Sub-photospheric GeV-TeV Neutrinos from Gamma Ray Burst Jets : Impacts of Central Engine Time Variabilities

GeV-TeVニュートリノを用いた GRB駆動機構の時間変動・ジェット中の中性子量の推定

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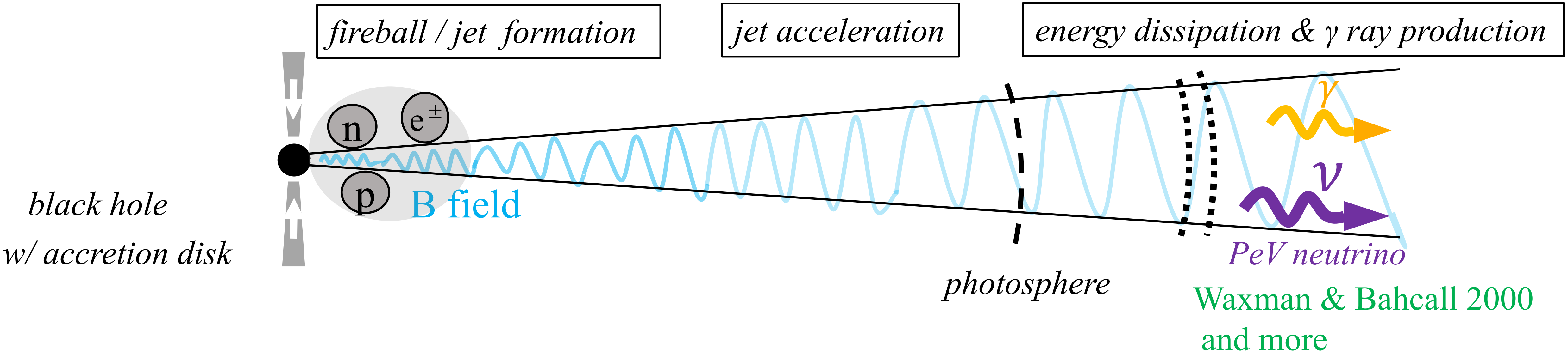
Gamma Ray Burst (GRB)

✓"Brightest" electromagnetic radiation $L_{iso} \sim 10^{52}$ erg/s in MeV γ ray

✓Relativistic jet   v > 0.9999 c (Lorentz factor $\Gamma \sim$ 100-1000)

