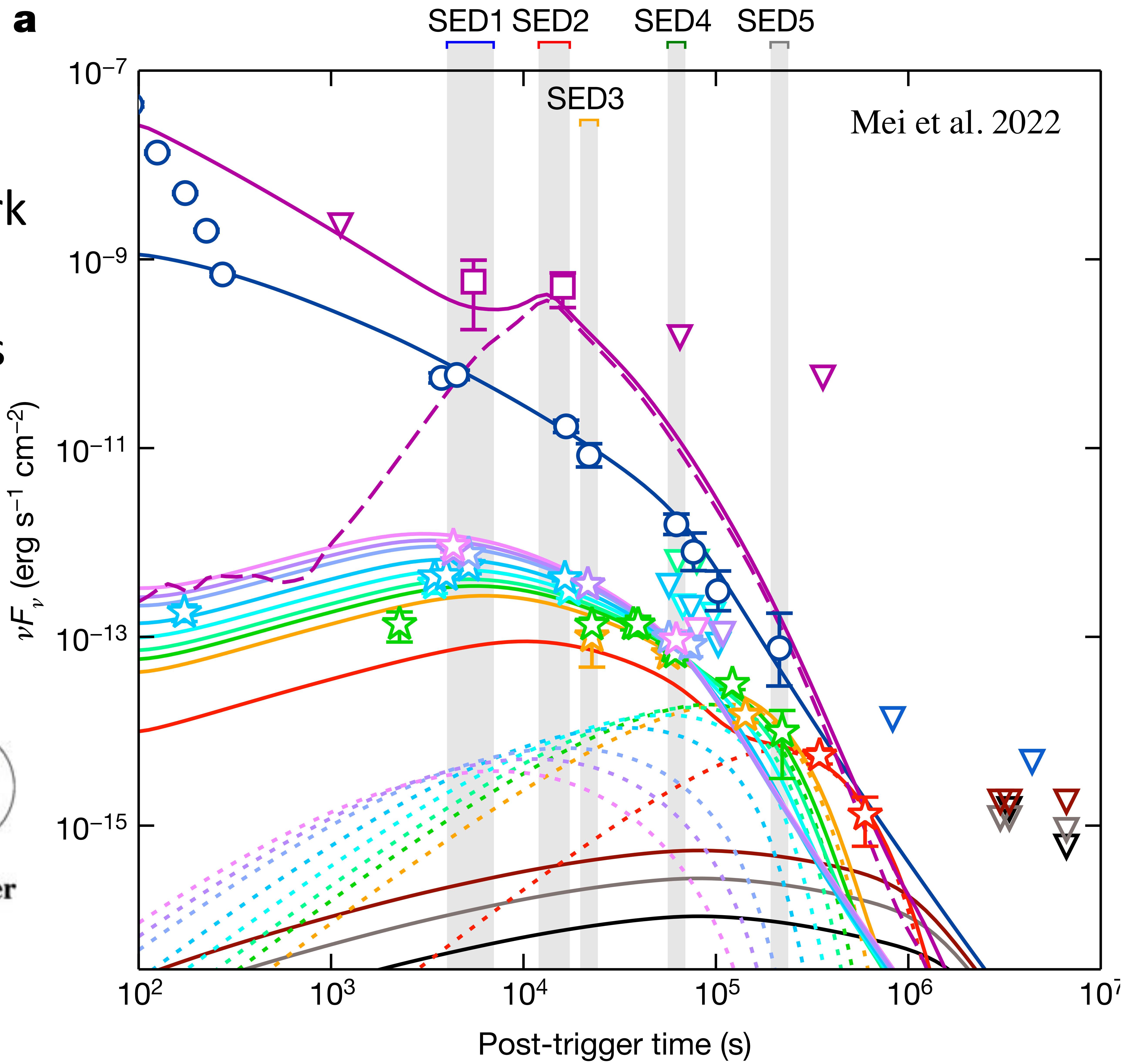


SSK et al. 2019



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Riki MATSUI

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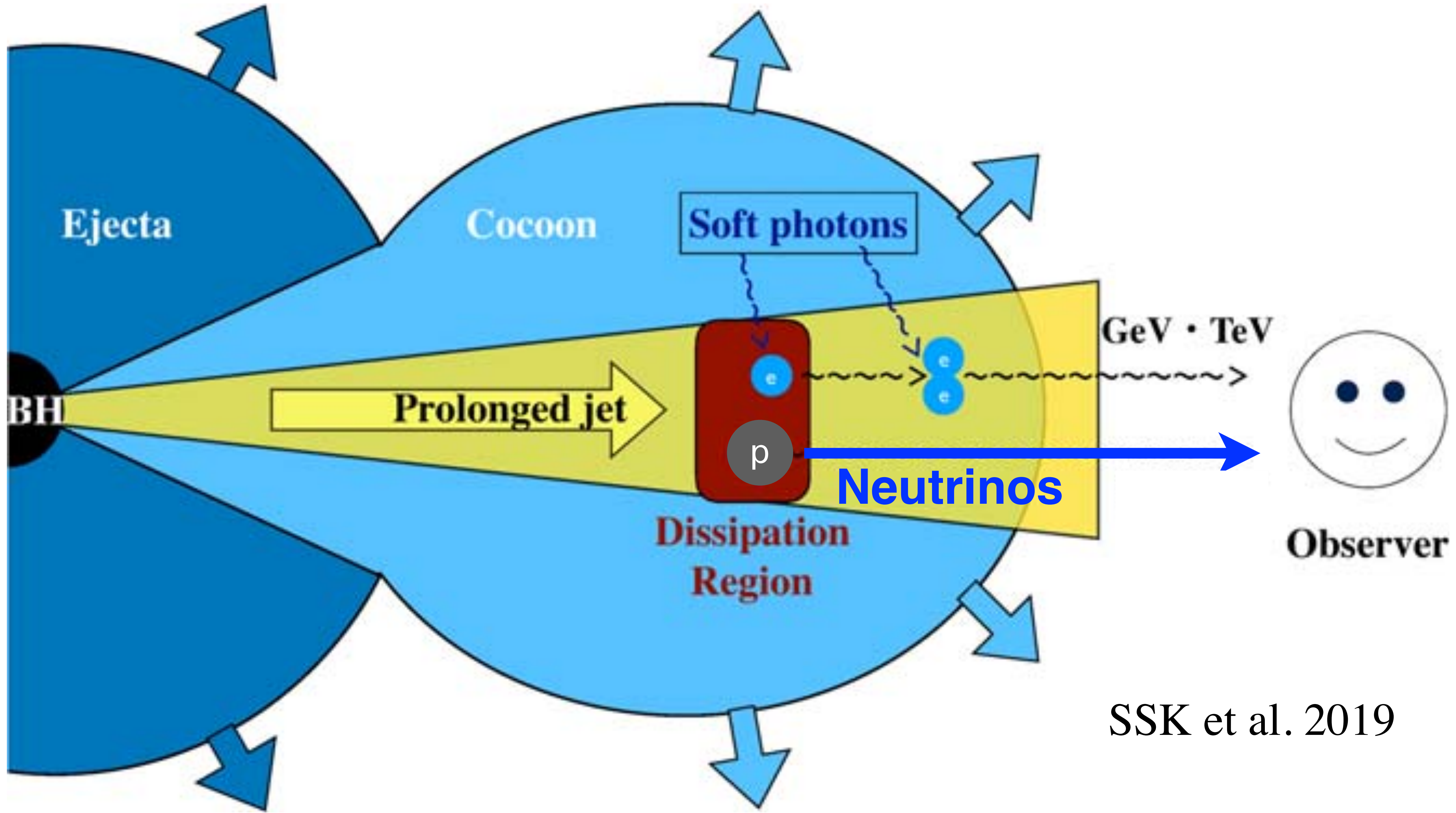
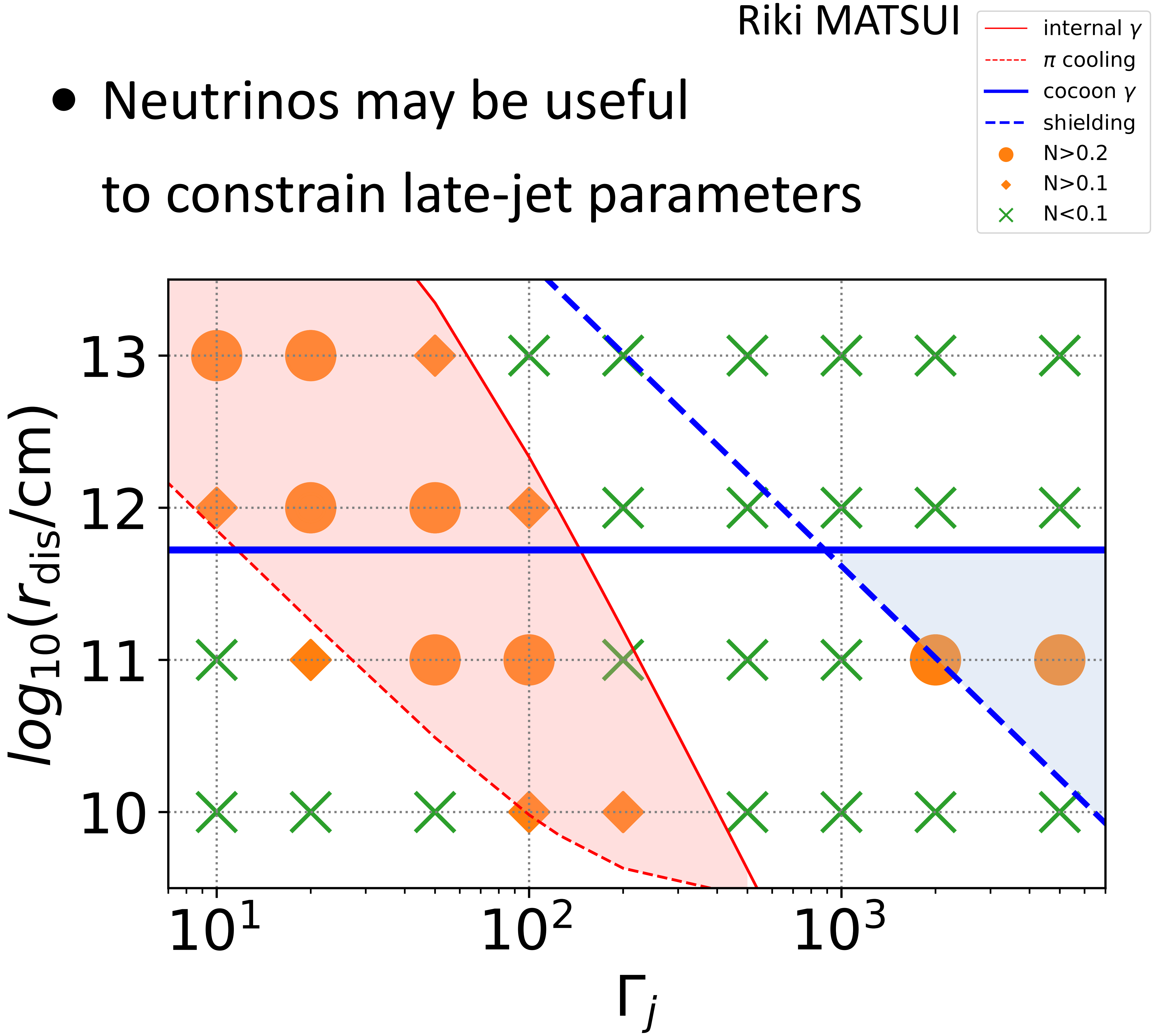


