Numerical Studies of High-Energy Neutrino Emission from a Radiatively Inefficient Accretion Flow with a 3D GRMHD Simulation

Kawashima & Asano 2025, ApJ, 989, 155

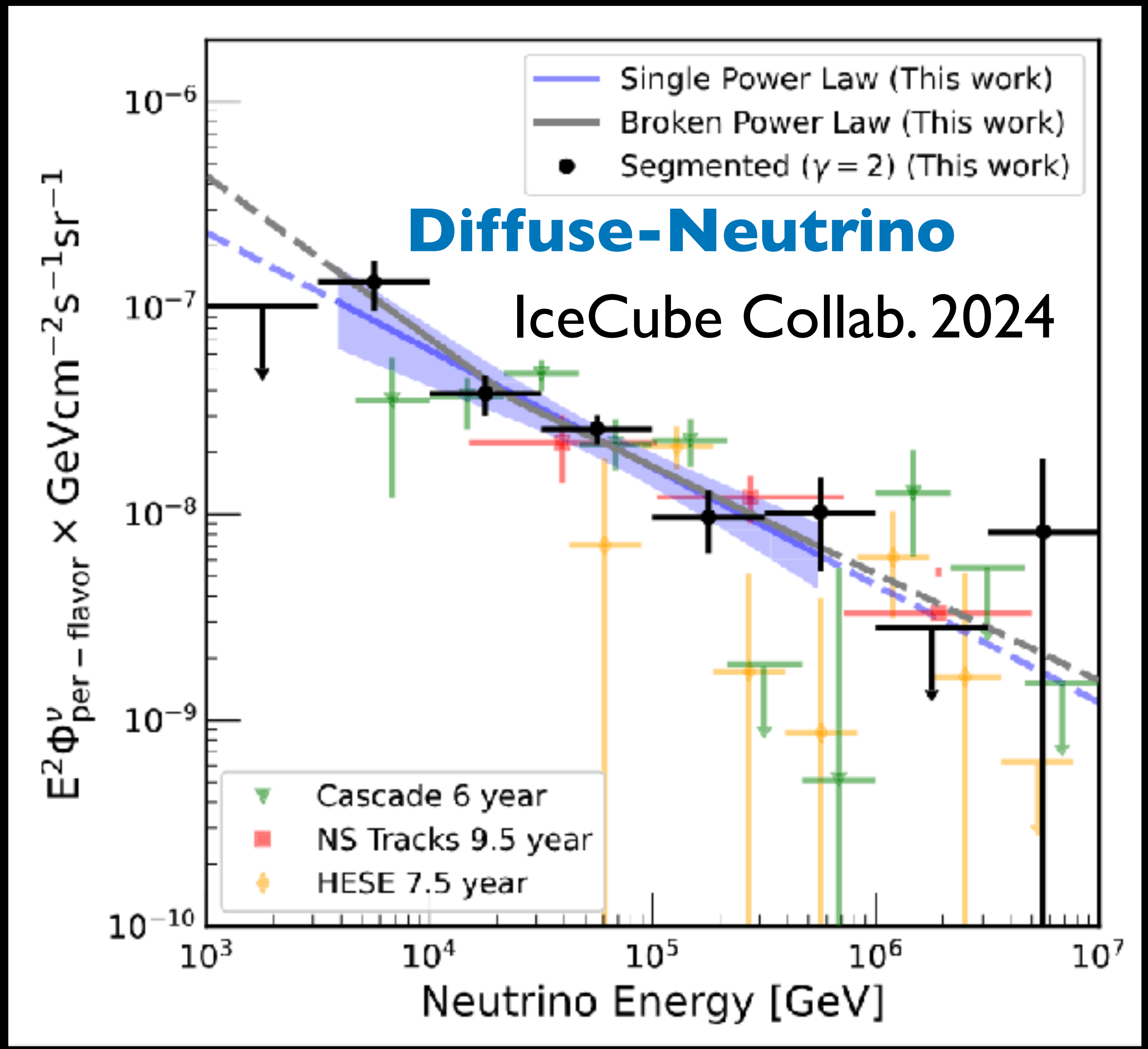
Tomohisa KAWASHIMA (NIT Ichinoseki Coll.)

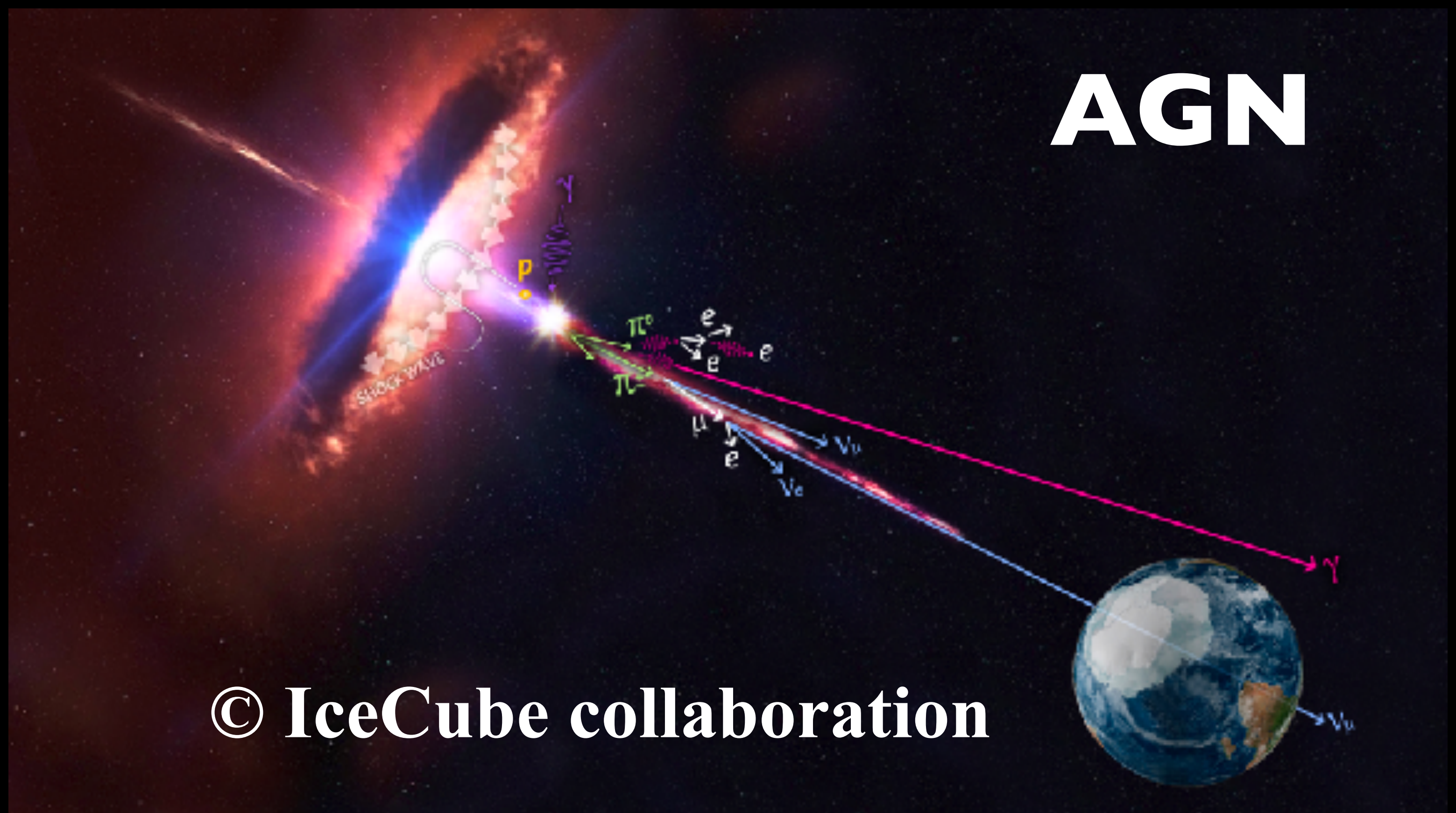
In collaboration with

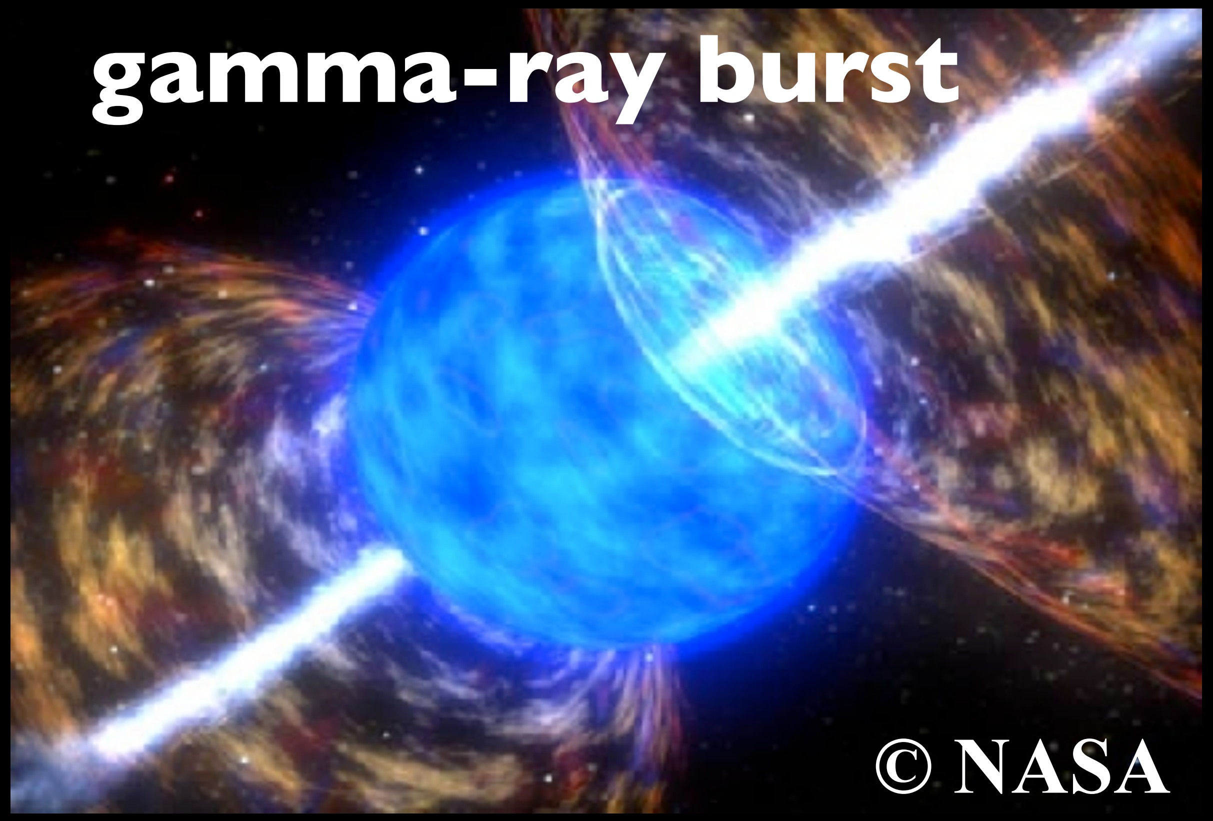
Katsuaki ASANO (ICRR, U. Of Tokyo)

Possible origin of extragalactic HE neutrino

- IceCube has detected extragalactic neutrinos, but has not yet fully constraint the neutrino sources.
  - ✓Active Galactic Nuclei (AGN)
  - ✓Galaxy Clusters
  - ✓Starburst Galaxies
  - ✓Low Luminosity Gamma-Ray Bursts