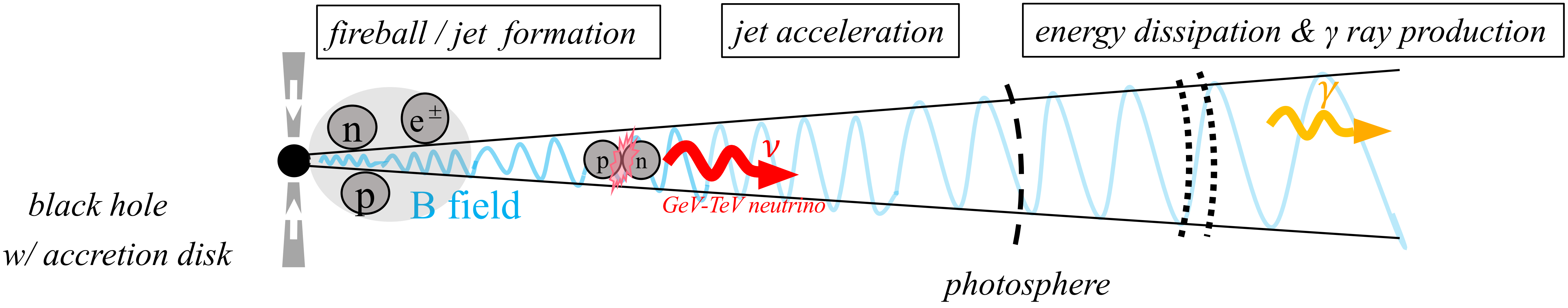
The fireball model for GRBs



disk … high $\dot{M}$ → thermal equilibrium state …neutron rich

a comparable number of neutrons to protons in the jet

Unsolved problems in GRBs



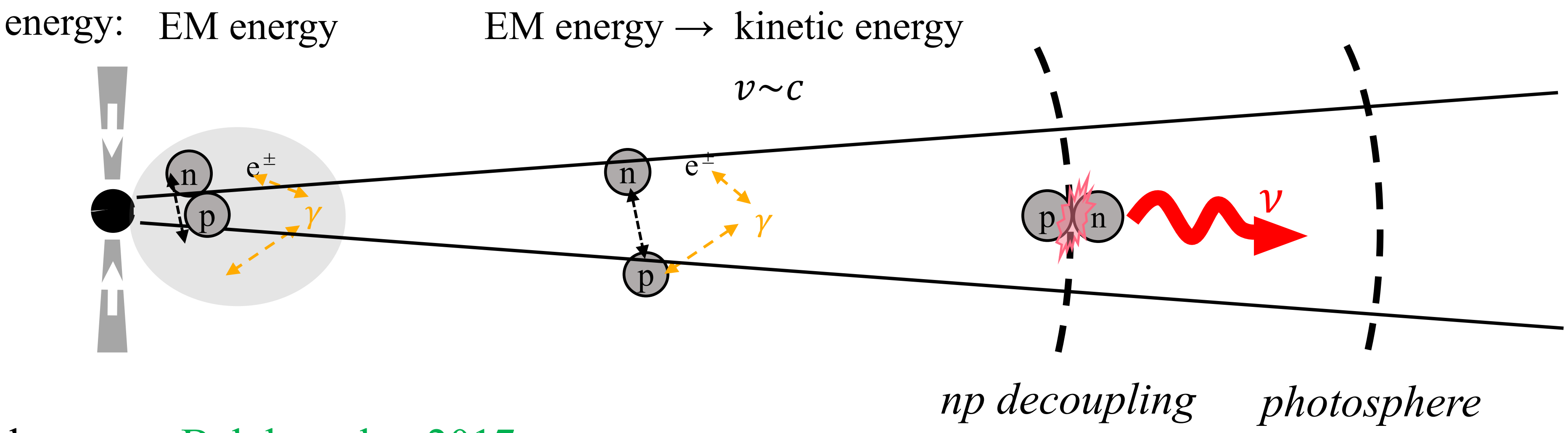
1. Baryon loading … where & how
2. Acceleration mechanism
3. Radiation mechanism

Messenger from sub-photospheric dissipation can be the key?

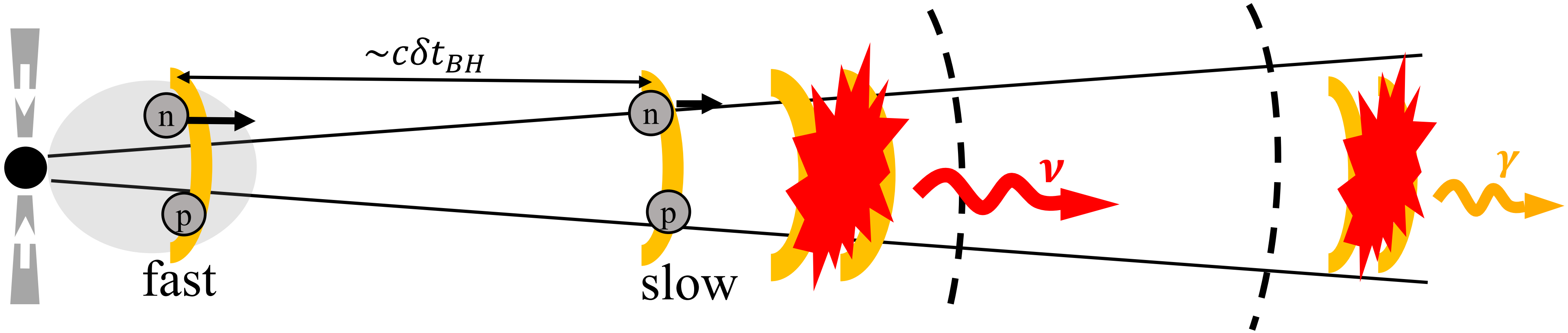
GeV-TeV ν !