SSK et al. 2019

- Neutrinos may be useful to constrain late-jet parameters

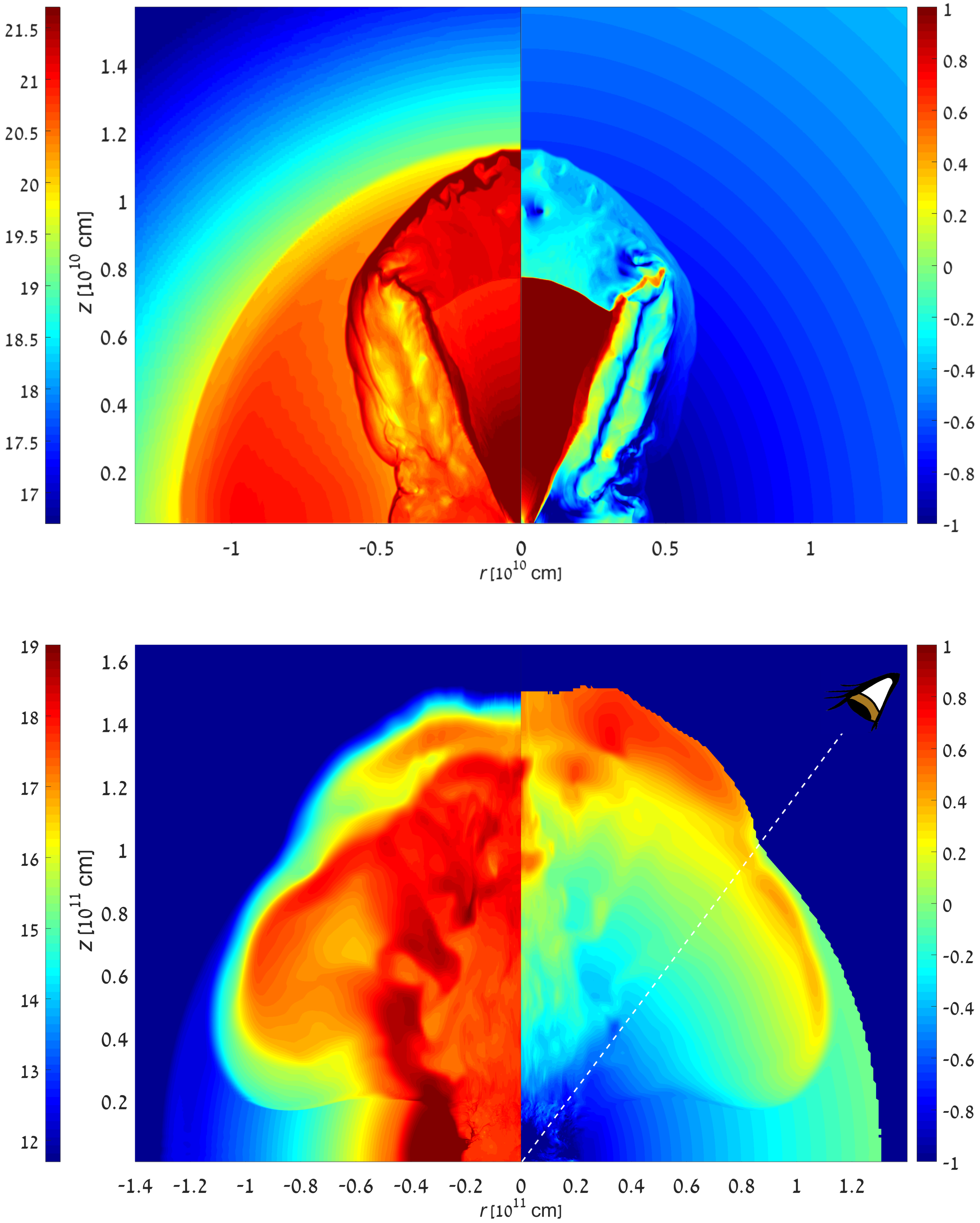


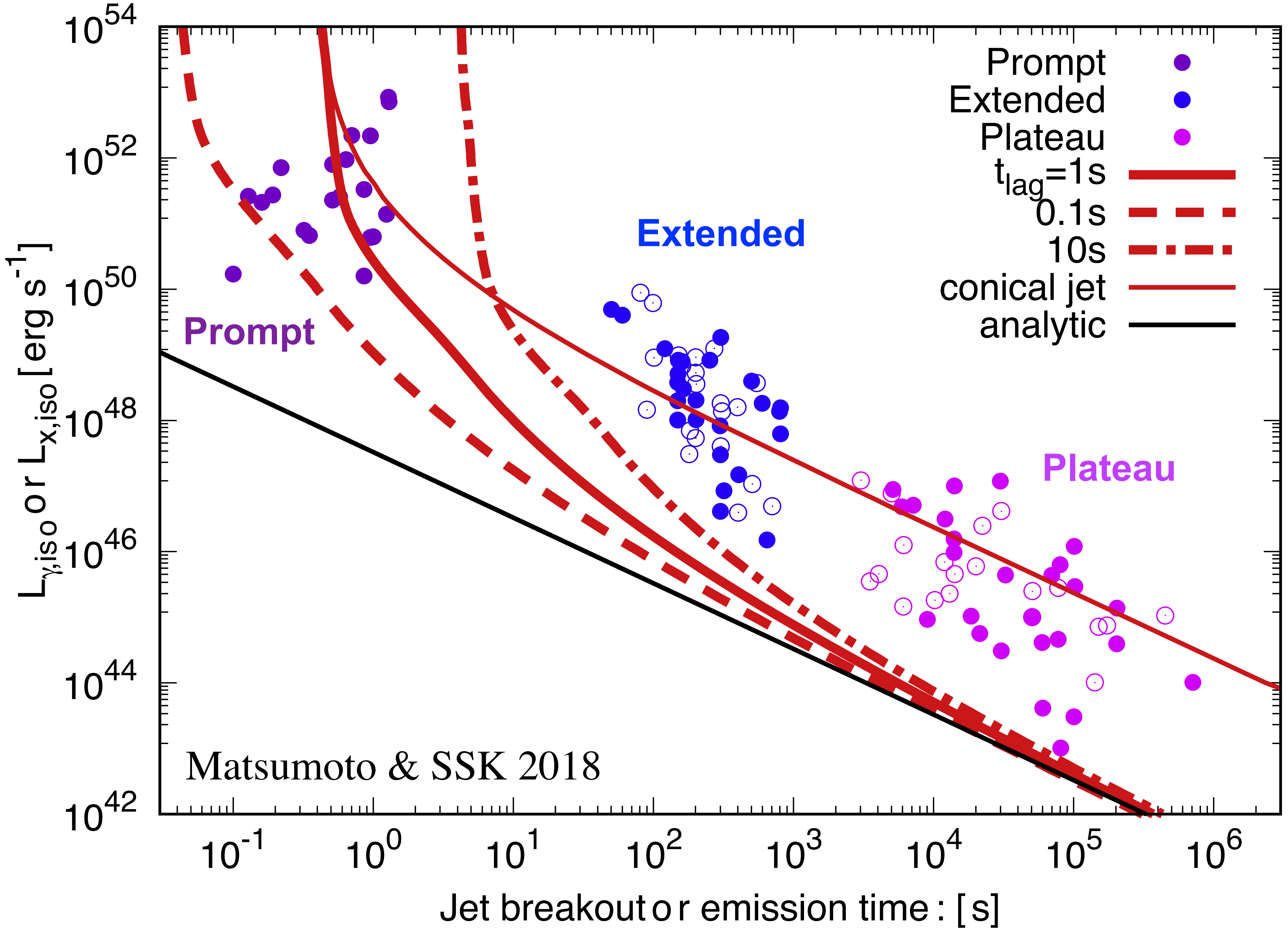
Matsui, SSK et al. 2023

Neutrino Emission Sites for BNS mergers

Choked short GRBs?

Gottlieb et al. 2018





- BNS merger produce ejecta

—> Jet needs to propagate inside the ejecta

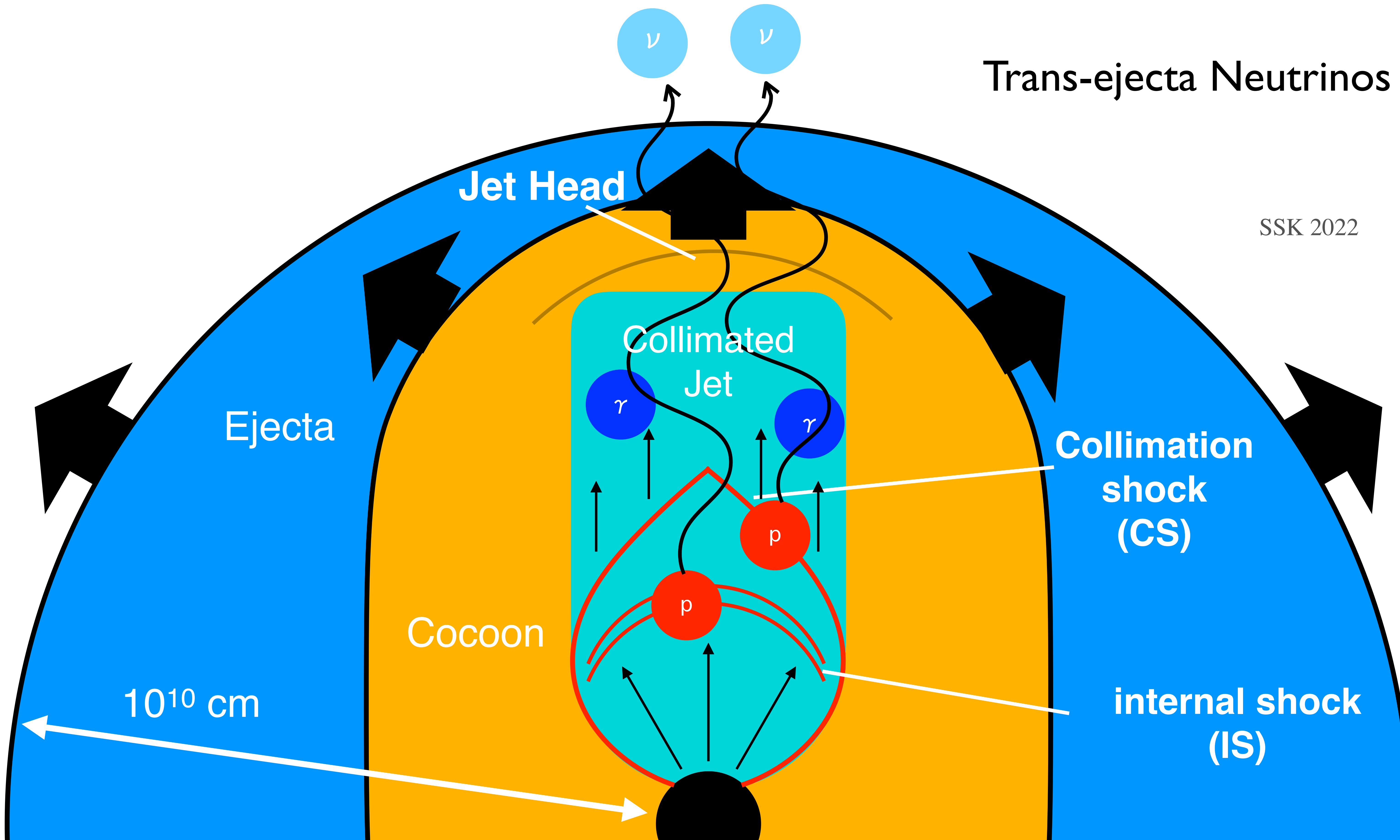
—> some prompt jet fails to penetrate the ejecta