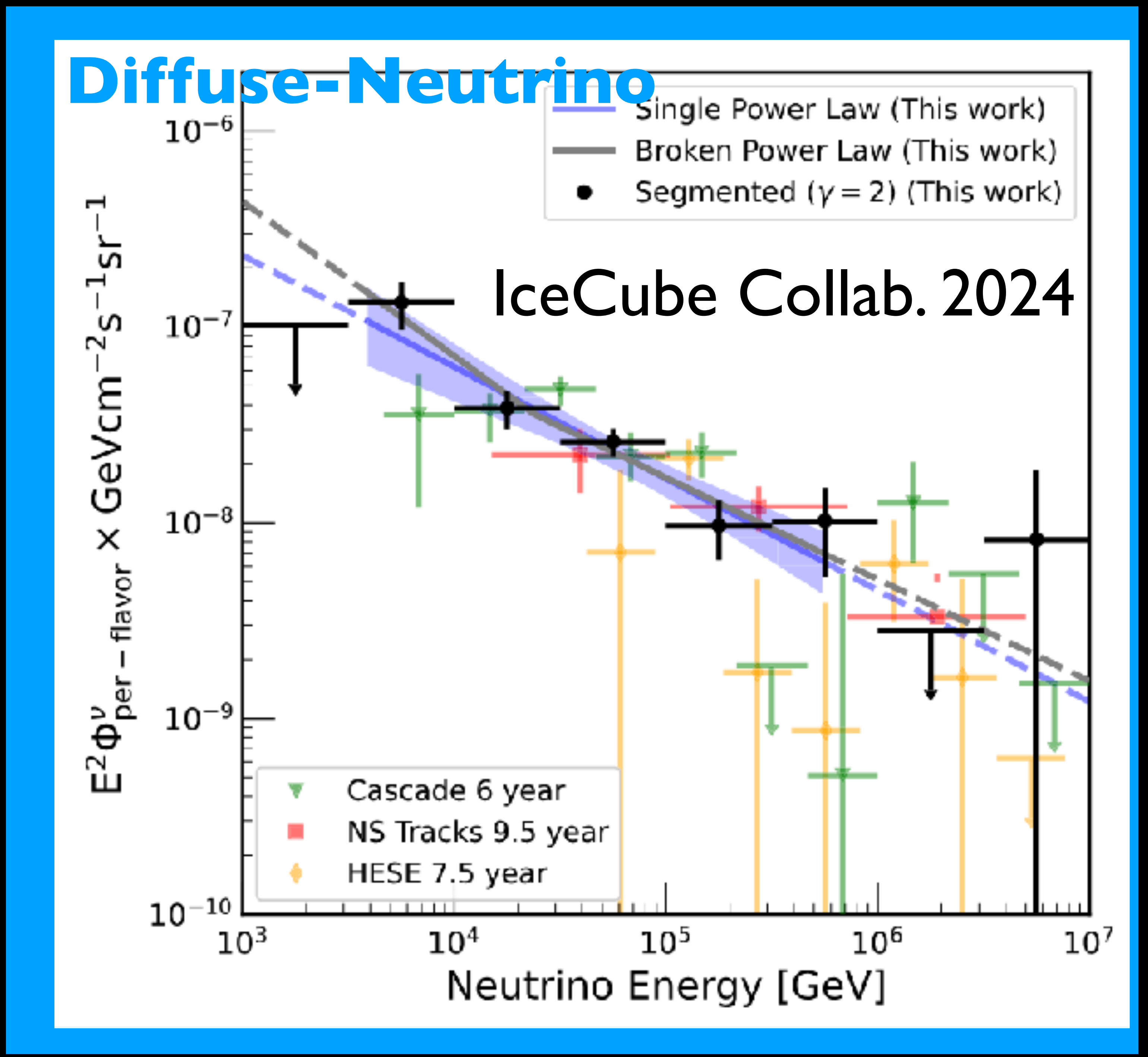






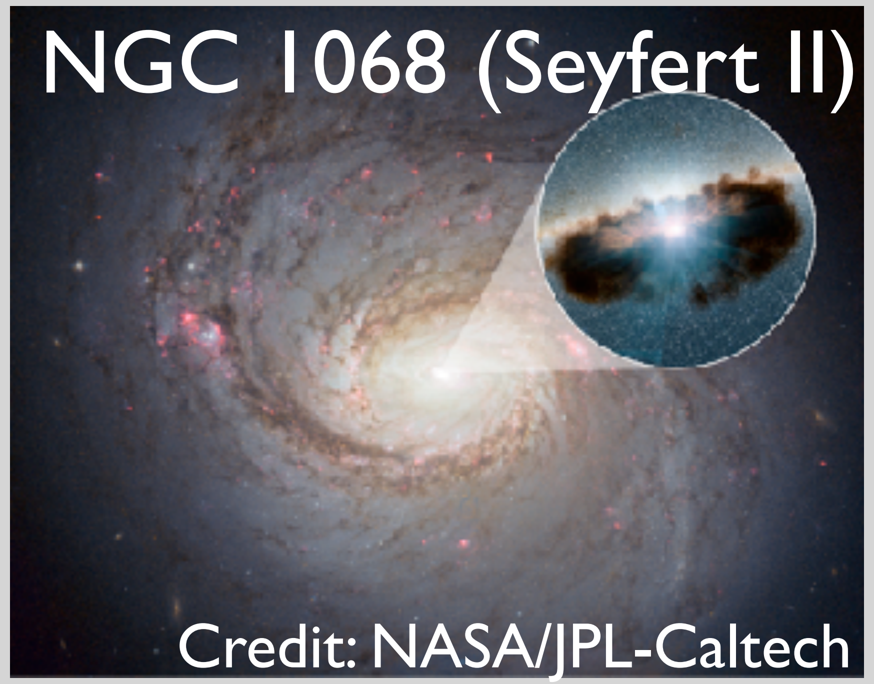
Diffuse-Neutrino SED

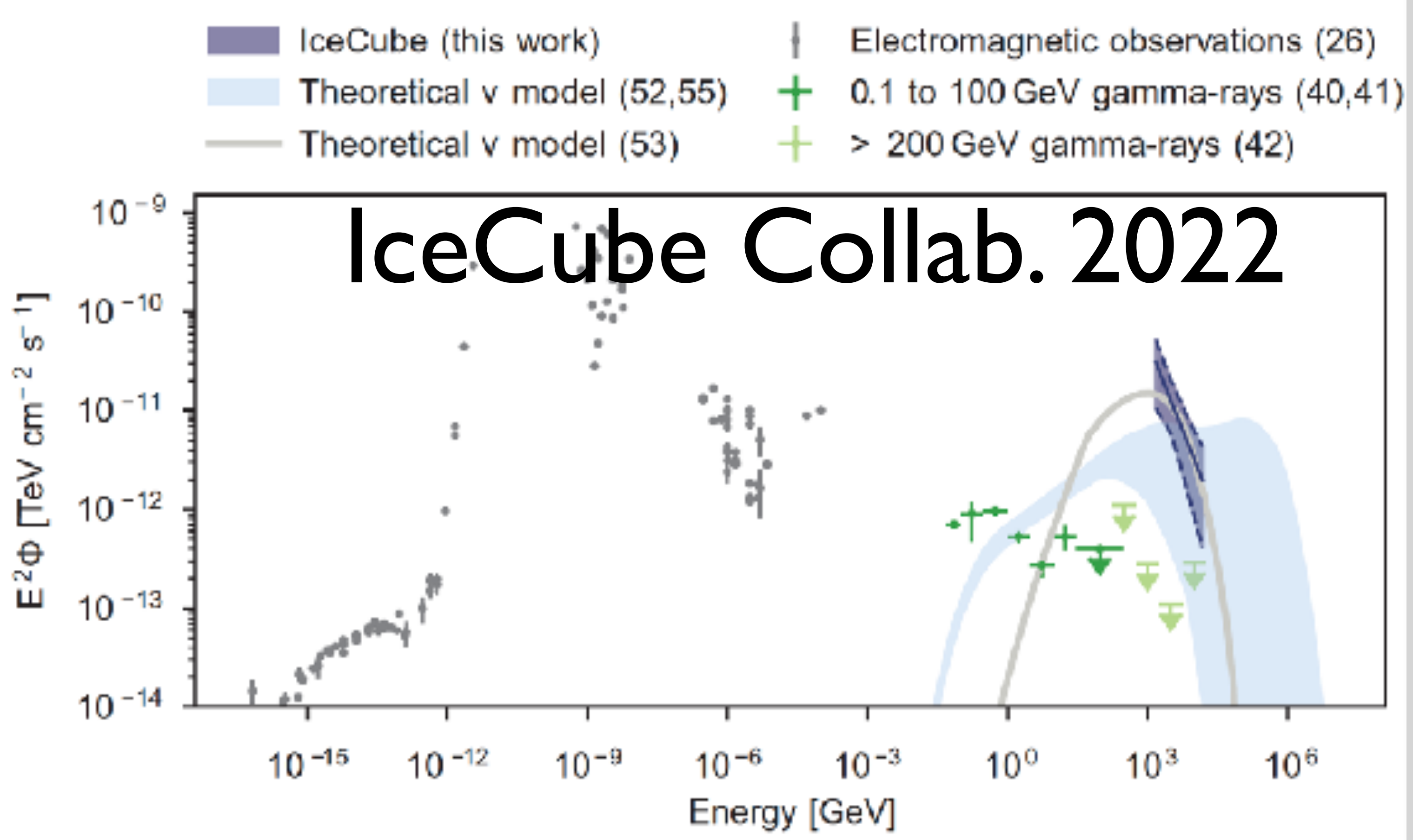
- Diffuse neutrino: moderately flat (power-law index ~ 2.64) SEDs (e.g., IceCube Collab. 2024)
- A neutrino hotspot NGC1068 detected by a decadal survey: steep(power law index ~3) SED (e.g., IceCube Collab. 2022)
  → Various types of neutrino SED may exist
- Models for neutrino emission in AGNs
  ✓(Radiatively Inefficient) Accretion Flows (e.g., Kimura + 2015)
  ✓Disk-Corona (Inoue Y. + 2020, Murase + 2020, Kimura + 2022)
  ✓Disk-Wind (Inoue S. 2022)
  ✓Weak Jet (Fang+2023)



We consider radiatively inefficient accretion flow model for low-luminosity AGN, in this work.