Sub-photospheric dissipation via inelastic proton-neutron collisions

(1) Proton-neutron decoupling   Bahcall & Meszaros 2000

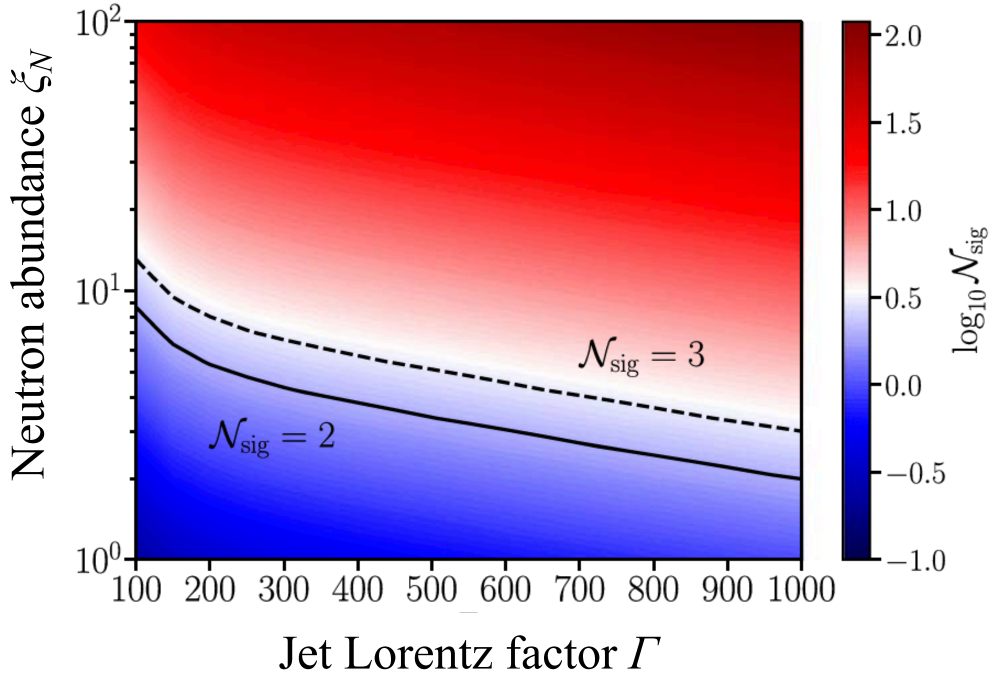


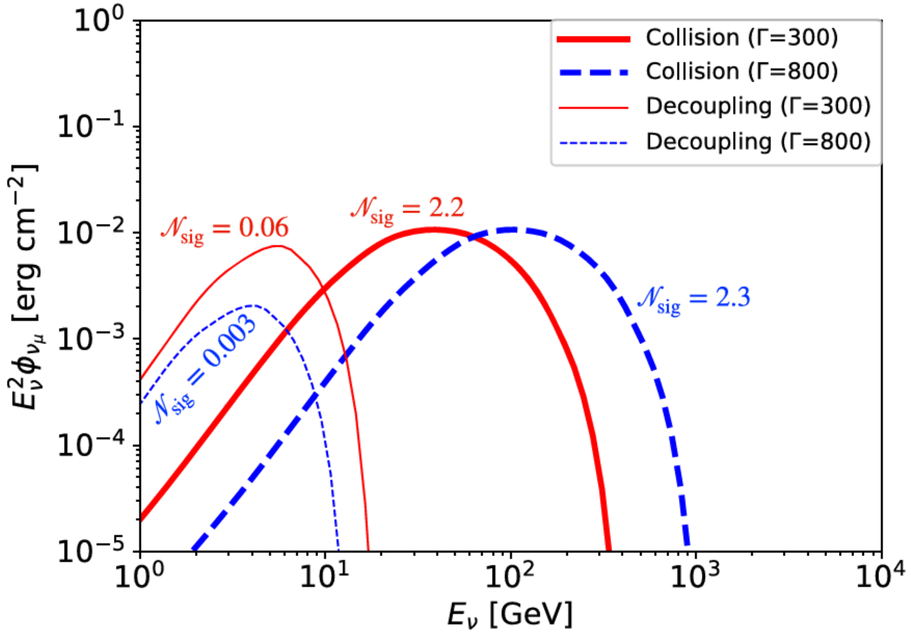
(2) Internal shocks   e.g., Beloborodov 2017