- Jets can dissipate energy inside the ejecta

—> sub-photosperic neutrino production

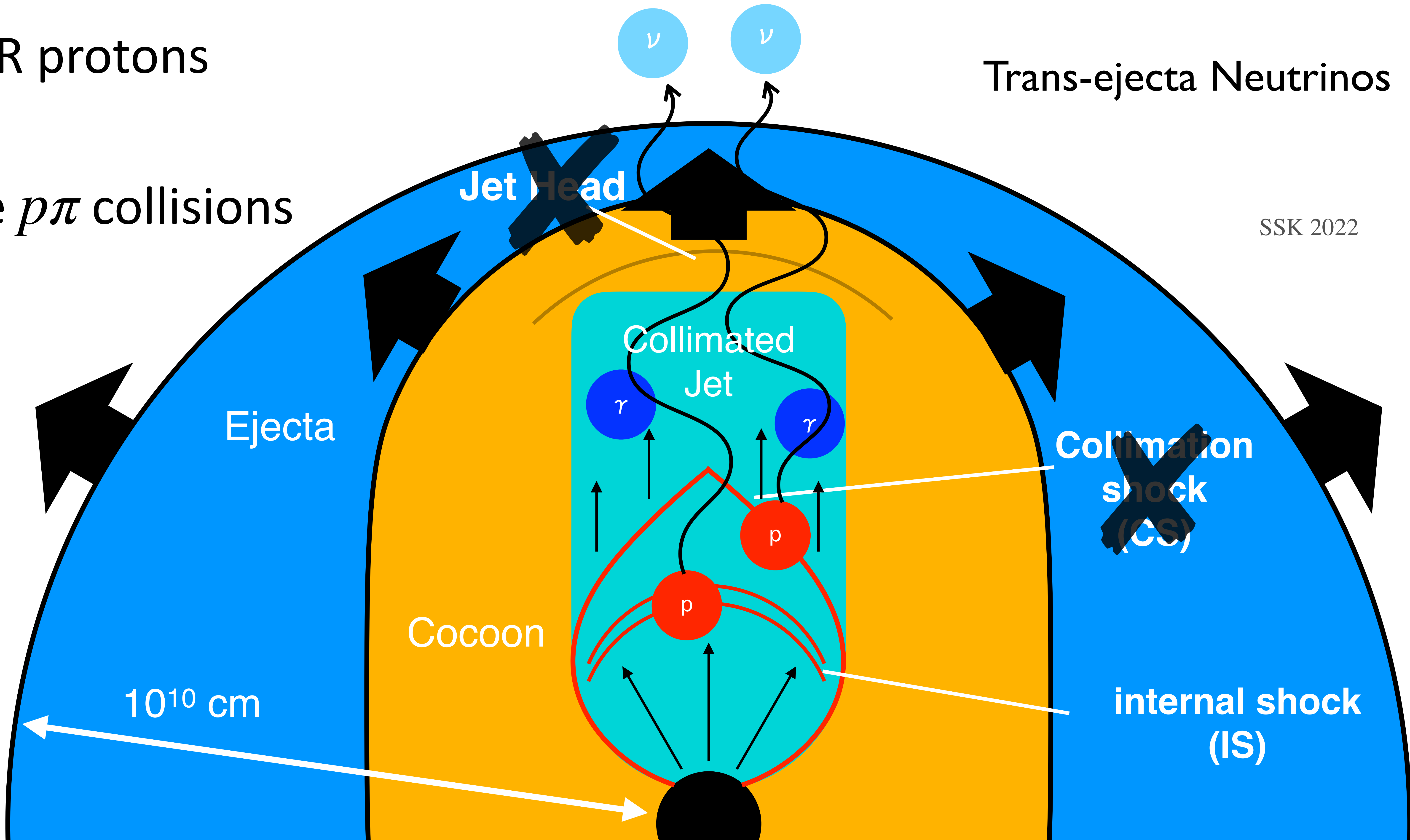
Schematic Picture & Shocks in choked jets

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

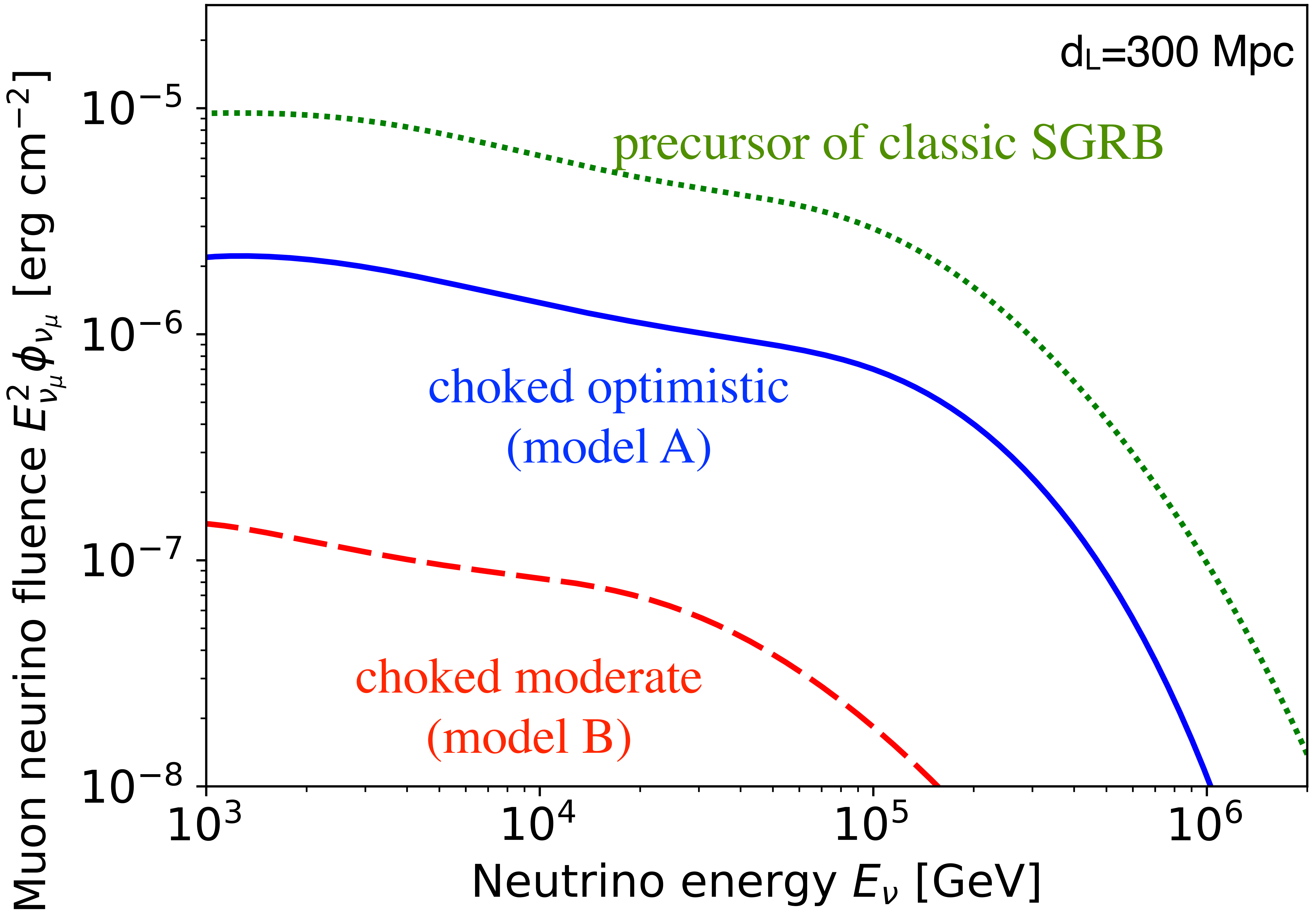


Schematic Picture & Shocks in choked jets

- jet sweeps up ejecta —> shocks at jet head
- cocoon surrounding the jet
  —> push the jet inward —> 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 $p\pi$ collisions
- **HE neutrinos are emitted only from internal Shock**



Trans-ejecta neutrino spectrum



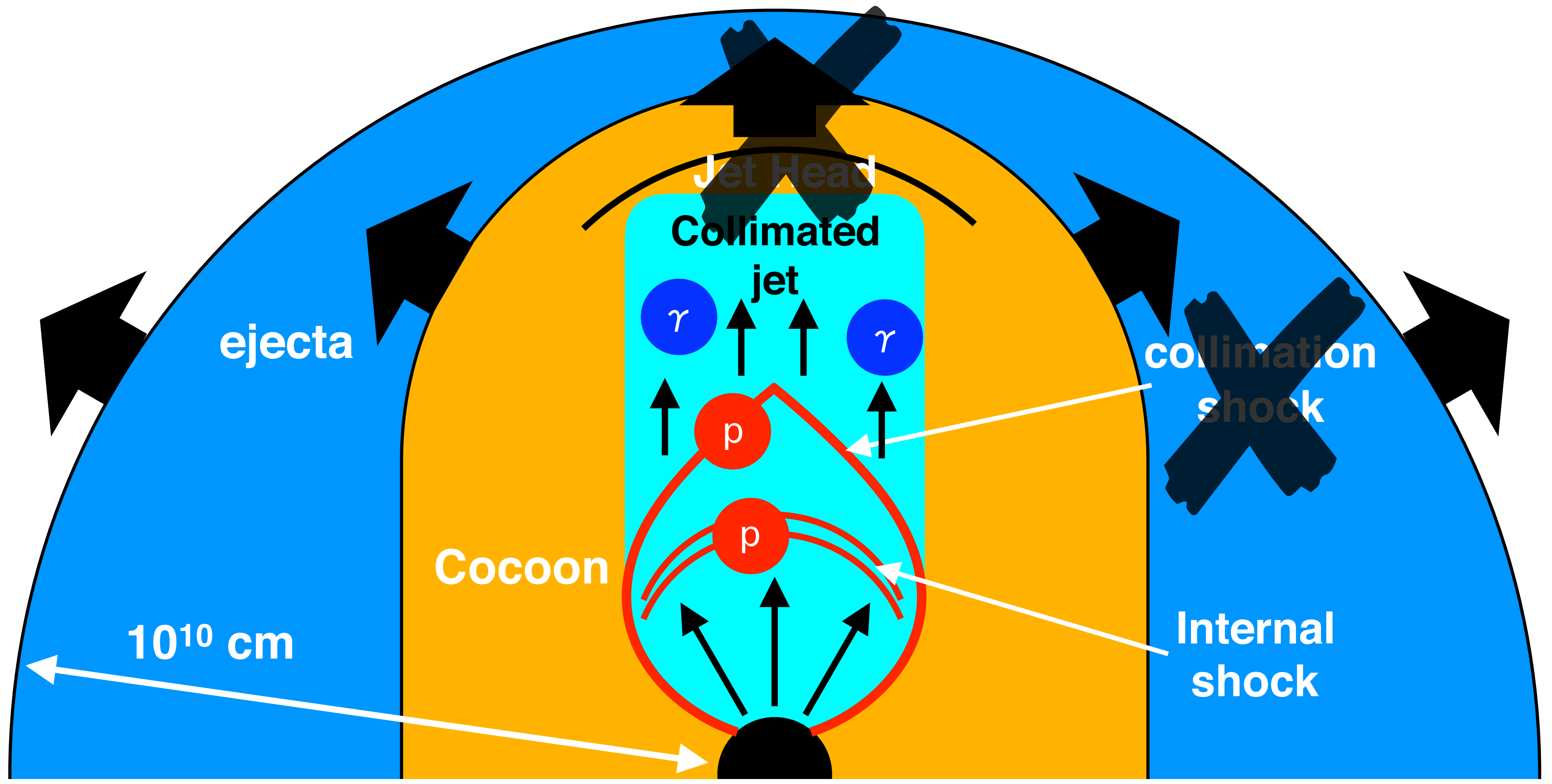
$$E_p^2 \frac{dN}{dE} = \frac{\epsilon_p E_{k,\mathrm{iso}}}{\ln(E_{p,\max}/E_{p,\min})}$$