c.f.
neutrino hotspot

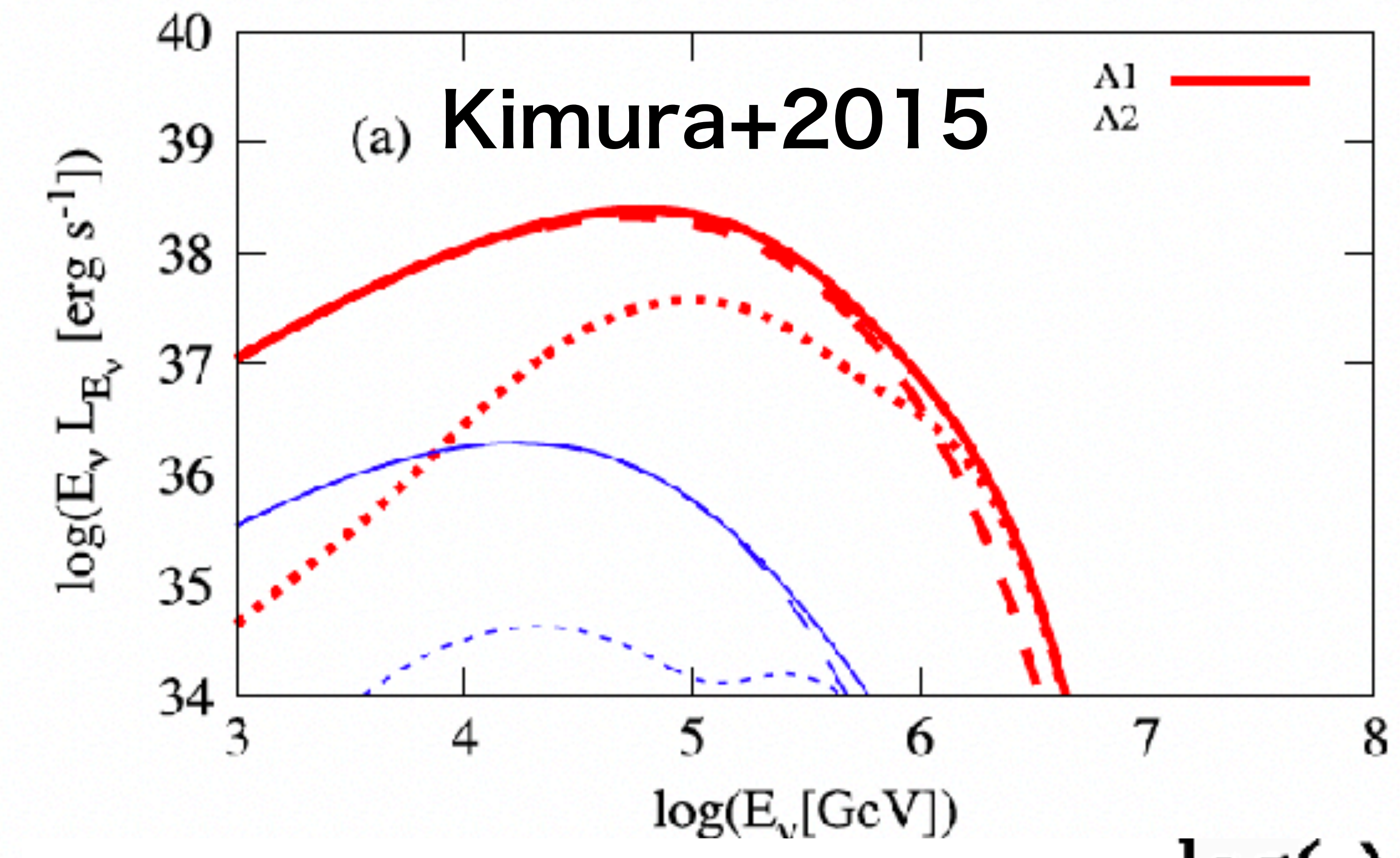




Purpose of This Work

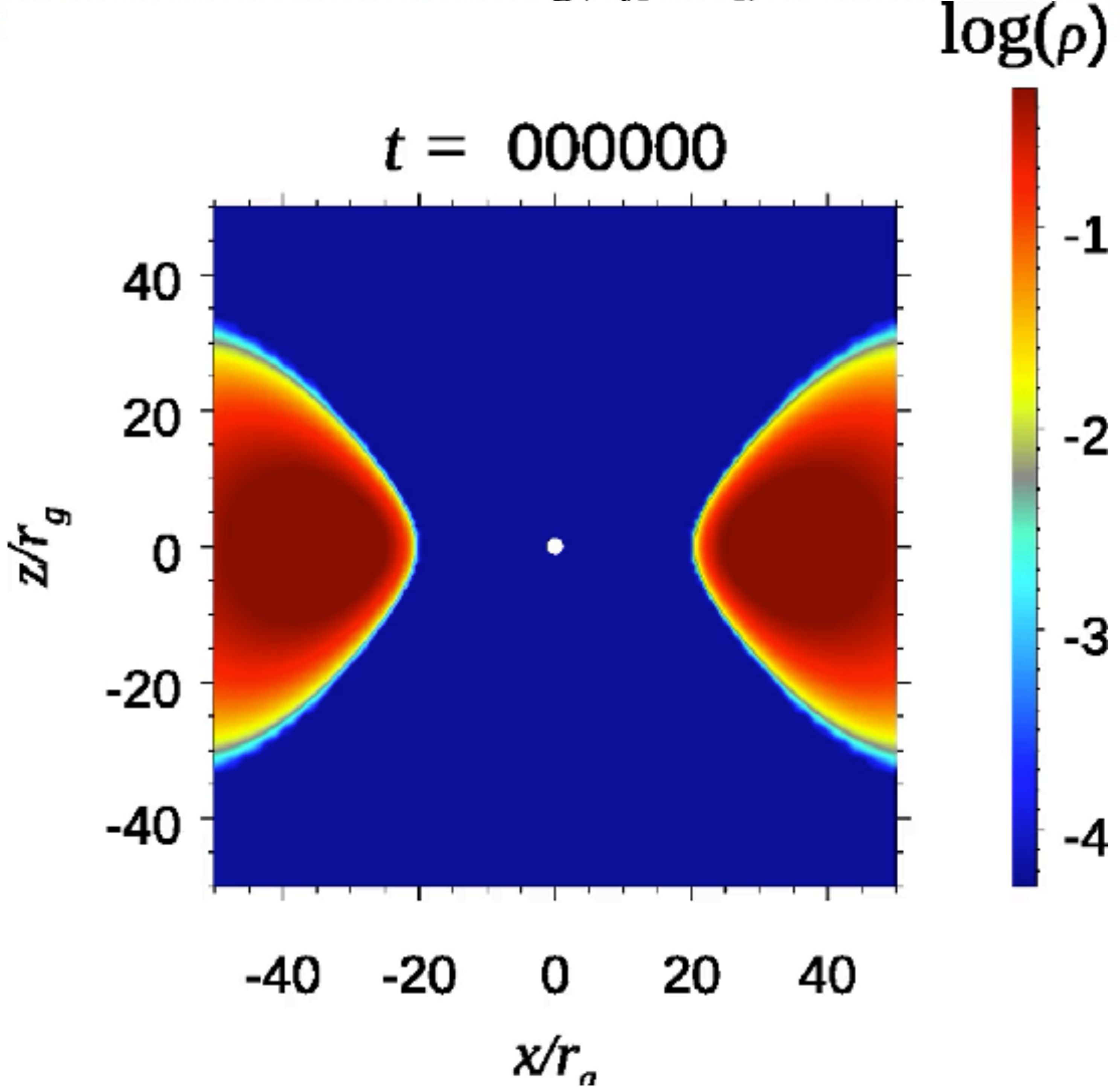
- There exists a pioneering work on neutrino emission in accretion flows (e.g., Kimura+2015, see also Dermer+ 1996)
- However, single-zone (1-zone) approximation has been adopted in all of previous works.

Q: How does the global structure of the accretion flows affect the neutrino SEDs？



Purpose of this work：

Studying the global effect of accretion flow on HE neutrino SEDs considering CR acceleration (via kinetic scale turbulences) and neutrino emission via pp collisions.
← 3D genelal relativistic MHD (GRMHD) simulations of accretion flows + CR acceleration & neutrino emission computation [a new code *ν*-RAIKOU (ν-来光) code]



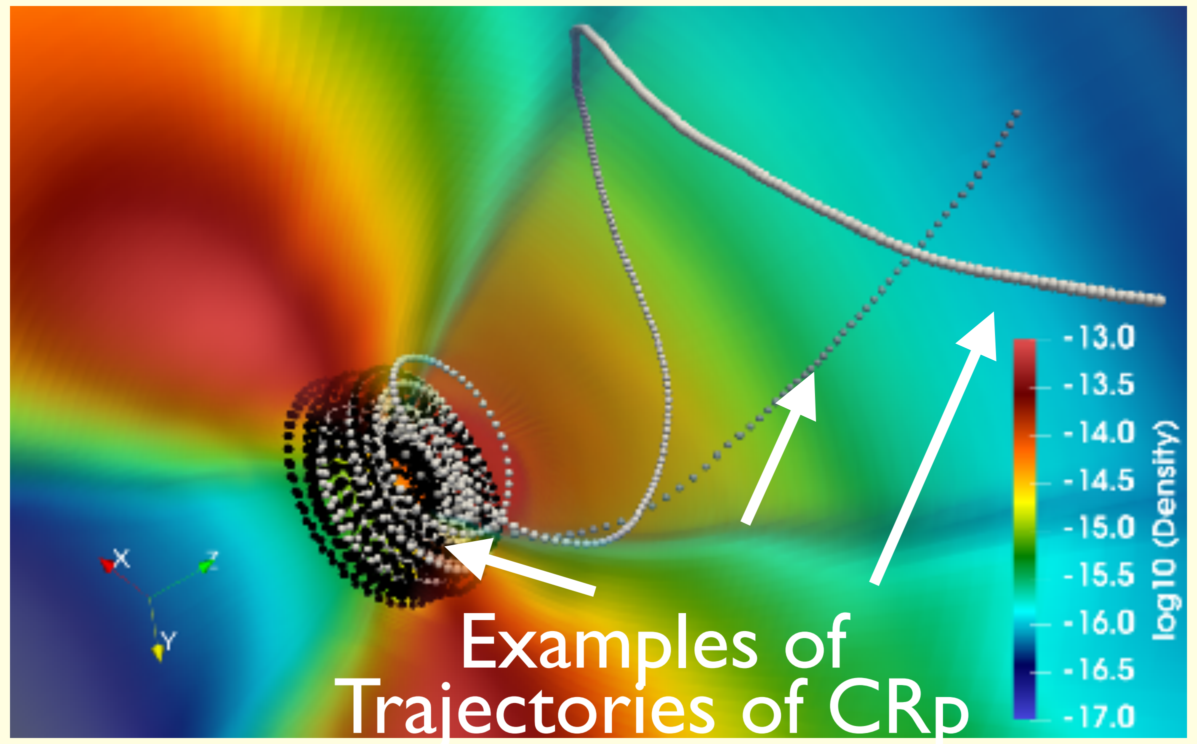
c.f. odríguez-Ramírez + (2019): propagation of CRs and neutrino emission using GRMHD simulation

Computation Method ($M_{\rm BH} = 10^8 M_\odot$, $\dot{M} = 10^{-2} L_{\rm Edd}/c^2$)

(1) Trajectory of tracer particles of Cosmic-Ray proton (CRp) based on 3D GRMHD data

- CRps are treated as Tracer particles (~1 million particles)
- Assumption: CRps moves along the streamlines being trapped by subgrid-scale turbulent B-filed.

  # we are interested in acceleration upto ~PeV (gyro radii < mesh size)
- GRMHD dataset of semi-MAD (moderately magnetized state) (TK+2023) simulated using GR(R)MHD code UWABAMI (Takahashi + 2016).

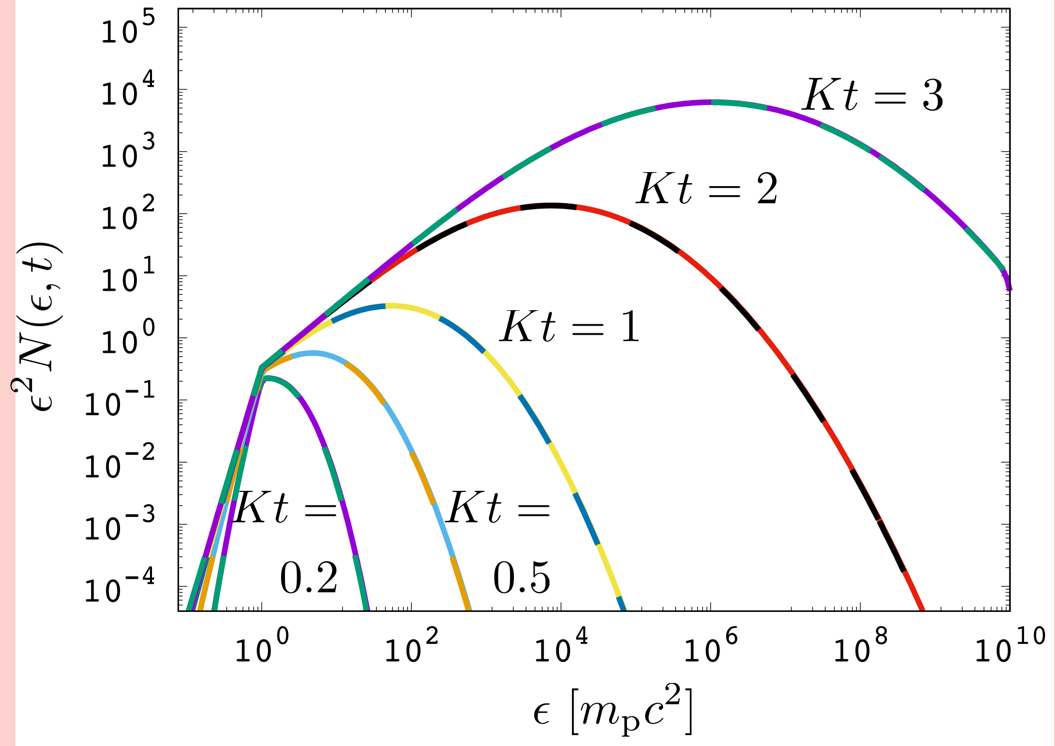


Δt update (sometimes, snapshot update)

(2) Computation of SED of CRp

- **Fokker-Planck Eqs** of tracer particle in the fluid-rest frame.
- Number of Energy Bin: 5600
- **Turbulent Acceleration** w/hard sphere approximation ($D(\varepsilon) = K\varepsilon^2$).
- Compression/expansions effects are also included.

Test calculation comparing w/ Asano & Meszaros (2016)



(3) Computation of Neutrino SED

- ***pp* collisions** of tracer particle of CRps with thermal protons of GRMHD simulation data.
- Gravitational redshift are taken into consideration

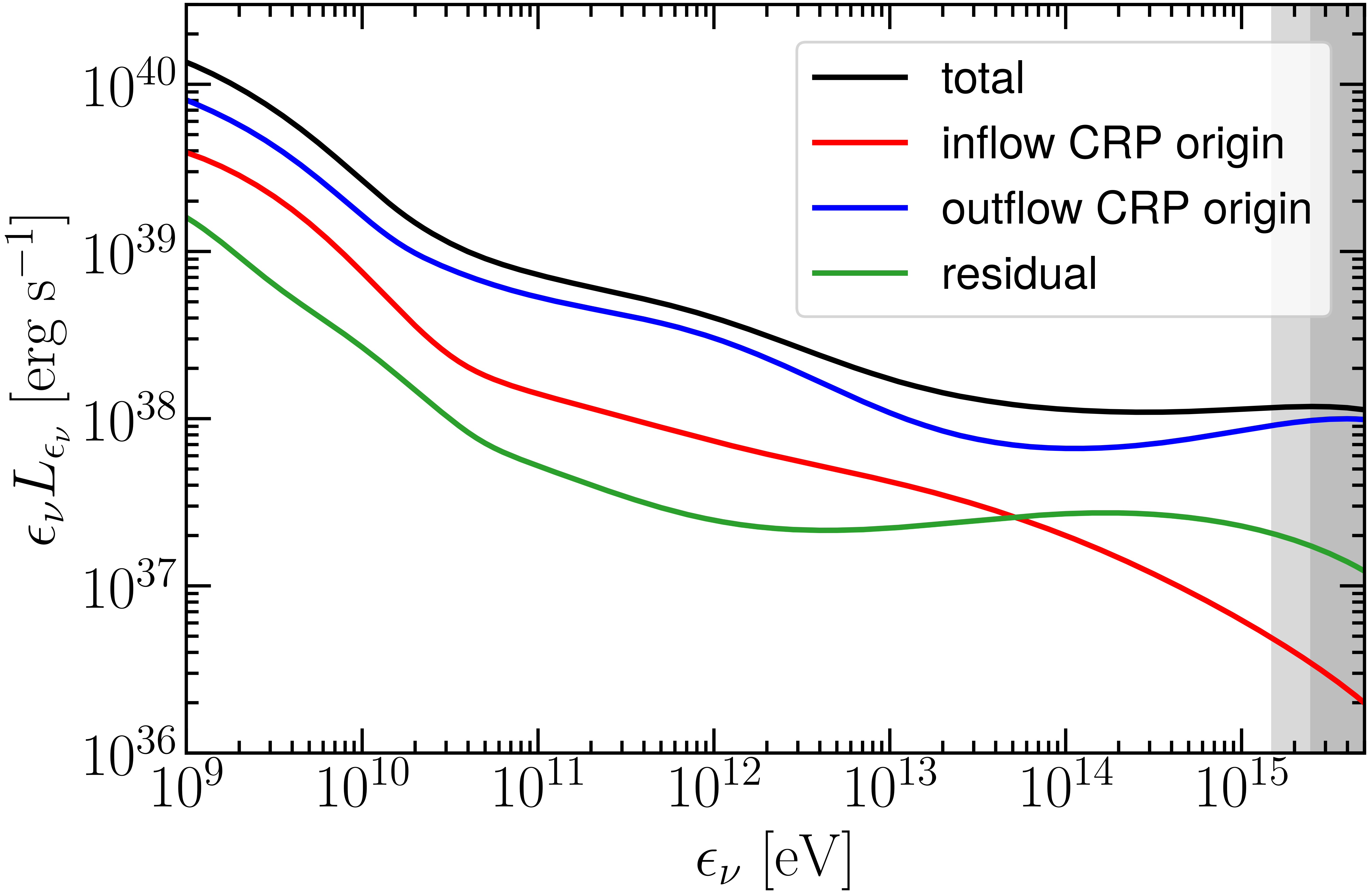
- (1)-(3) are computed with using time-evolved snapshots of simulation data.
- Finally, **Time-averaged** neutrino SEDs are computed