GeV-TeV neutrino astrophysics with BOAT GRB

Murase et al 2022, Ice Cube collaboration2022

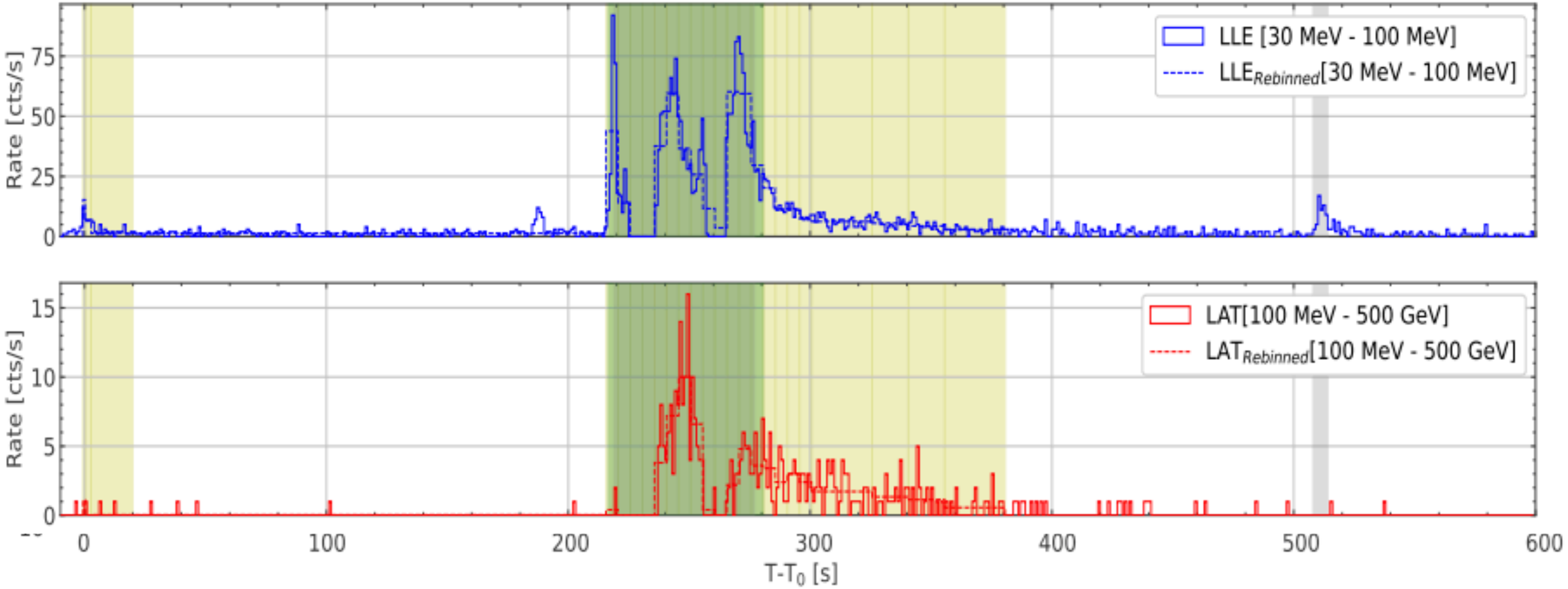




- ✓ A meaningful constraint on the neutron abundance in the jet was obtained for the first time!
- ✓ The theoretical template of the GeV-TeV neutrino spectrum is calculated based on the "one-zone" model, i.e., decoupling and collisions in a uniform jet with a set of constant Lorentz factor and relative velocity.

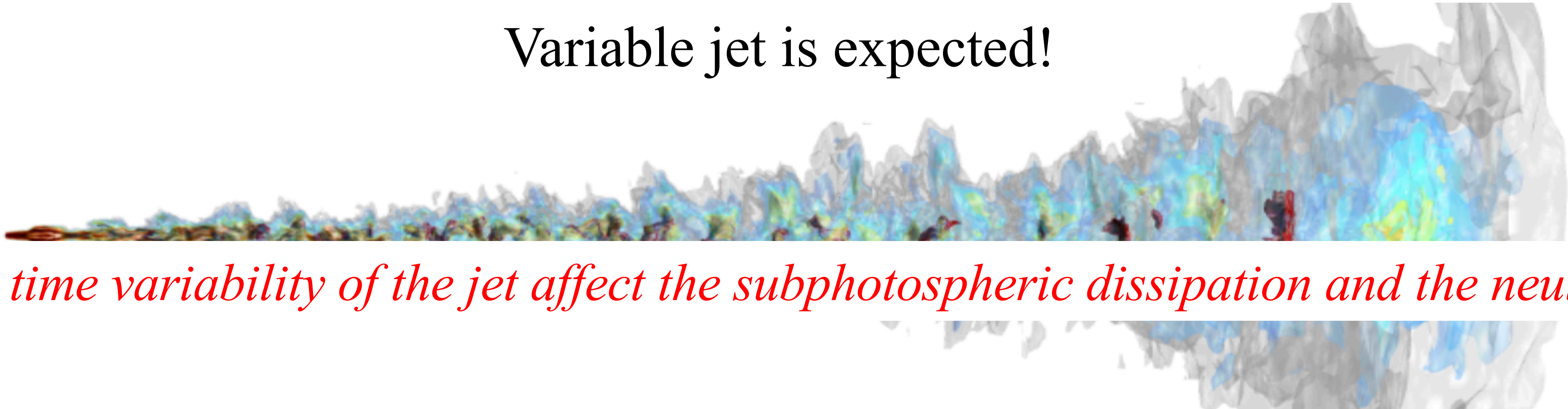
Motivation of this study

The gamma-ray light curve of the brightest of all time (BOAT) GRB 221009A Fermi LAT collaboration 2024



Variable jet is expected!

Gottlieb+ 2021



Q: How does the time variability of the jet affect the subphotospheric dissipation and the neutrino emission?