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

$$f_{p\gamma} = t_{p\gamma}^{-1}/t_{p,\mathrm{cl}}^{-1}$$

$$f_{\sup\pi} = 1 - \exp(-t_{\pi,\mathrm{cool}}/t_{\pi,\mathrm{dec}})$$

- Neutrino spectrum is flat for E ~ 1-100 TeV
- If BNS merger rate is 10^3 Gpc^{-3} yr^{-1}
  detectable by 10-yr operation with 10 km^3 detectors



Neutrino Emission Sites for BNS mergers

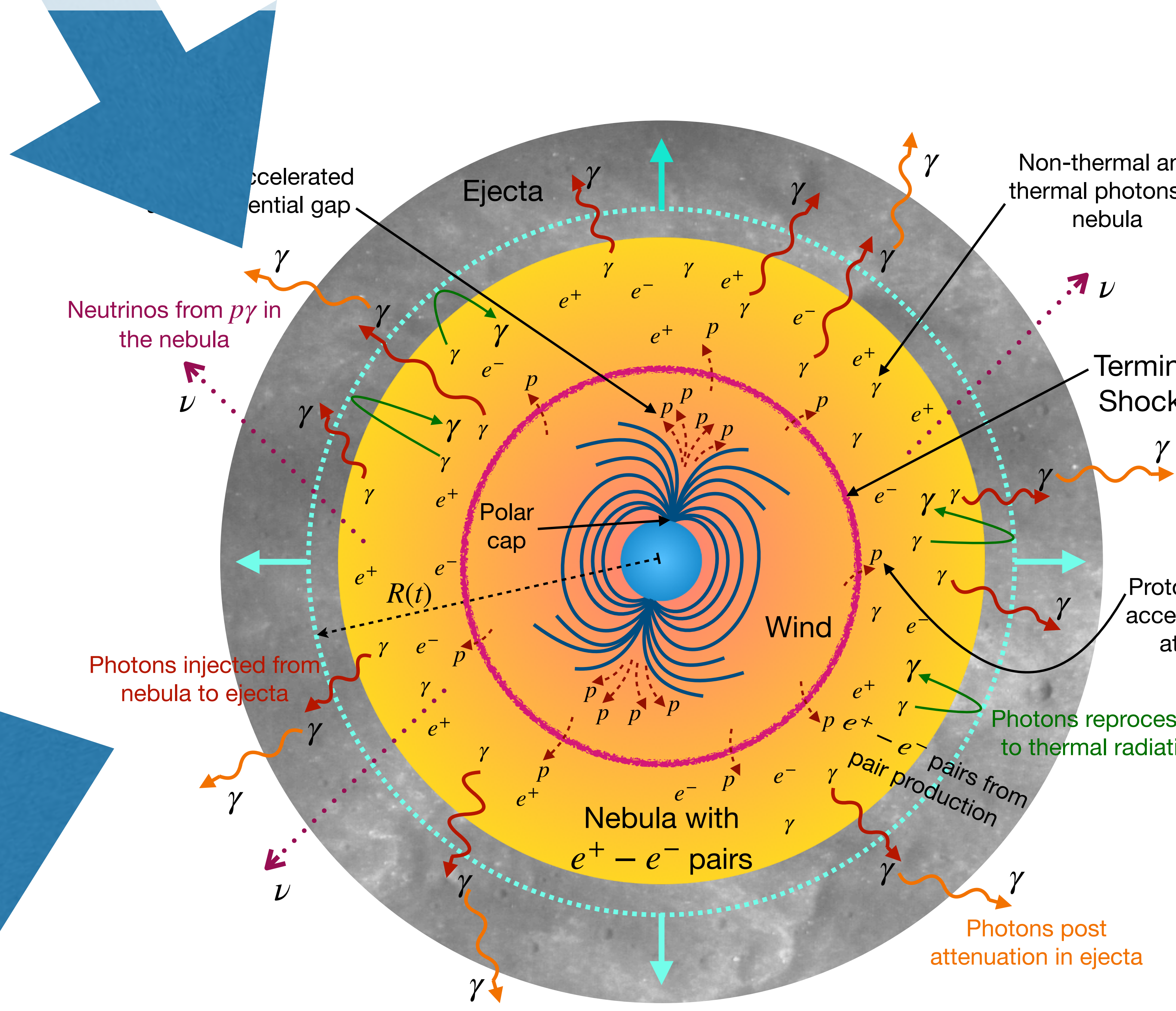
SSK et al. 2017; Biehl et al. 2018
Matsui, SSK, et al. 2023;
Matusi, SSK et al. in prep.

Successful jets
(sGRBs)