Time-Averaged Neutrino SEDs

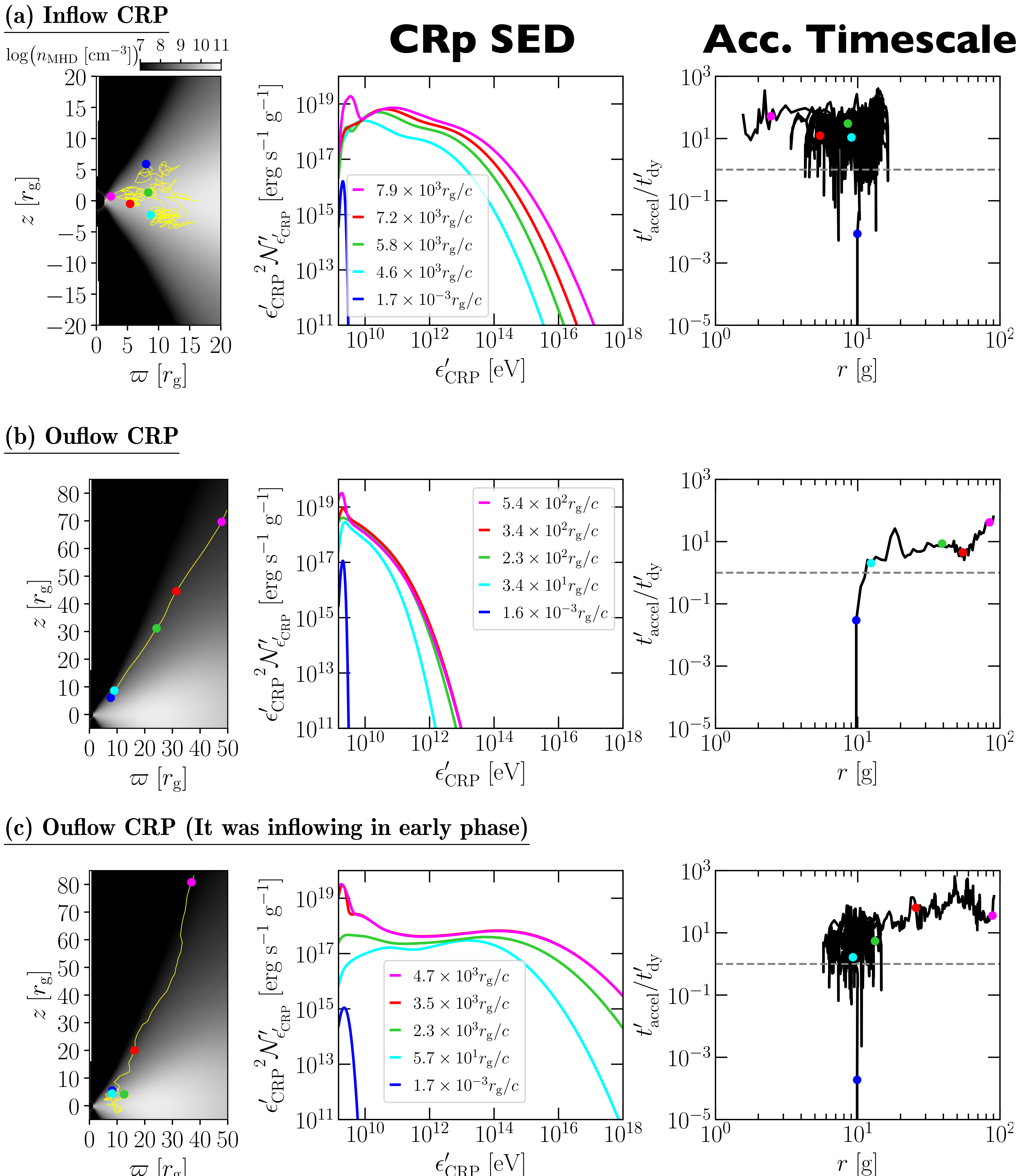
- **SEDs <u>flatter</u> than 1-zone models appear**
- Neutrino SEDs decomposed into origin of CRps in inflow, outflow, (residual)
- Neutrinos originated from (finally)-outflow-CRp $\gtrsim$ inflow-CRp.

pγ are non-negligible →

streamline treatment is not valid →



CRp trajectory & timescale



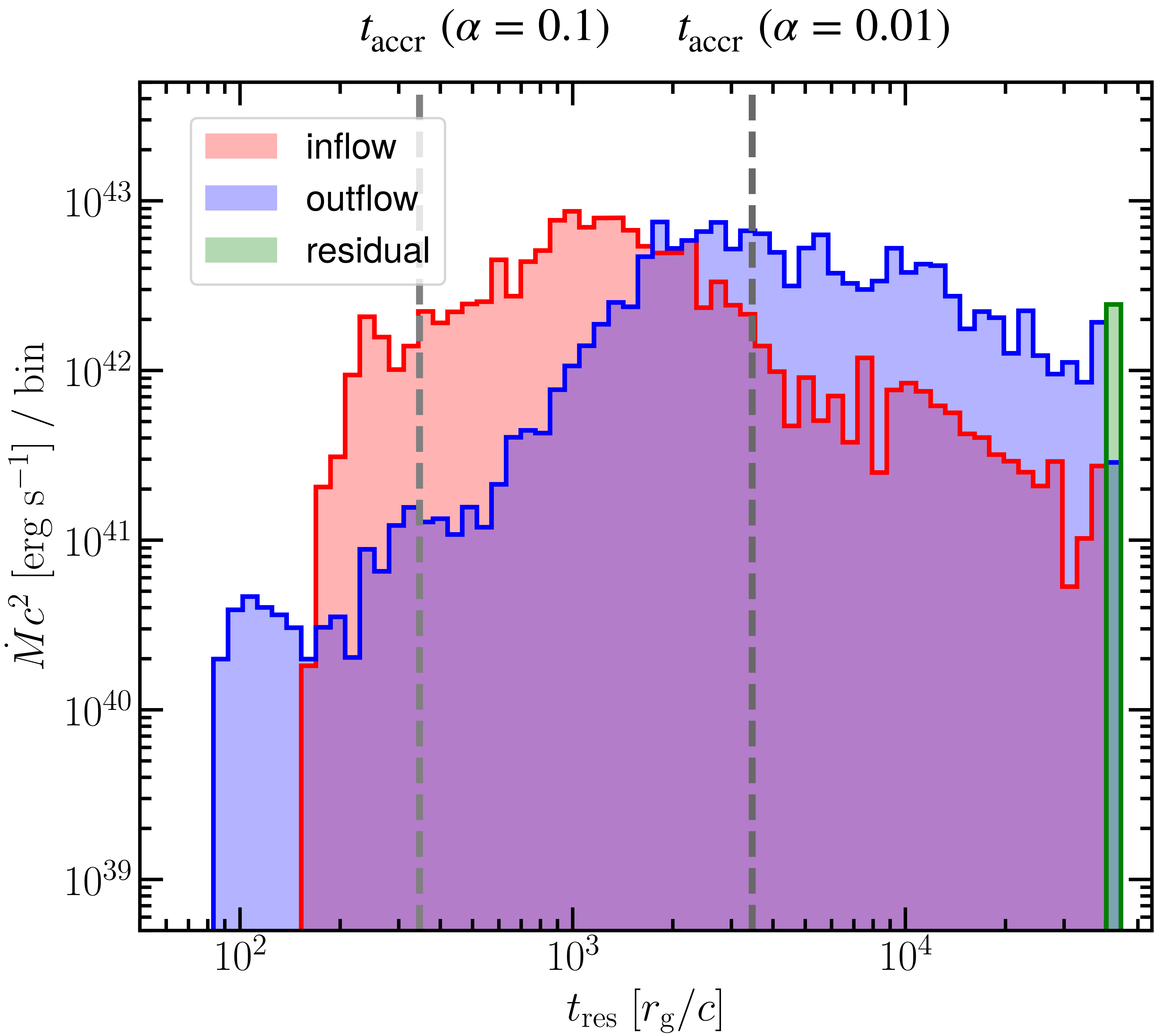
- CRp-SEDs depend on the position and trajectories.
- Summation of various CRp

SEDs are flatter in our global models

Escape timescale from the simulation region

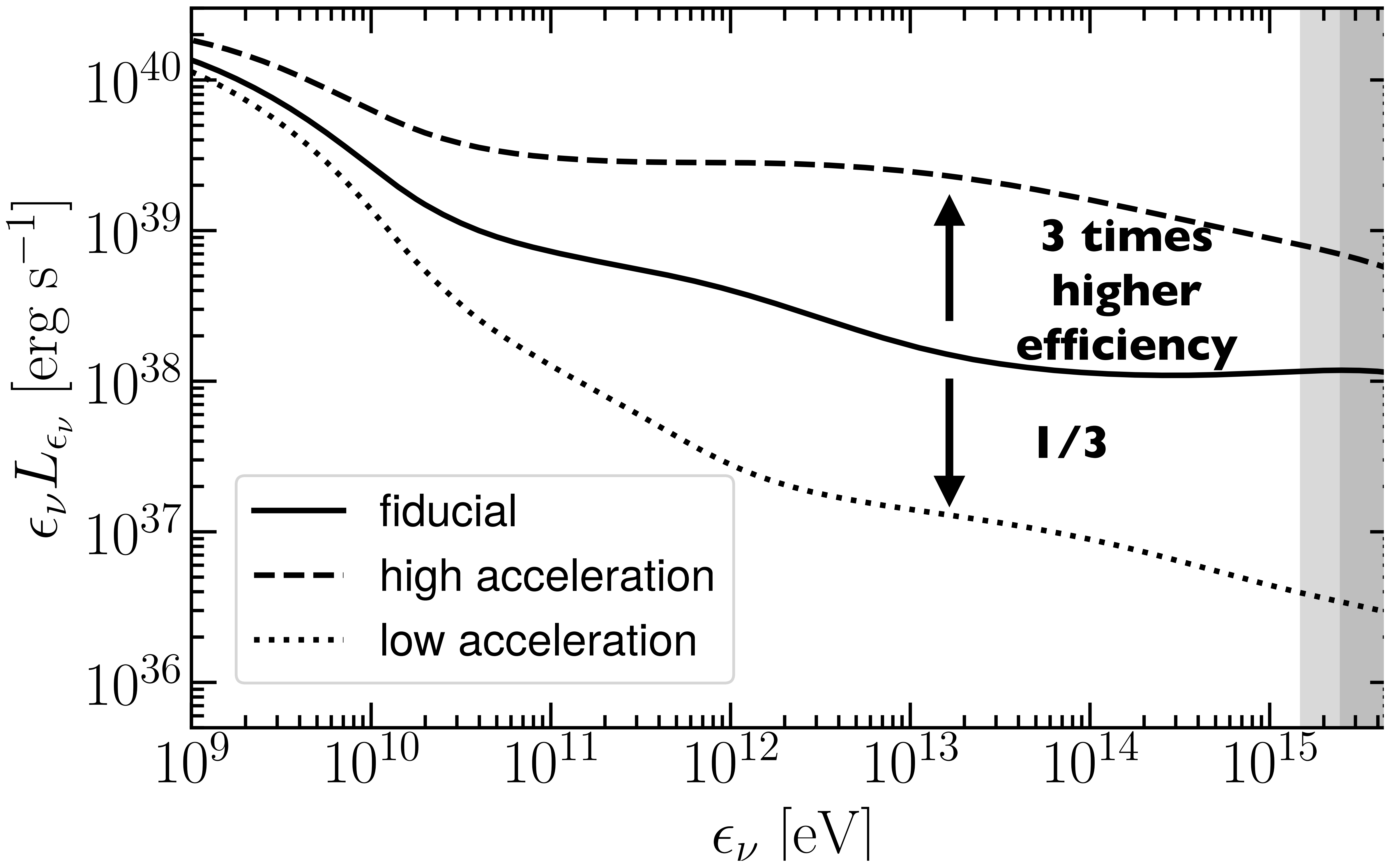
- Accretion timescale agrees well with the escape (swallowed by BH) timescale of inflowing CRps.
- bimodal distribution of Outflowing CRp.