The Monte Carlo simulation of a variable (long-)GRB jet

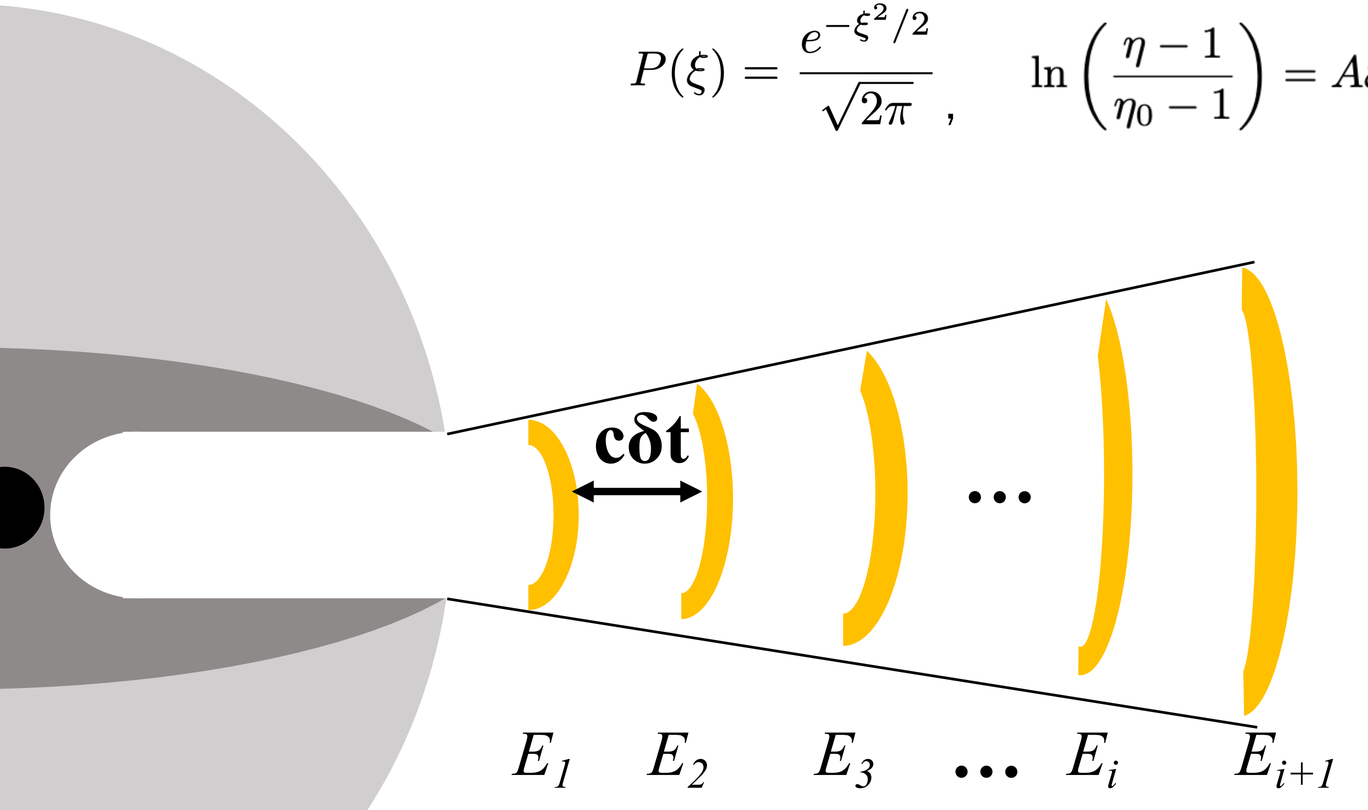
e.g., Kobayashi et al 97; Beloborodov 00

① Modeling of the time variability

- ✓ Variability timescale δt **δt = 1ms, 10ms, 100ms**
- ✓ Lognormal distribution of the baryon loading

$$P(\xi) = \frac{e^{-\xi^2/2}}{\sqrt{2\pi}}, \quad \ln\left(\frac{\eta - 1}{\eta_0 - 1}\right) = A\xi.$$