NS-NS merger

Choked jets

SSK et al. 2018

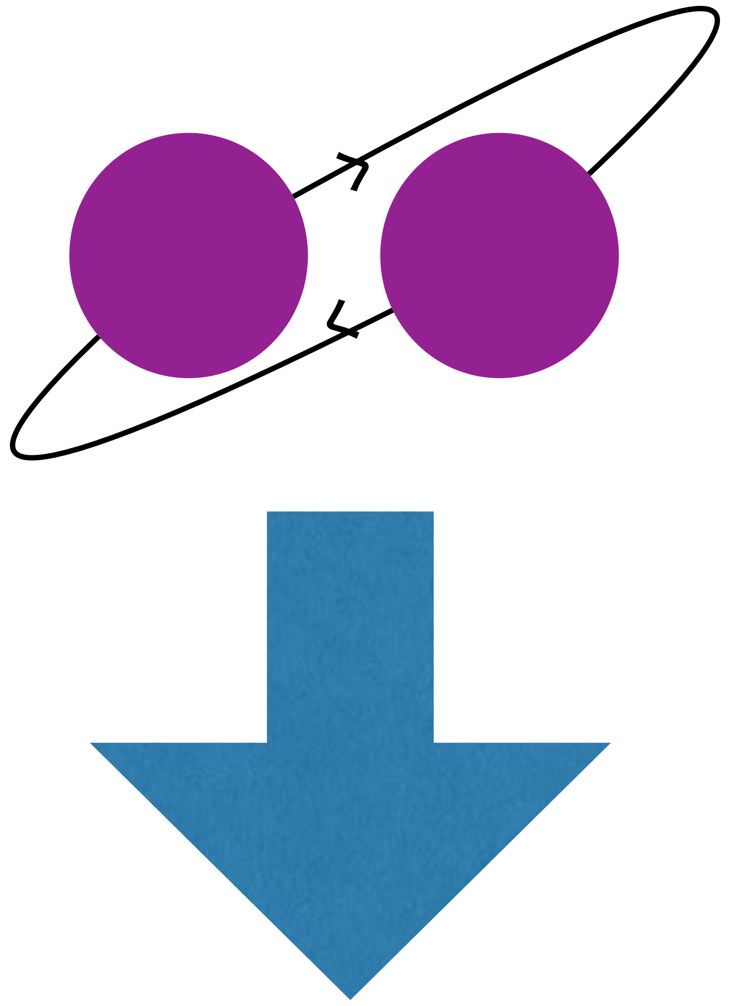


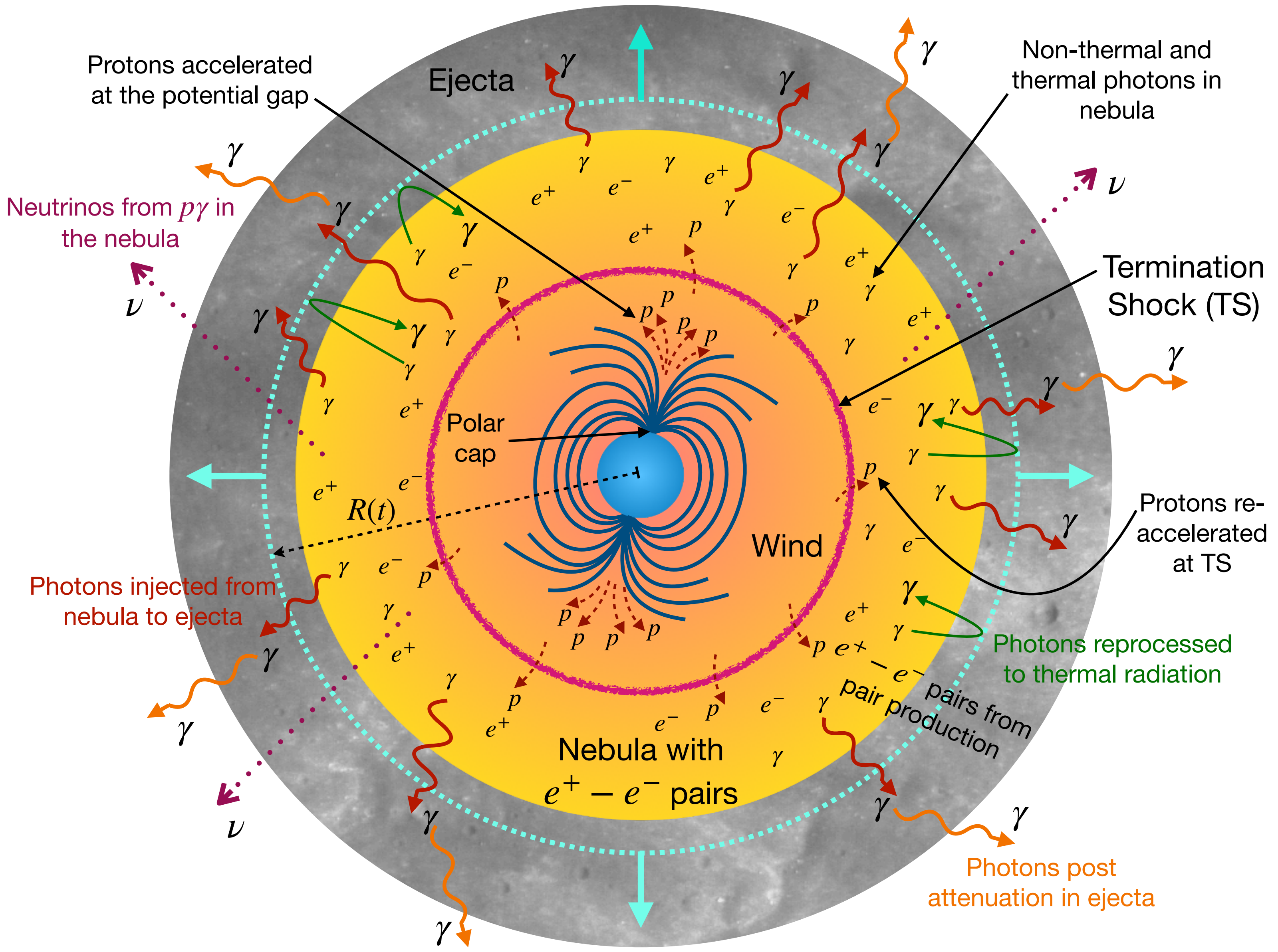
Merger remnants

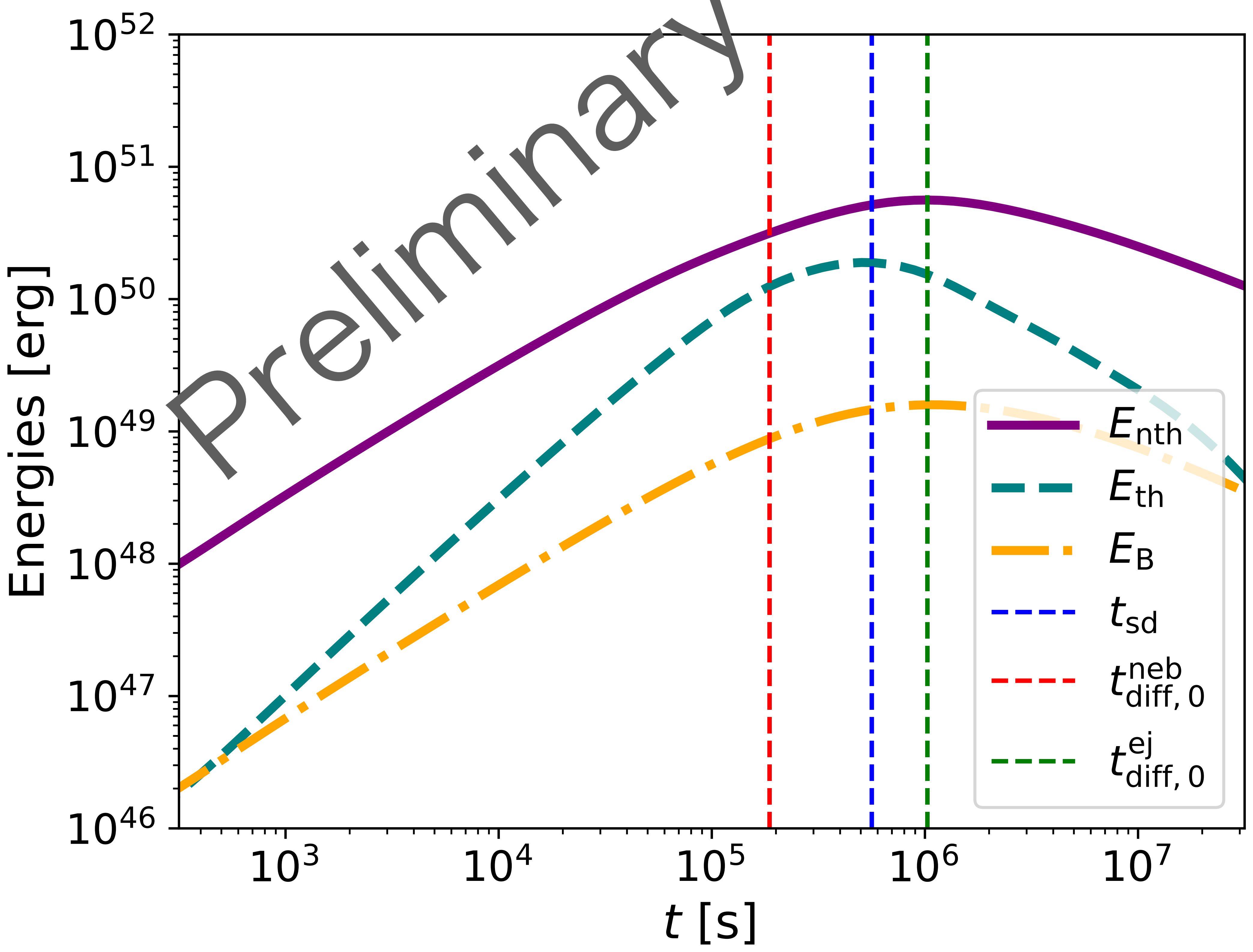
Gao et al. 2013; Fang & Metzger 2017
Mukhopadyay & SSK in prep.