Due to the longer stay of Outflow CRP in the simulation domain, the acceleration works well.
→ hard SED!

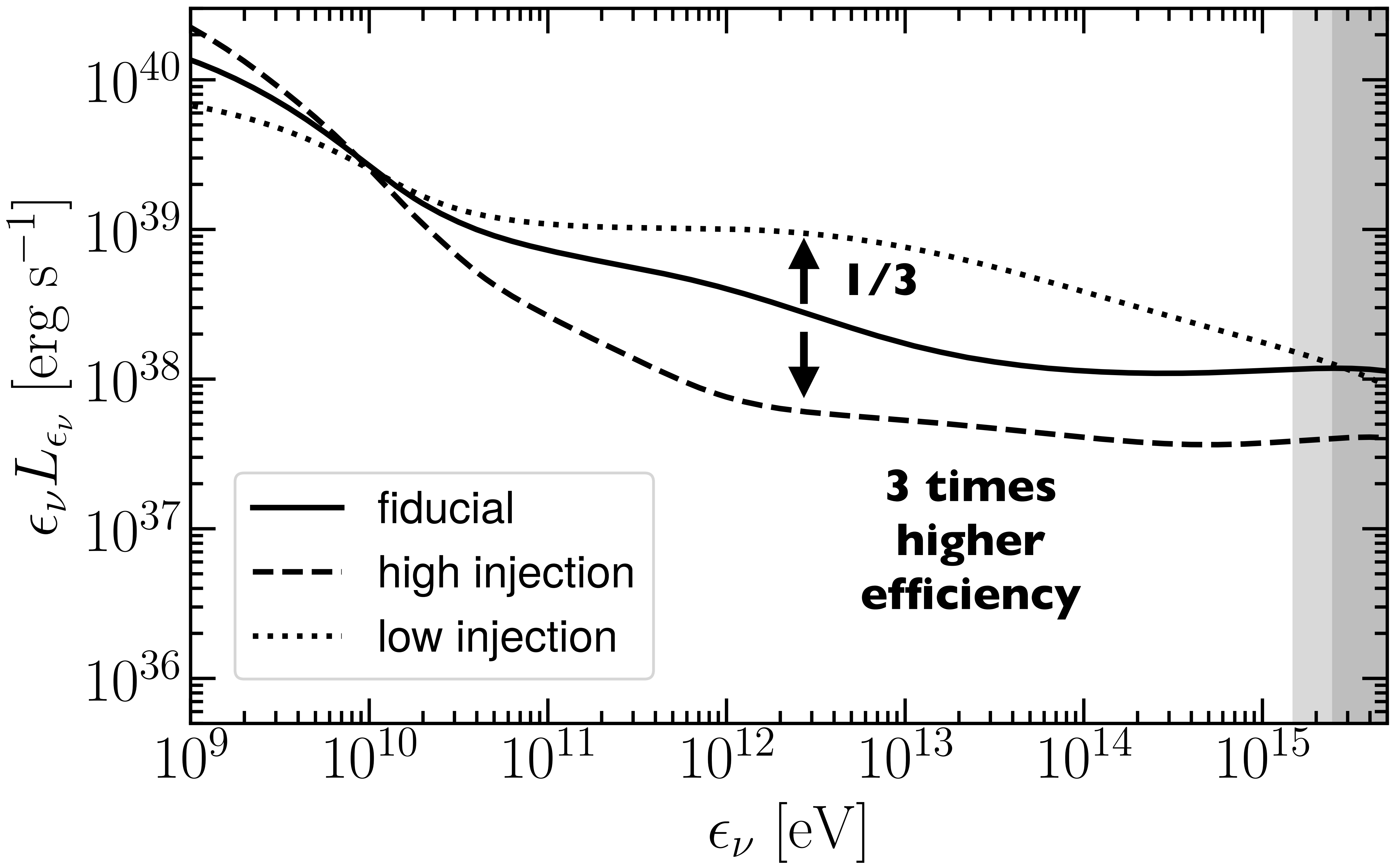


Dependence on the Acceleration/Injection Coefficients

Acceleration

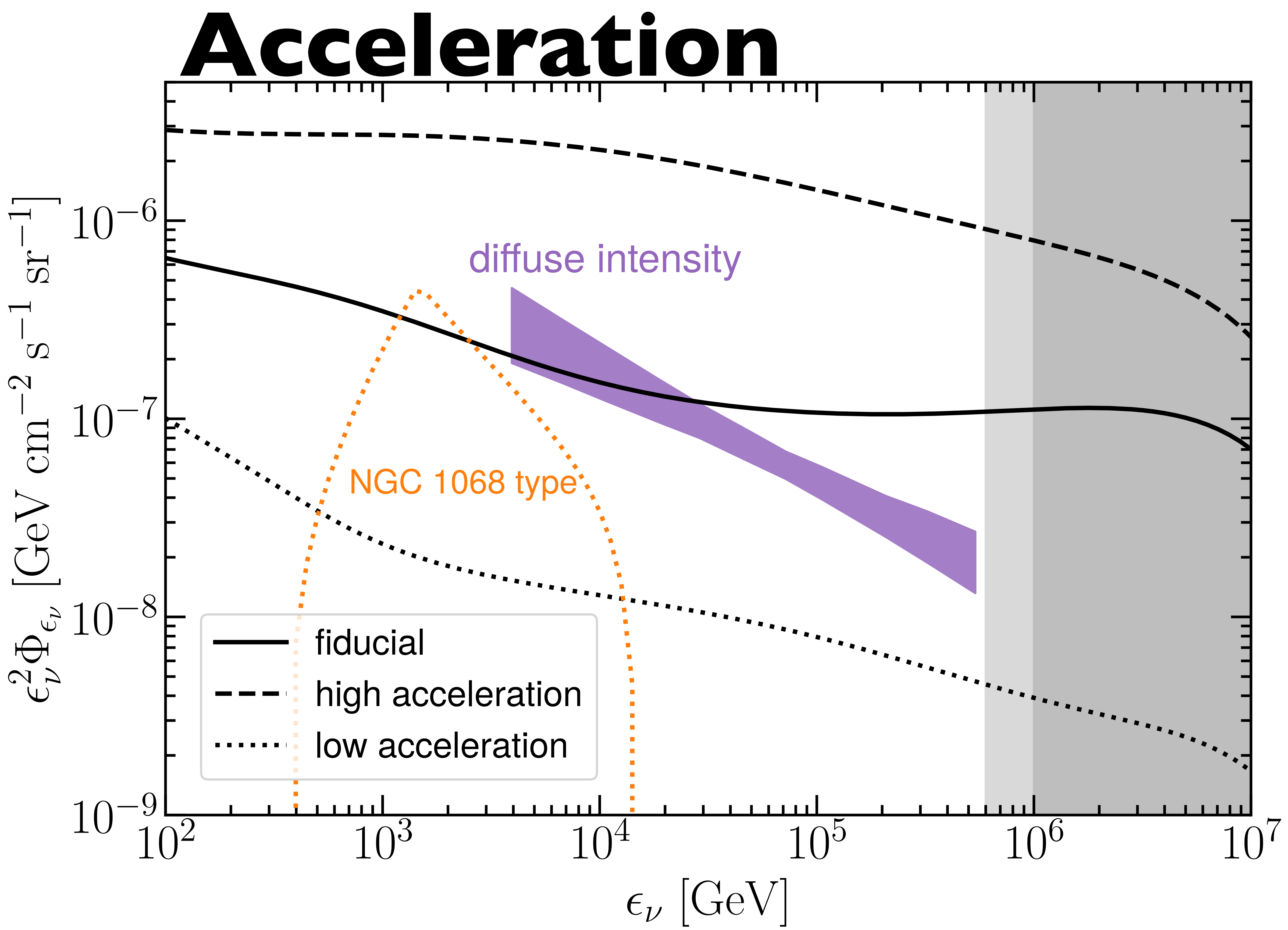


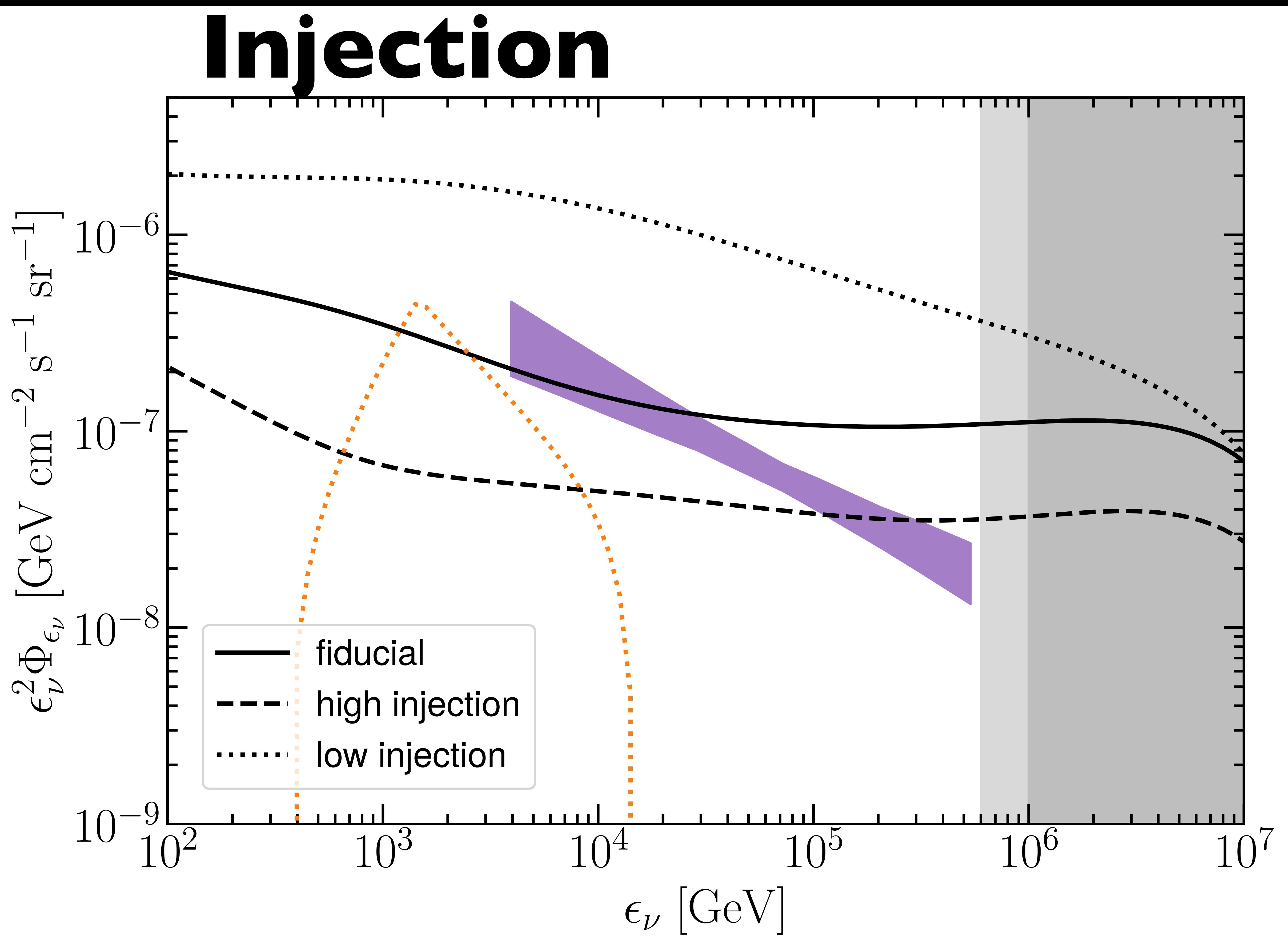
Injection



- Higher acceleration efficiency → harder neutrino SED
- Higher injection rate → softer neutrino SED. (∵ acceleration rate ∝ CR energy)

Comparison w/ IceCube Diffuse Neutrino Fluxes





- We integrated the neutrino SEDs assuming the luminosity function of Ho + (2008) w/ assuming $\epsilon L_\epsilon \propto \dot{M}^2$
- Magnitudes of diffuse neutrinos are consistent w/ observed SED.
- Combination w/ Seyfert (NGC1068 type) may be required.