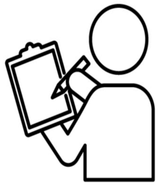
A = 1, 2, 4



$$E_i = \eta_i M c^2$$

② Record

- ✓ Internal shocks
- ✓ Proton-neutron decoupling



③ Calculate neutrino spectra with geant4

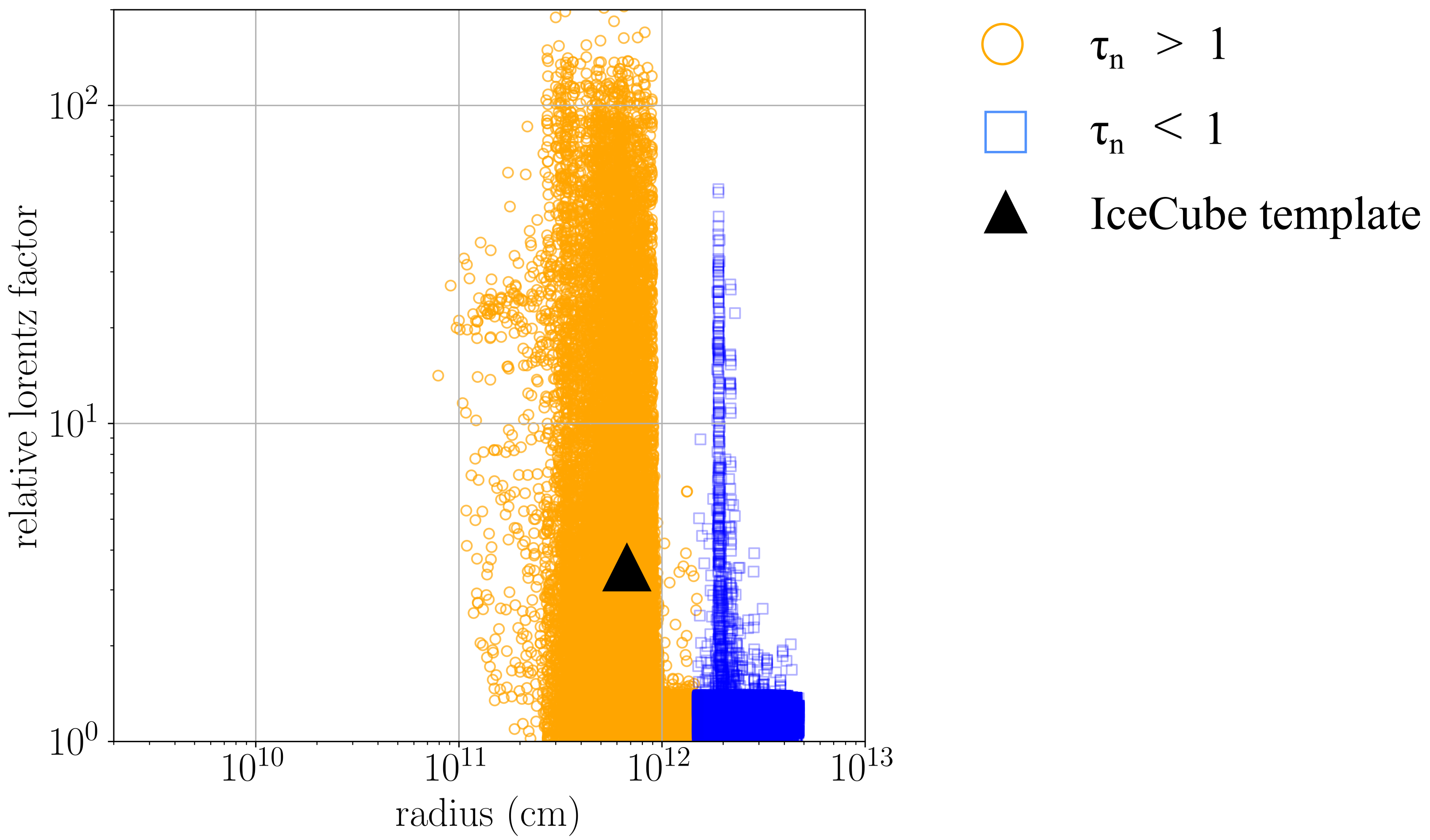
GEANT4 A SIMULATION TOOLKIT

We newly include the dissipation processes at sub-photosphere!

Results : radii and relative Lorentz factors of the internal shocks

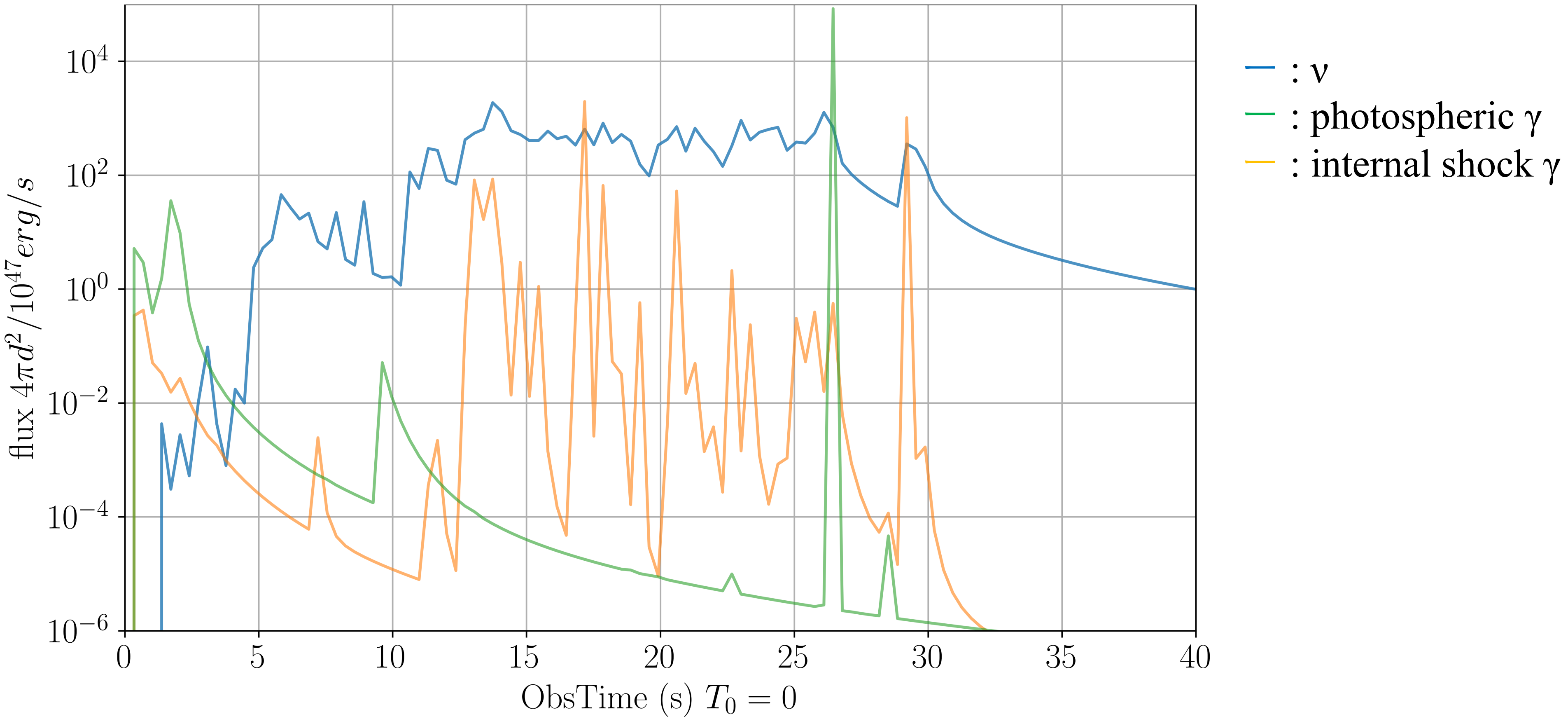
$A = 4$, $\delta t = 10$ ms, $\eta_{av} \sim 500$