Neutrinos powered by remnants

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







Mainak Mukhopadhyay

- 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 PeV) for T > 10^6 s
- **Detectable by 30-yr operation with 10 km^3 detectors**

Neutrinos powered by remnants

Mukhopadhyay, SSK+ in prep.
(see also Fang & Metzger 2017;
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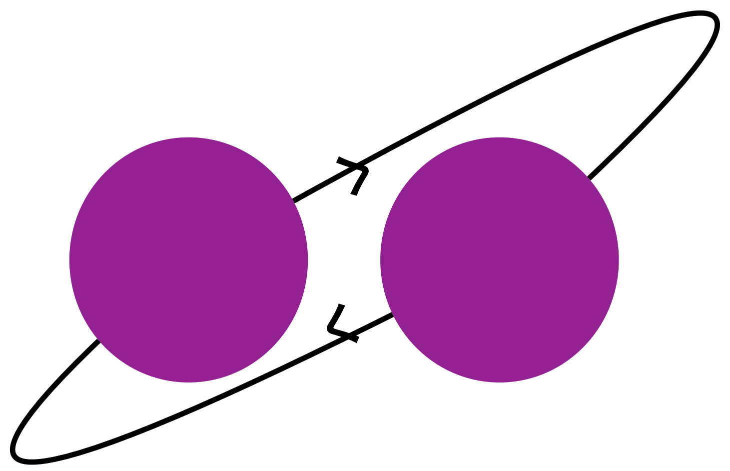