Summary

- The first attempt to compute CRp acceleration & Neutrino emission of global accretion flows based on 3D GRMHD simulation data.
- Due to the global effect (superposition of various injection of accelaration of CRp), the flatter SEDs appear in our model.
- The neutrino emission, which originated from outflowing-CRp accelerated in inflow, predominate the SEDs.
- More code development (incl., e.g., p-γ processes) will be addressed in near future.

Backup Slides

Why Are High Energy (HE) Neutrinos Important?

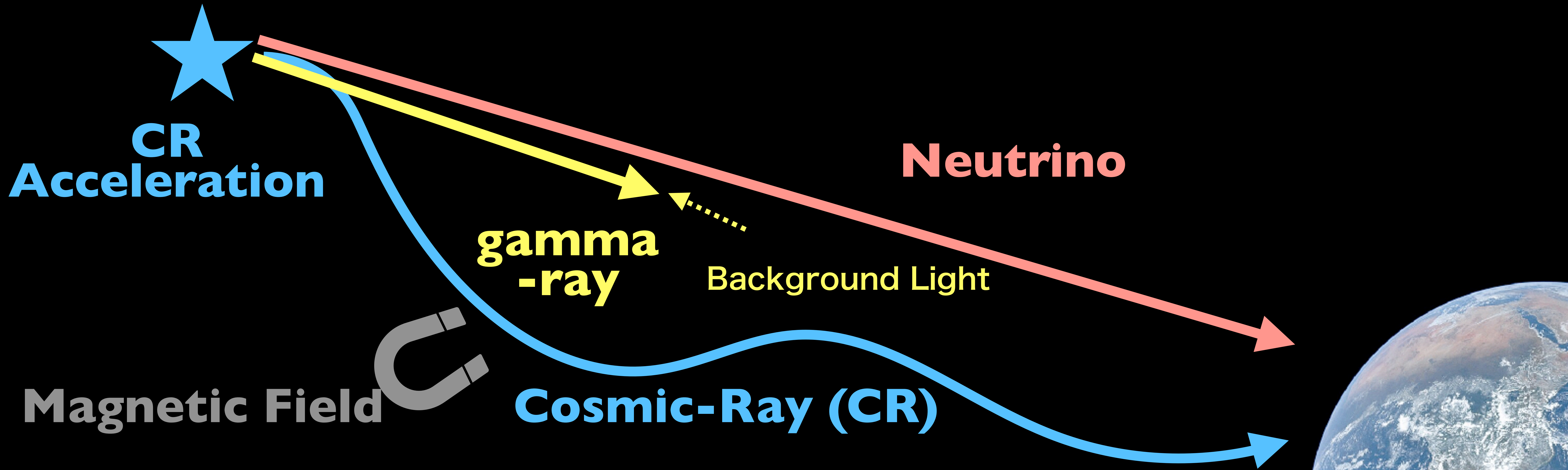
- Mystery of acceleration mechanism/site of high-energy cosmic rays (CRs)
- Smoking gun of CR acceleration, because…

$(p + p$ and/or $p + \gamma \to \pi^0, \pi^\pm, \quad \pi^0 \to \gamma + \gamma, \quad \pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu)$

✓Cosmic Rays : Trajectories are bent by magnetic fields

✓Gamma-Rays : Optically thick agains background light ($\gamma + \gamma \to e^+ + e^-$)

✓Neutrino : Freely propagates towards us!

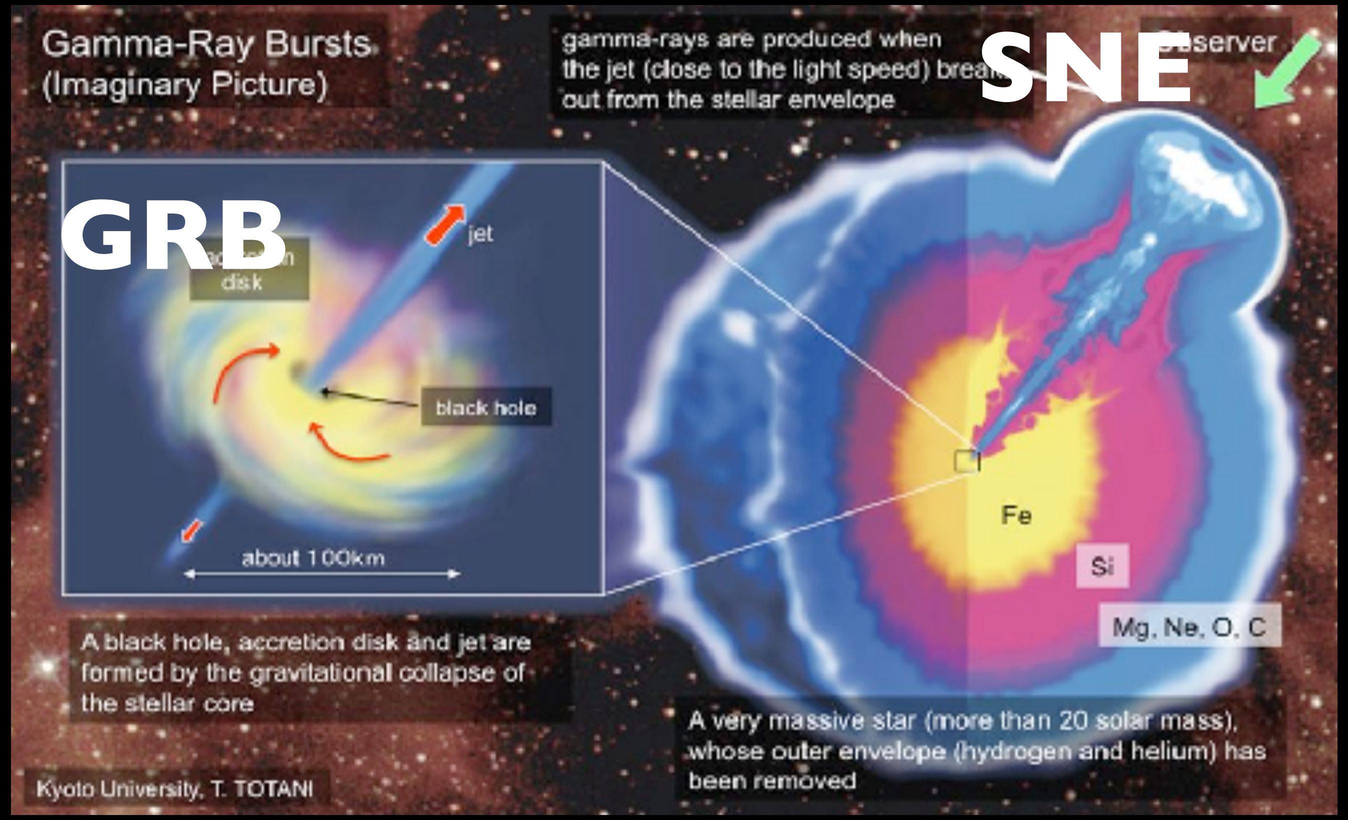


c.f. Energy of Neutrinos

GeV-TeV

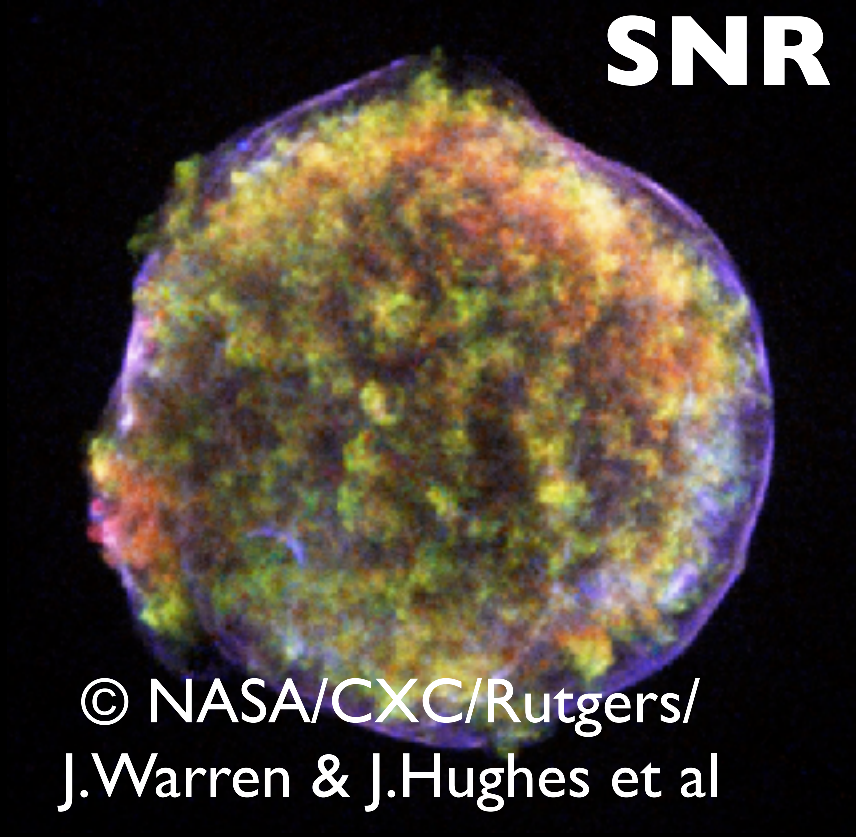
Neutrino Energy

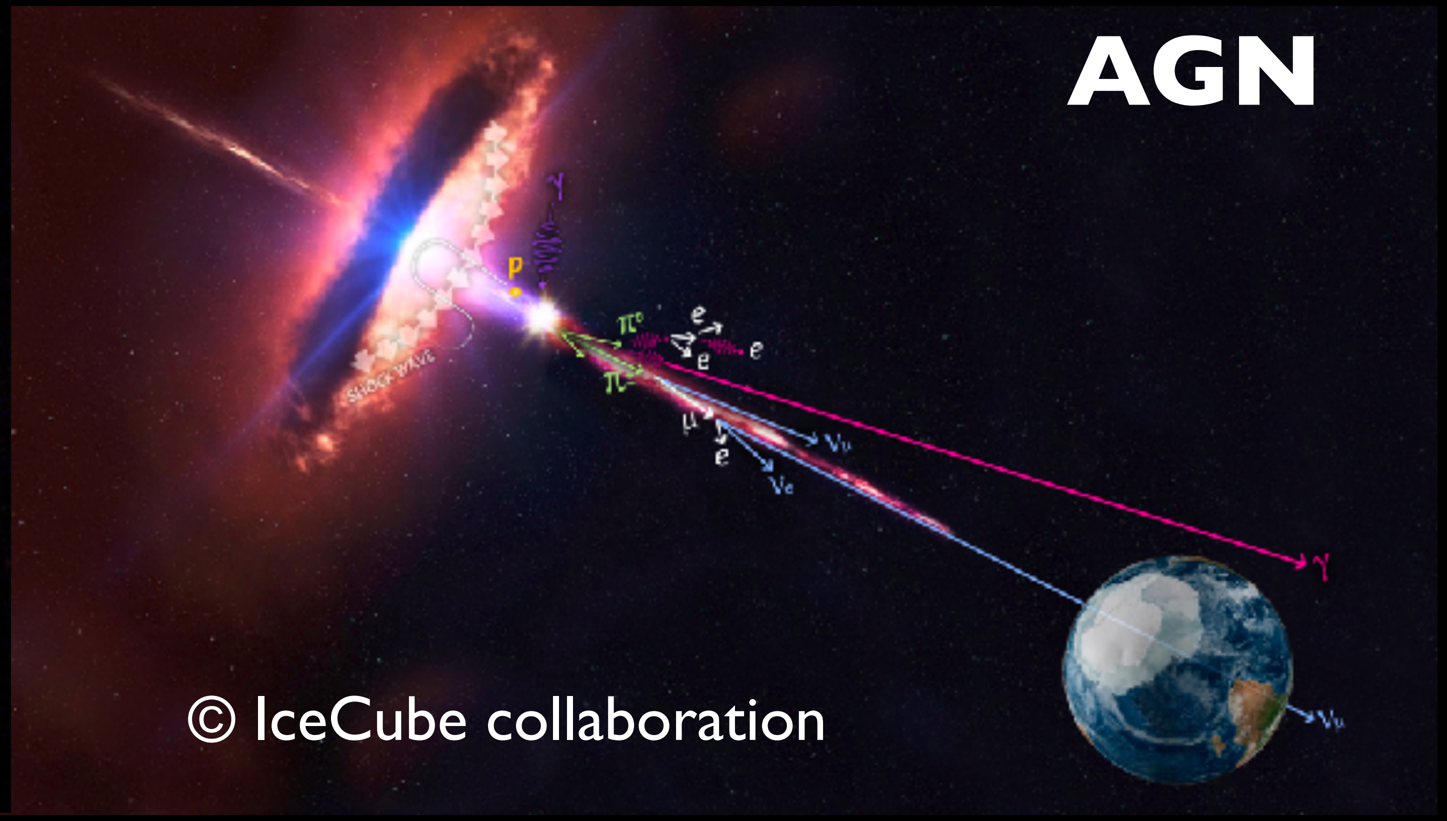
- Thermo-Nuclear Reaction (~10MeV)
- High Density: Supernova Explosion, Gamma-Ray Burst (Central Engine), Stellar Interia, etc.