$$\Gamma_{rel} \sim 0.5 \frac{\Gamma_{fast}}{\Gamma_{slow}}$$



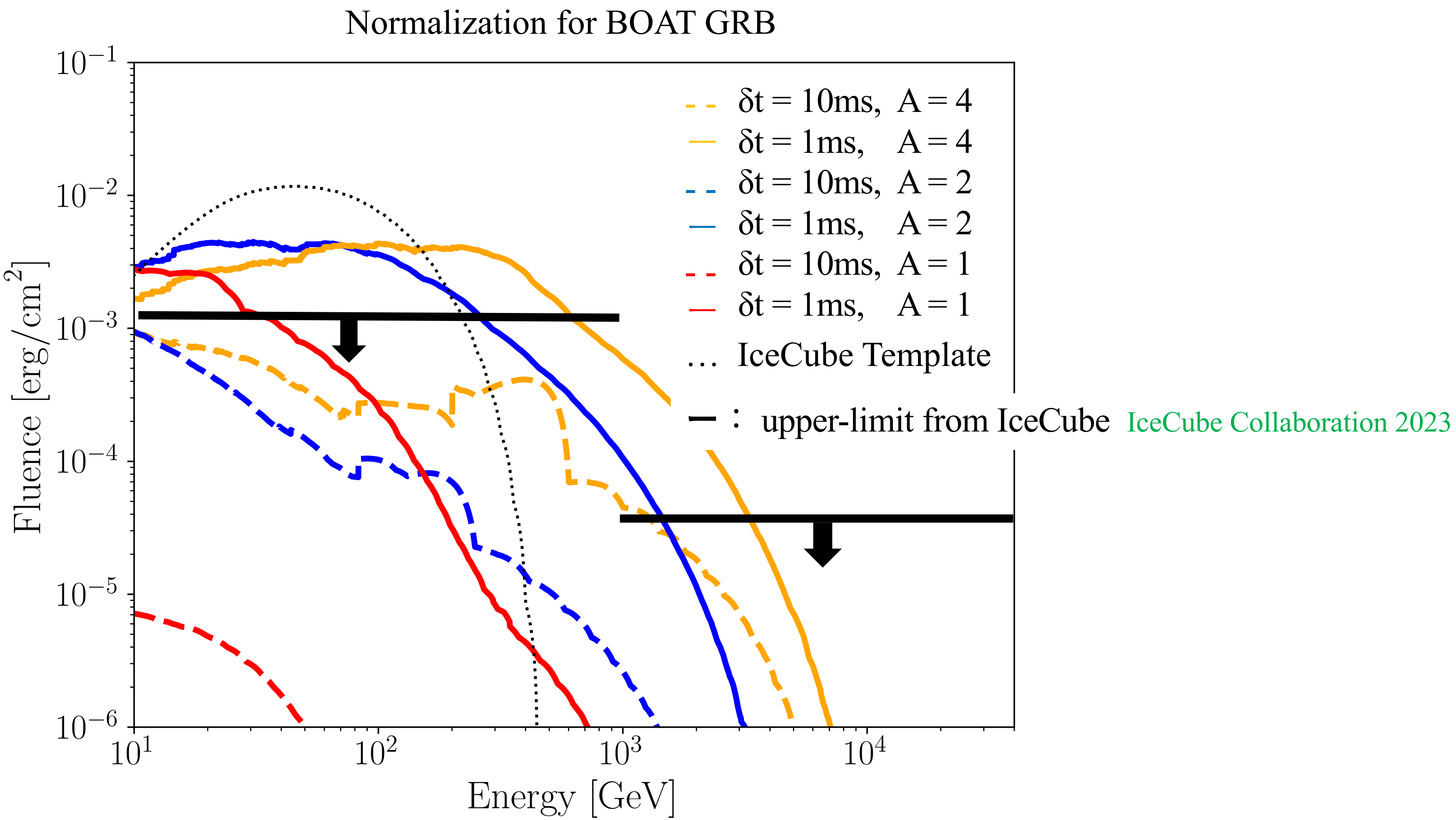
Due to the time variability, the inelastic proton-neutron collisions occur at various radii and relative Lorentz factor.