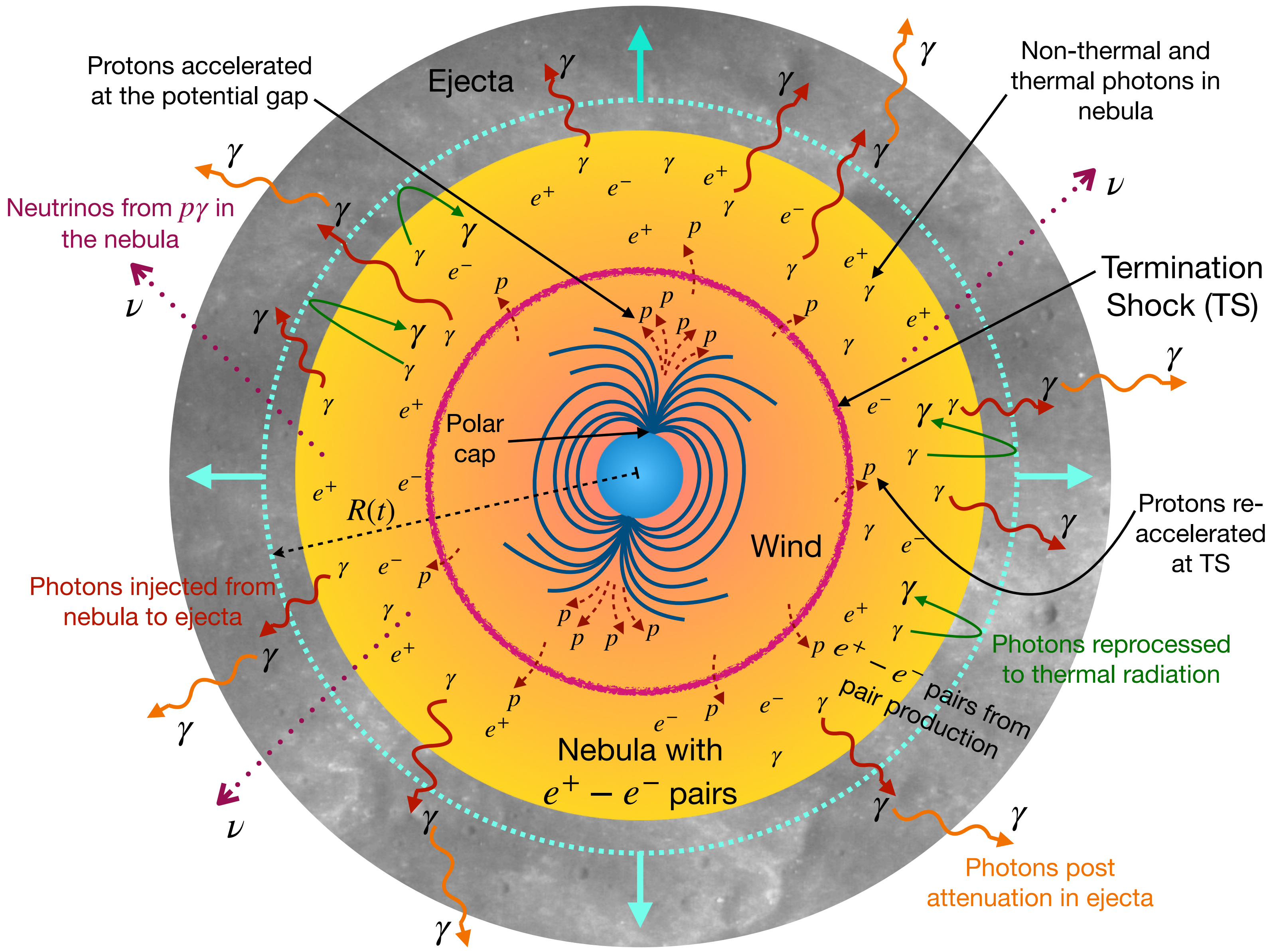

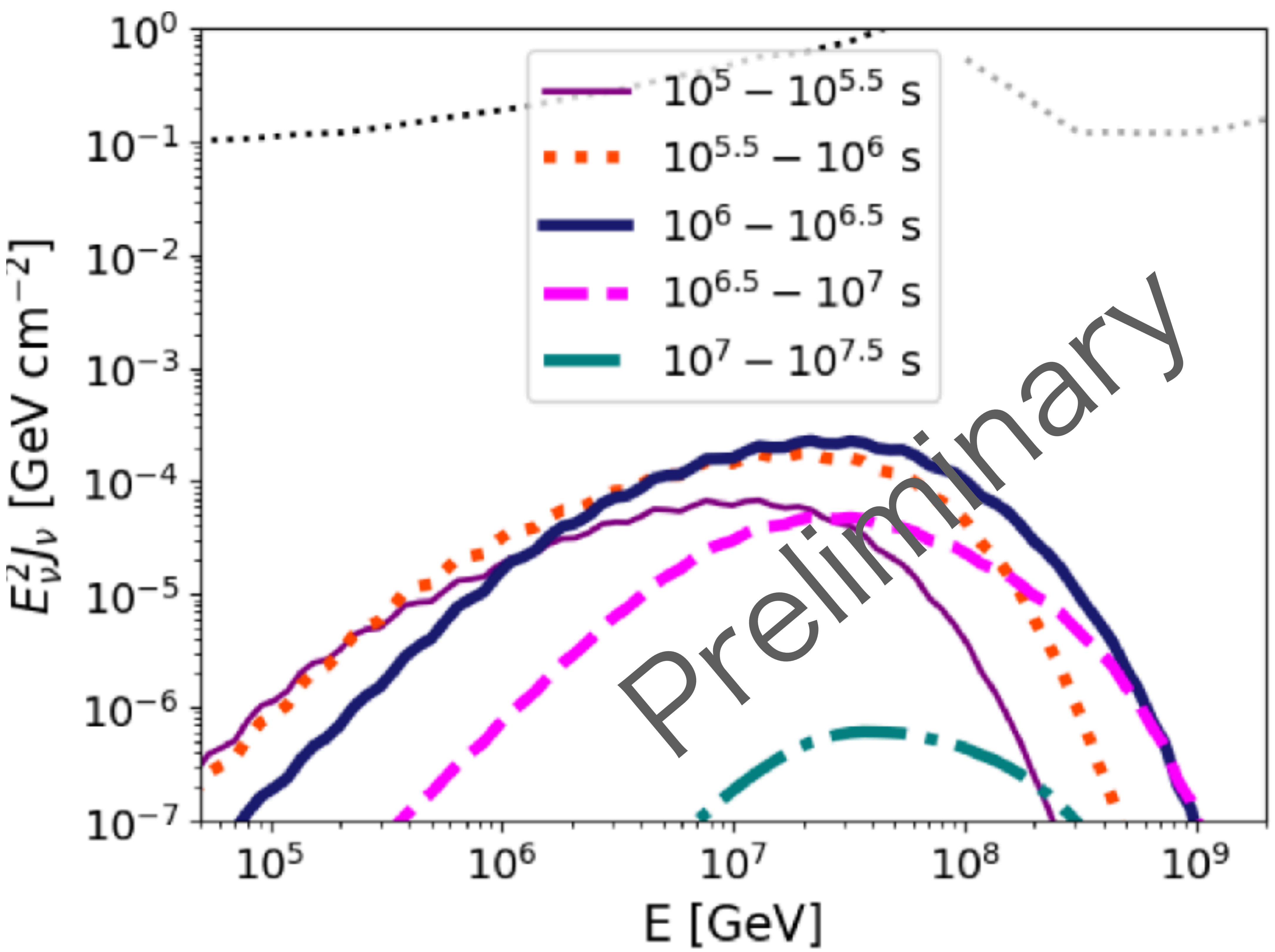

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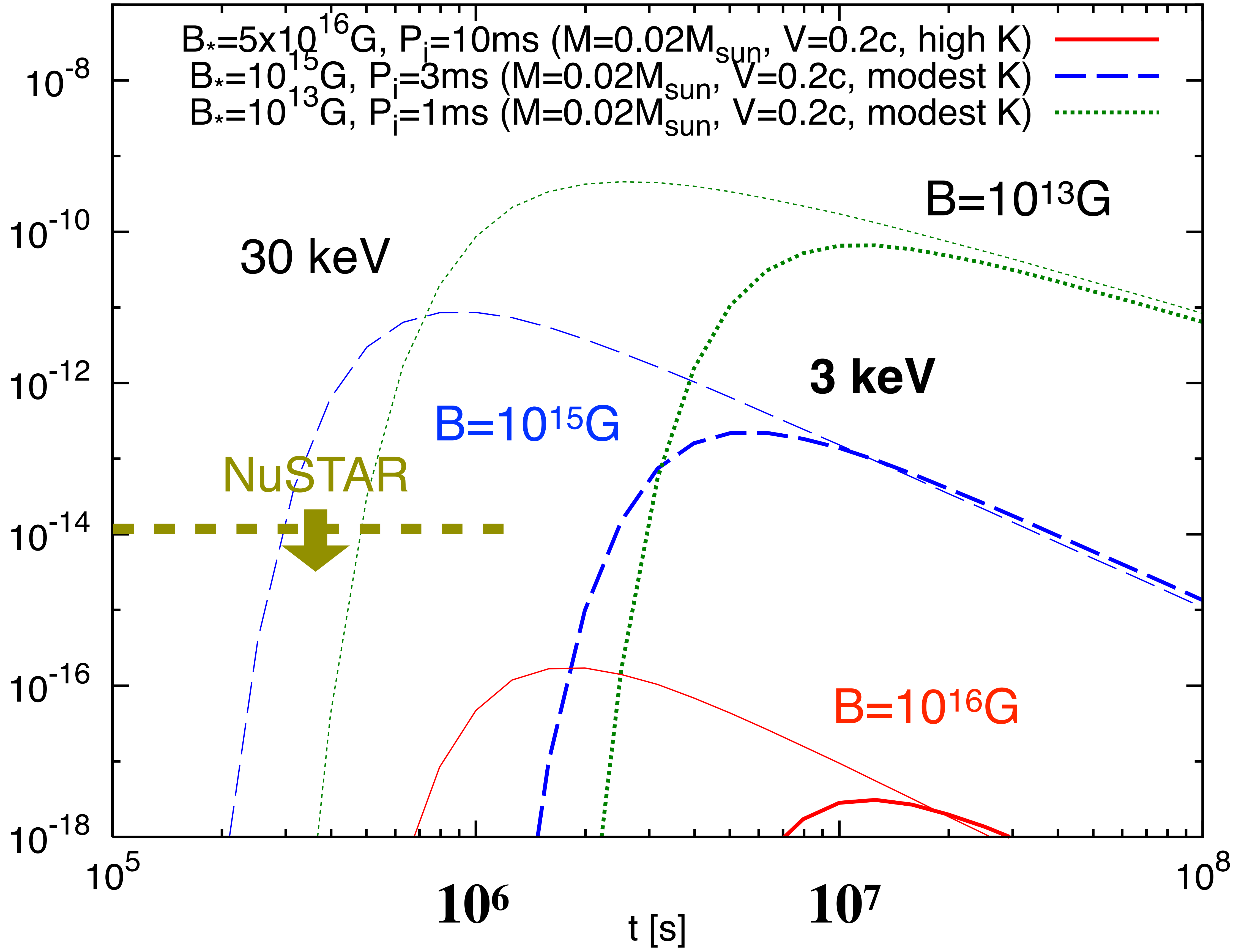
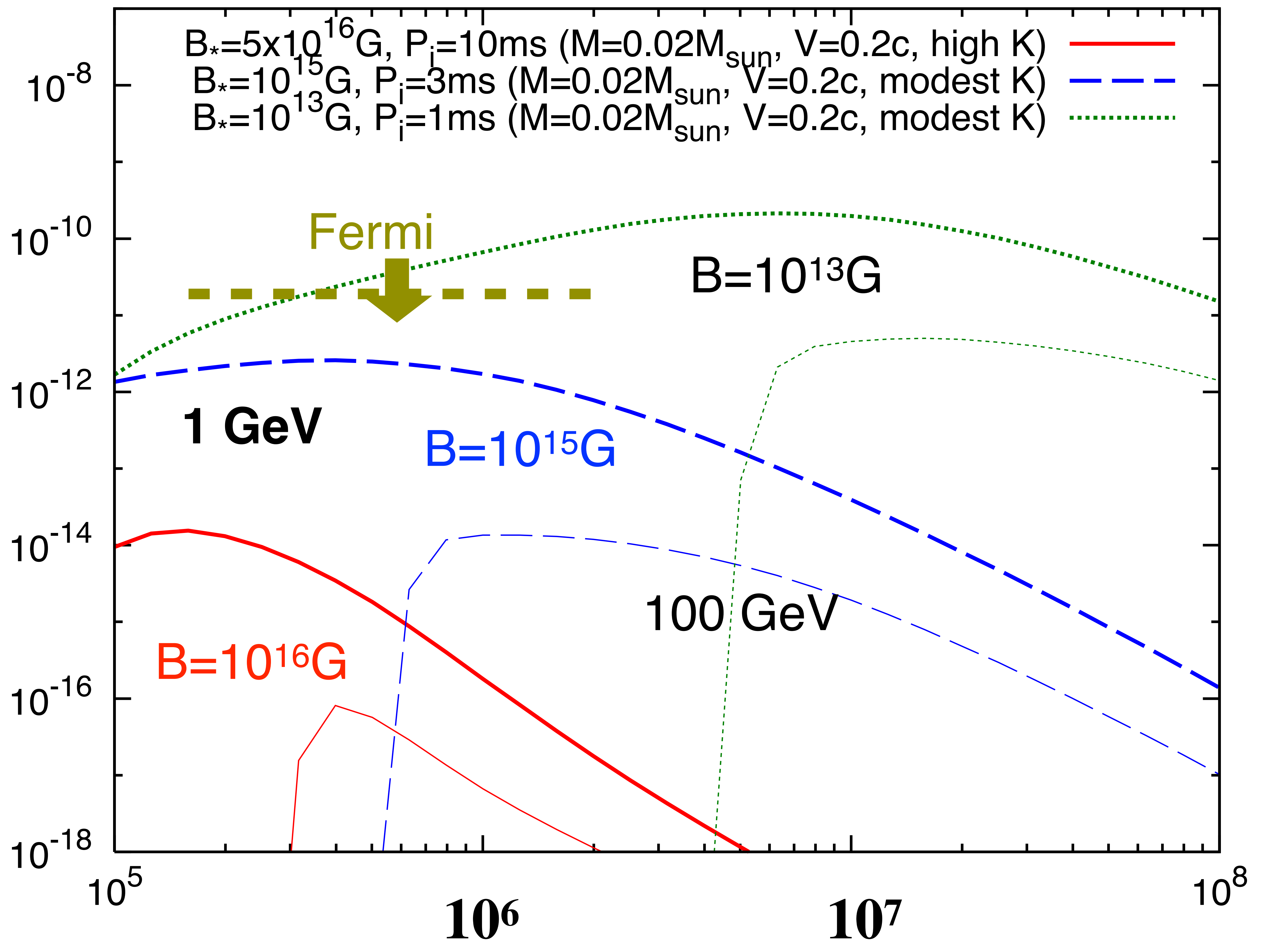
EM counterpart powered by remnants

Murase et al. 2018 (incl. SSK)

- X-ray Light Curve



- γ-ray Light Curve



- Very bright X-rays & γ-rays unless B >10^{16} G for P < 10 ms
- GW170817: B should be very high (> 10^{16} G) or lifetime of magnetar should be short

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Summary

- Binary neutron star mergers have been discussed as multimessenger sources, 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 ν 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