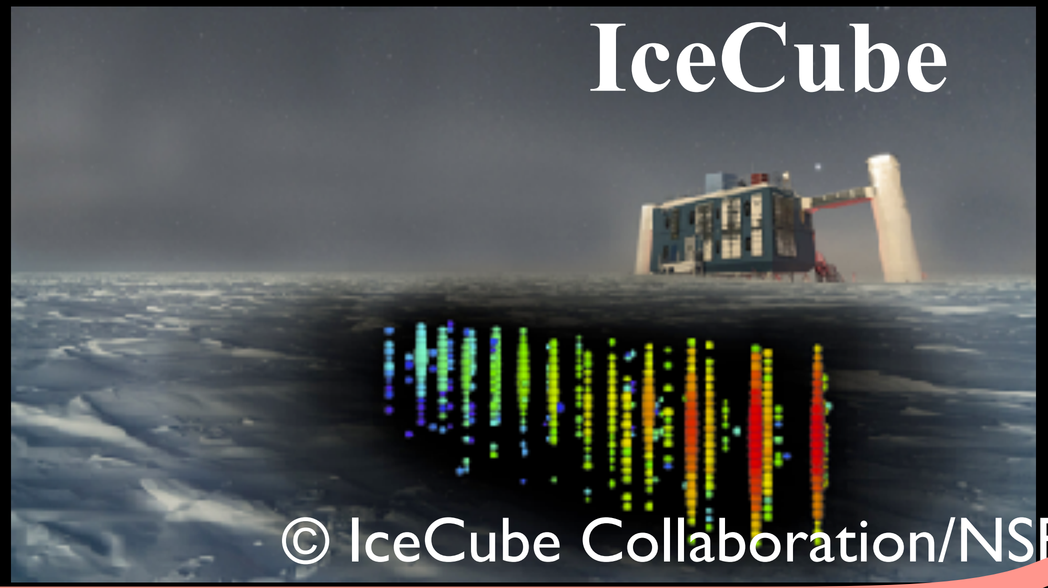
- Messenger of Steller Interia and Governing the Dynamics of Explosions/Bursts
- Super Kamiokande, etc.

- Hadronic Processes of Cosmic Rays ($\gtrsim$ TeV)
- Low-Density: Supernova Remnant, Active Galactic Nuclei, Jet of Low-Lum. Gamma-ray Burst, etc.





- Messenger of Cosmic-Ray Acceleration and Tests of Elementary Particle Physics
- IceCube, etc.



Computation Method ($M_{BH} = 10^8 M_\odot$, $\dot{M} = 10^{-2} L_{Edd}/c^2$)

(1) Trajectory of tracer particles of Cosmic-Ray proton (CRP) post-processing 3D GRMHD data

Δt update (sometimes, snapshot update)

(2) Computation of SED of CRPs

(Fokker-Planck Eqs w/ phenomenological turbulent acc.)

(3) Computation of Neutrino SED

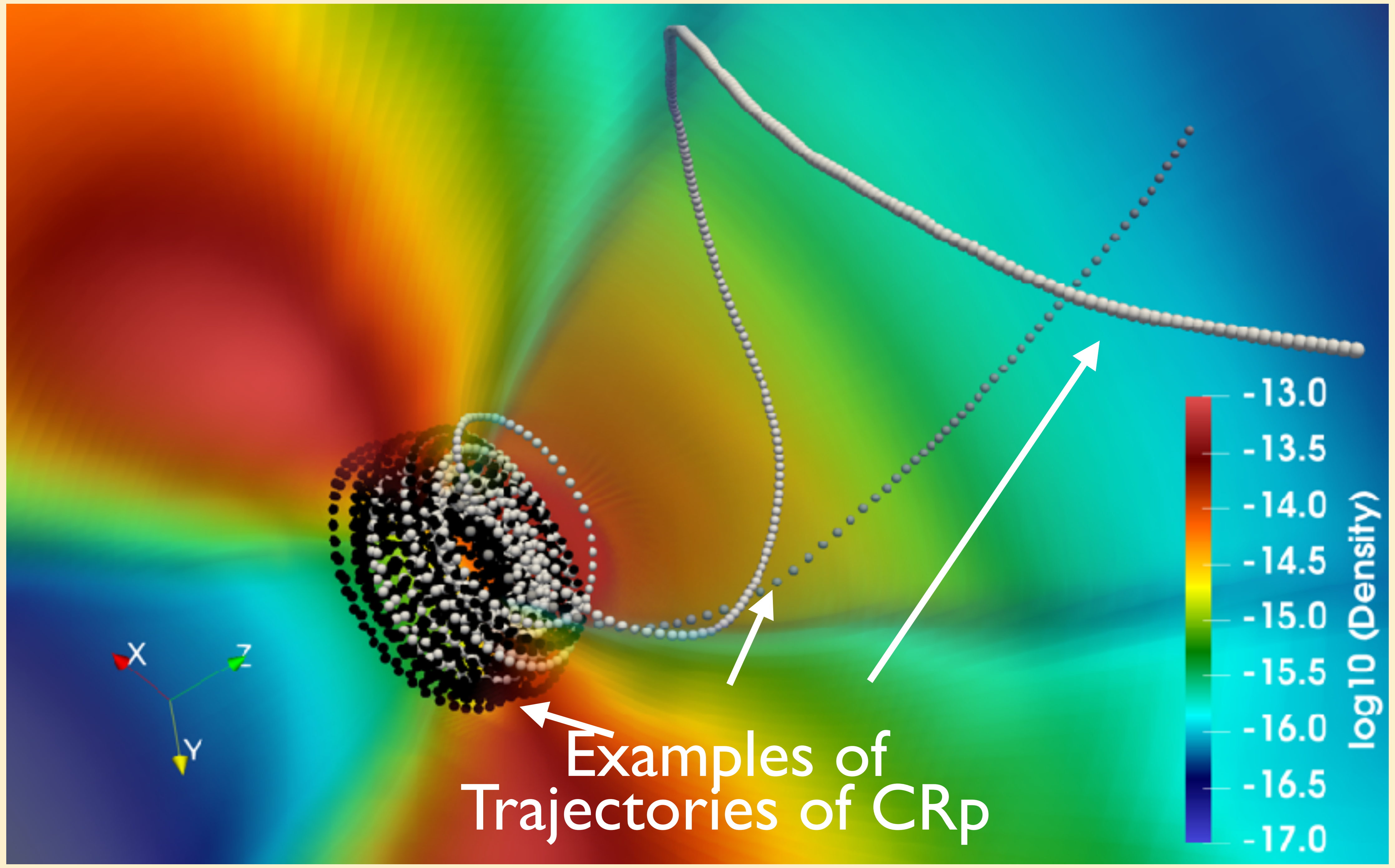
(***pp*** **collisions** w/ GRMHD protons)

Computation Method (I)

Trajectory of tracer particles of Cosmic-Ray proton (CRp) post-processing 3D GRMHD data

- CRps are treated as Tracer particles (~1 million particles)
- Assumption: CRps moves along the streamlines being trapped by subgrid-scale turbulent B-filed.

  # we are interested in acceleration upto ~PeV (gyro radii < mesh size)
- GRMHD dataset of semi-MAD (moderately magnetized state) (TK+2023) simulated using GR(R)MHD code UWABAMI (Takahashi + 2016).



Computation Method (2)

Computation of SED of CRp

- **Fokker-Planck Eqs** of tracer particle in the fluid-rest frame. (Number of Energy Bin: 5600)

$$\frac{\partial \mathcal{N}'_{\rm CRP}(\epsilon'_{\rm CRP}, t')}{\partial t'} = \frac{\partial}{\partial \epsilon'_{\rm CRP}}\left[D(\epsilon'_{\rm CRP})\frac{\partial \mathcal{N}'_{\rm CRP}(\epsilon'_{\rm CRP}, t')}{\partial \epsilon'_{\rm CRP}}\right] - \frac{\partial}{\partial \epsilon'_{\rm CRP}}\left[\frac{2D(\epsilon'_{\rm CRP})}{\epsilon'_{\rm CRP}}\mathcal{N}'_{\rm CRP}(\epsilon'_{\rm CRP}, t')\right] + \dot{\mathcal{N}}'^{\rm comp}_{\rm CRP}(\epsilon'_{\rm CRP}, t') + \dot{\mathcal{N}}'^{\rm inj}_{\rm CRP}(\epsilon'_{\rm CRP}, t'),$$

- **Turbulent Acceleration** w/hard sphere approximation ($D(\varepsilon) = K\varepsilon^2$).

Free parameters

$$K = \frac{\eta_{\rm accel}}{4}\frac{|D\boldsymbol{v}/Dt'|}{|\boldsymbol{v}|}\frac{U'_{\rm th}}{U'_{\rm CRP}},$$

- Injection of CRPs which may be triggered by reconnections

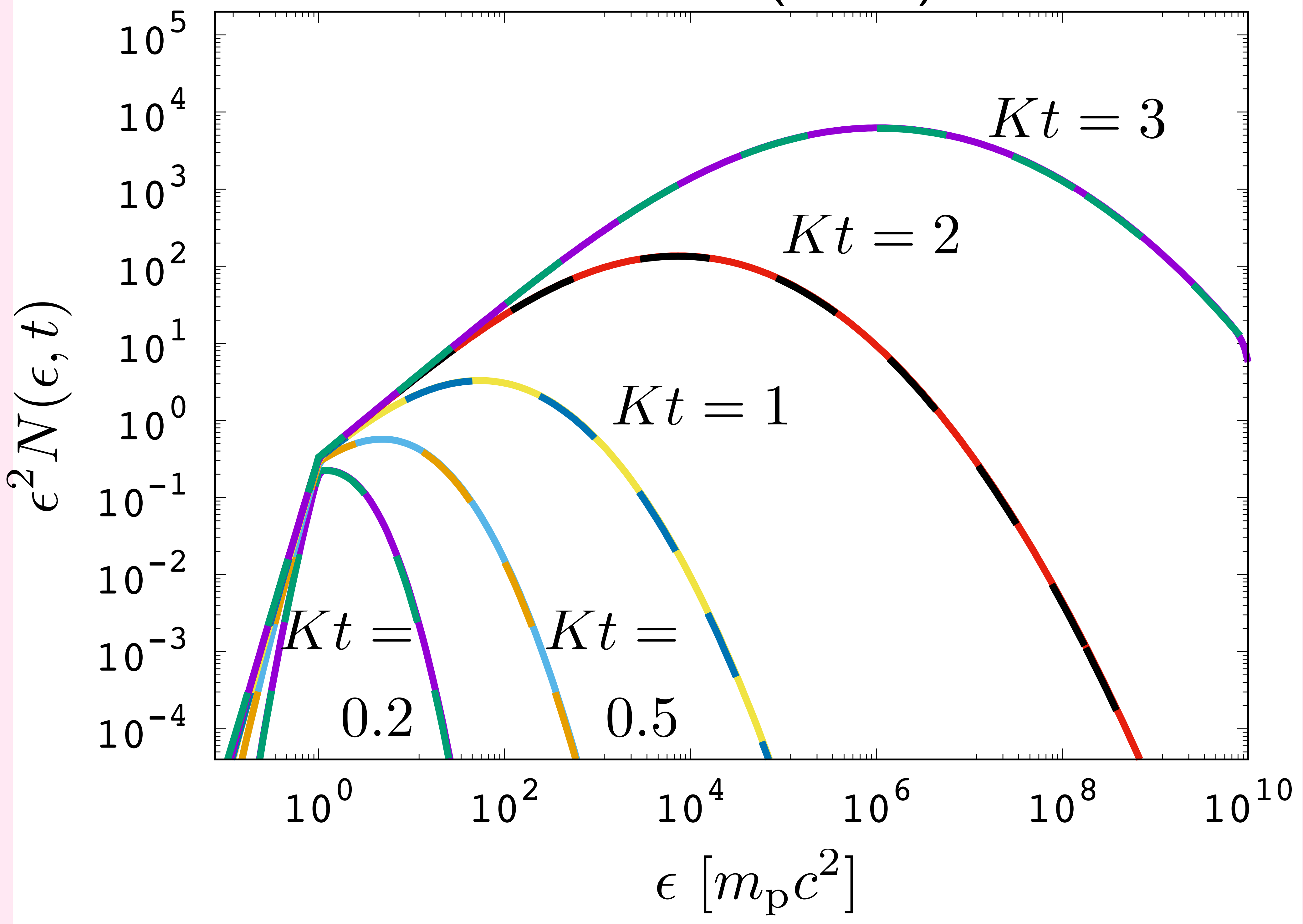
$$\dot{\mathcal{N}}'^{\rm inj}_{\rm CRP}(\epsilon'_{\rm CRP}, t') = \frac{\eta_{\rm inj}}{m_{\rm p}}\max(1, \beta^{-2}_{\rm mag})\frac{|DB'/Dt'|}{|B'|}f_{\rm inj}(\epsilon'_{\rm CRP}).$$

- Compression/expansions effects are also included.