Results : Light Curve



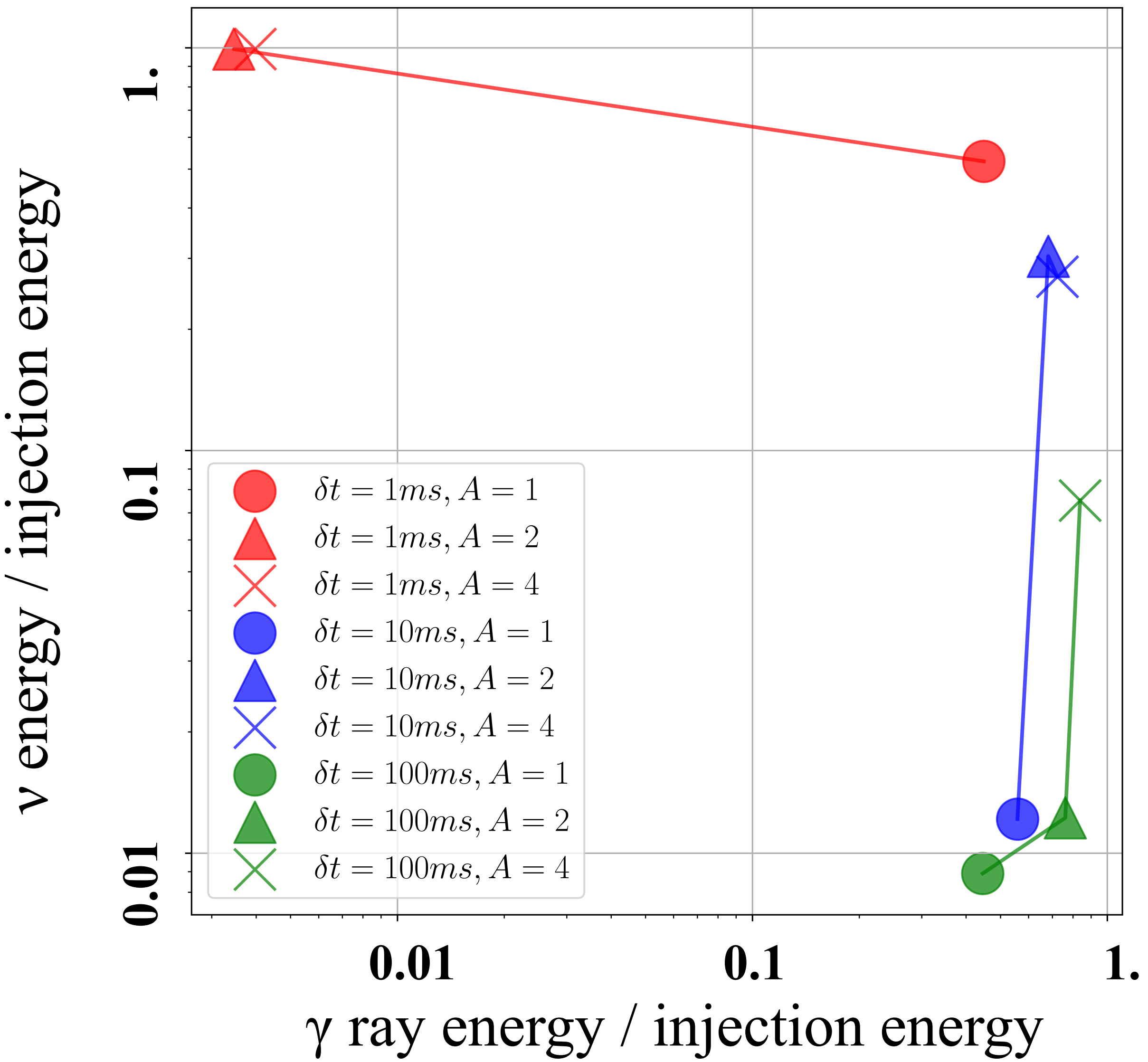
Photons and neutrinos arrive almost simultaneously.

Result : GeV-TeV Neutrino energy spectra



- *Even for a given jet luminosity and neutron abundance, more variable, i.e., smaller δt or larger A, more neutrinos!*
- *The neutrino spectra becomes broader both at lower and higher energies.*

Results : efficiency of neutrinos V.S. efficiency of gamma rays



MeV gamma bright = GeV-TeV neutrino dim and vice versa

To detect GeV-TeV neutrinos, less luminous GRBs are rather expected.

Summary

- GeV-TeV neutrinos are produced at Sub-photospheric dissipation via inelastic proton-neutron collisions , which are sensitive to how the baryons are loaded in and accelerated in the fireball, which cannot be directly probed by electromagnetic waves.

- We study how does the time variability of the jet affect the subphotospheric dissipation and the neutrino emission?

- In Monte Carlo simulation of variable jet, we newly include the dissipation processes at sub-photosphere.

- Due to the time variability, the inelastic proton-neutron collisions occur at various radii and relative Lorentz factor.

- Increasing the variability causes the sub-photospheric dissipation to become too strong, resulting in less energy being transferred to the prompt and afterglow phases.
  ⇨ MeV gamma bright = GeV-TeV neutrino dim and vice versa,