$\eta_{\rm accel} = 3\times 10^5$, $\eta_{\rm inj} = 10^{-3}$

for our fiducial model

Test calculation comparing w/ Asano & Meszaros (2016)

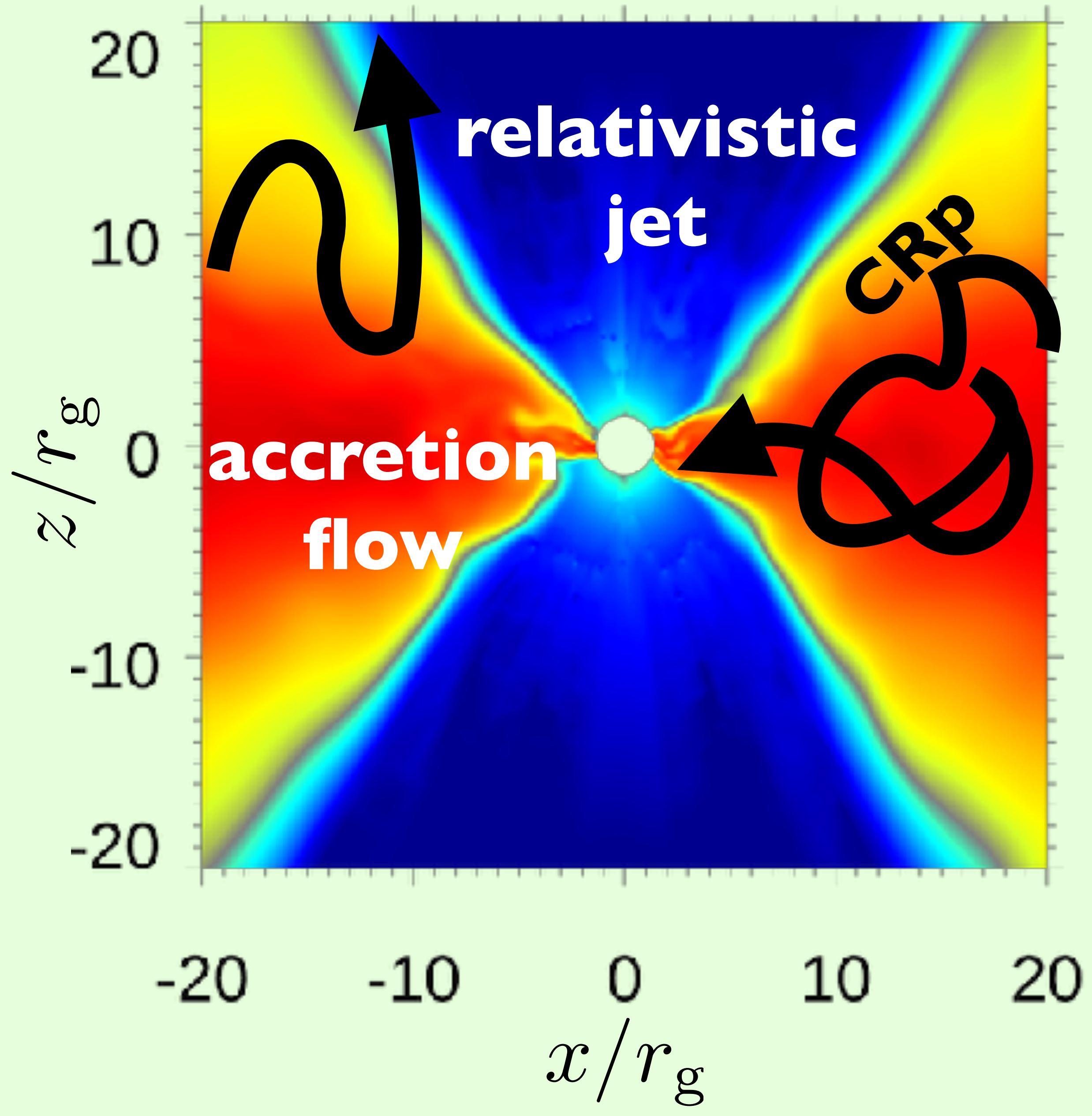


Computation Method (3)

Computation of Neutrino SED

- ***pp* collisions** $(p+p \to \pi^0, \pi^\pm, \quad \pi^0 \to \gamma+\gamma, \quad \pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu)$ of tracer particle of CRps with thermal protons of GRMHD simulation data.

- Kelner's semi-annalitic formula (Kelner + 2006) w/ pion production cross section (Kamae+ 2006, 2007).



- Gravitational redshift are taken into consideration

- Normalization by the time-averaged mass accretion rate onto BH and outflow rate:

$$\epsilon_\nu L_{\epsilon_\nu}^{(\mathrm{inflow})} = \dot{M}_{\mathrm{in}} \frac{\sum_{n_{\mathrm{in}}} \int dt \quad \epsilon_\nu \mathscr{E}_\nu^{(n_{\mathrm{in}})}(\epsilon_\nu) w^{(n_{\mathrm{in}})}}{\sum_{n_{\mathrm{in}}} w^{(n_{\mathrm{in}})}},$$

$$\epsilon_\nu L_{\epsilon_\nu}^{(\mathrm{outflow})} = \dot{M}_{\mathrm{out}} \frac{\sum_{n_{\mathrm{out}}} \int dt \quad \epsilon_\nu \mathscr{E}_\nu^{n_{\mathrm{out}}}(\epsilon_\nu) w^{(n_{\mathrm{out}})}}{\sum_{n_{\mathrm{out}}} w^{(n_{\mathrm{out}})}},$$

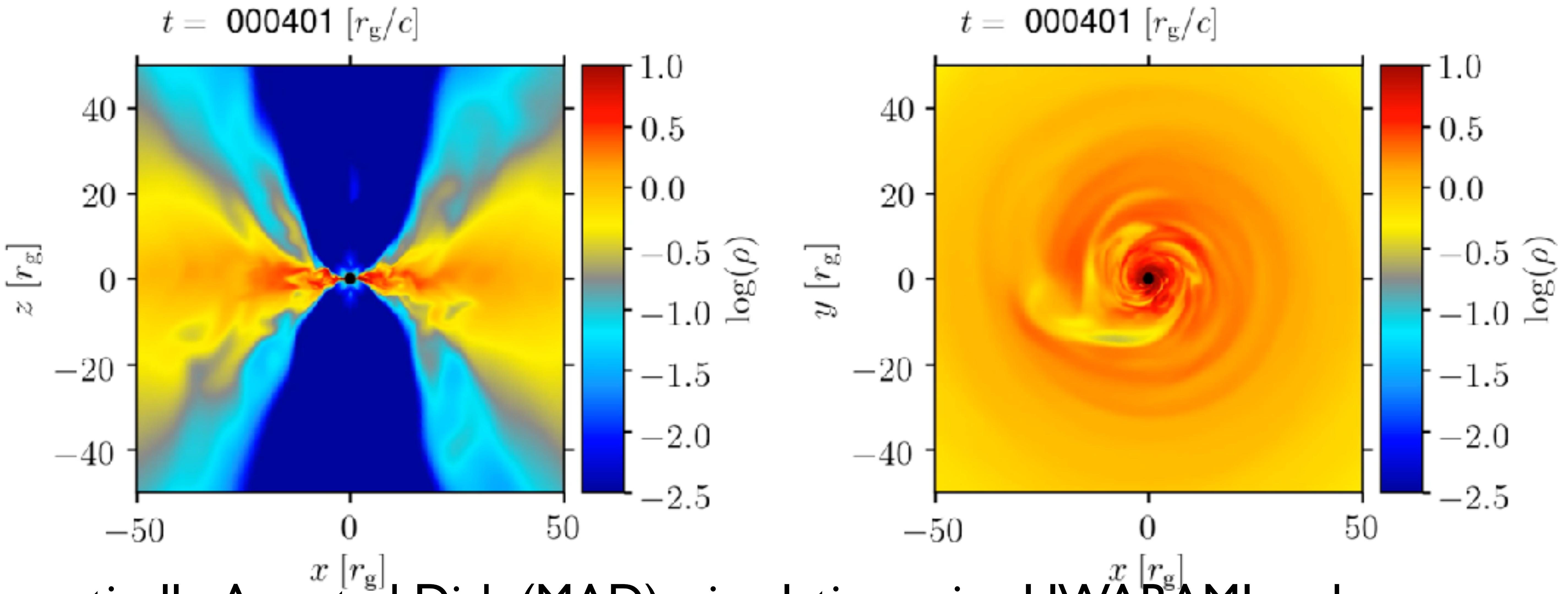
$\mathscr{E}'_\nu(\epsilon'_\nu)$

spectral neutrino emissivity per unit mass of proton

- No viewing angle dependence is considered.

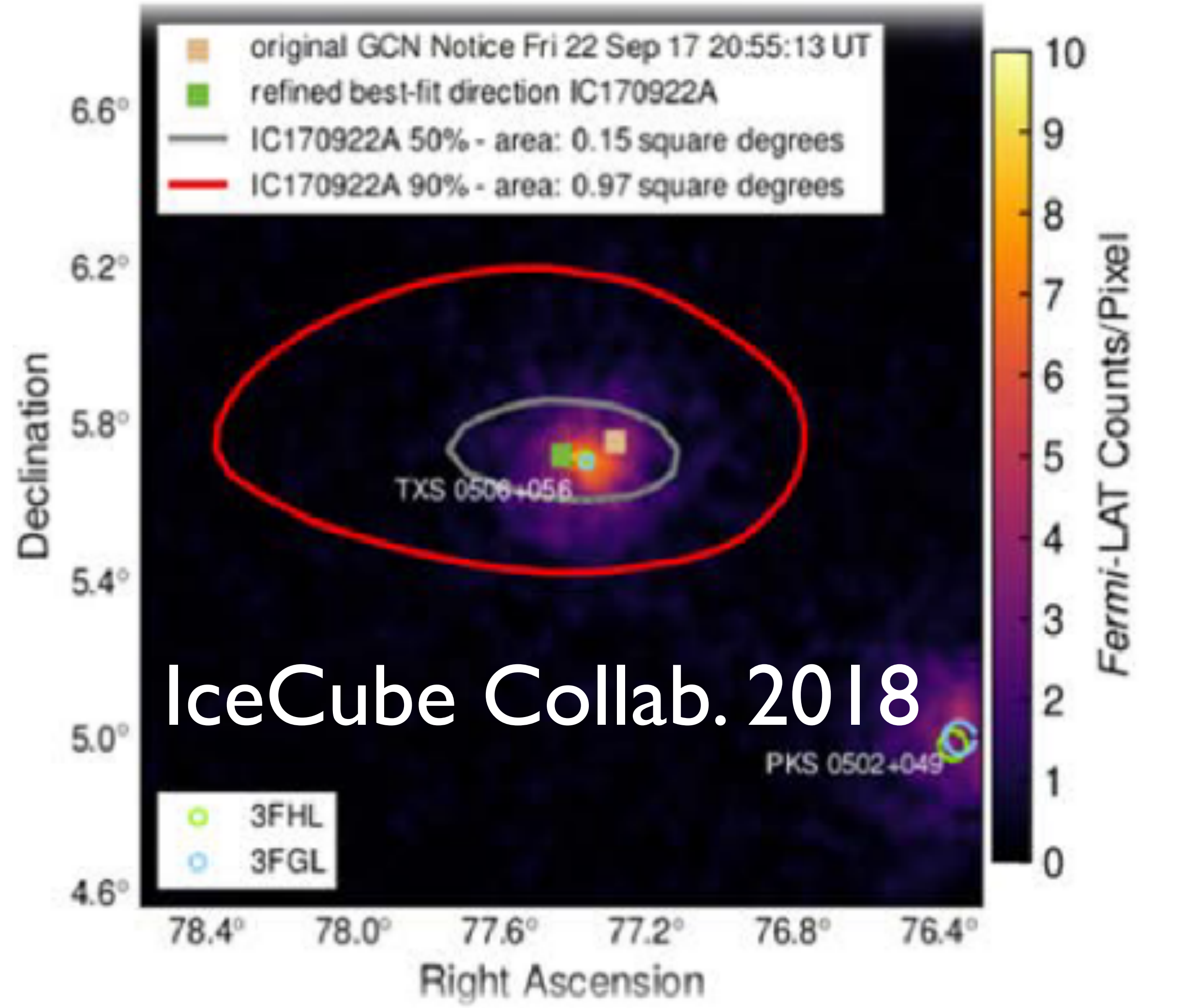
Prospects

- Developing w/ more sophisticated acc. and inj. models
- Fully time-dependent computation of neutrino emission



Magnetically-Arrested Disk (MAD) simulation using UWABAMI code

Neutrino associated w/ a gamma-ray flare in blazar TXS 0506+56？



- Incorporating $p\gamma$ process fully coupling w/ multi-wavelength general relativistic radiative transfer code RAIKOU (TK+23)