

# **High-energy neutrino emission from GRMHD accretion flows onto supermassive black holes**

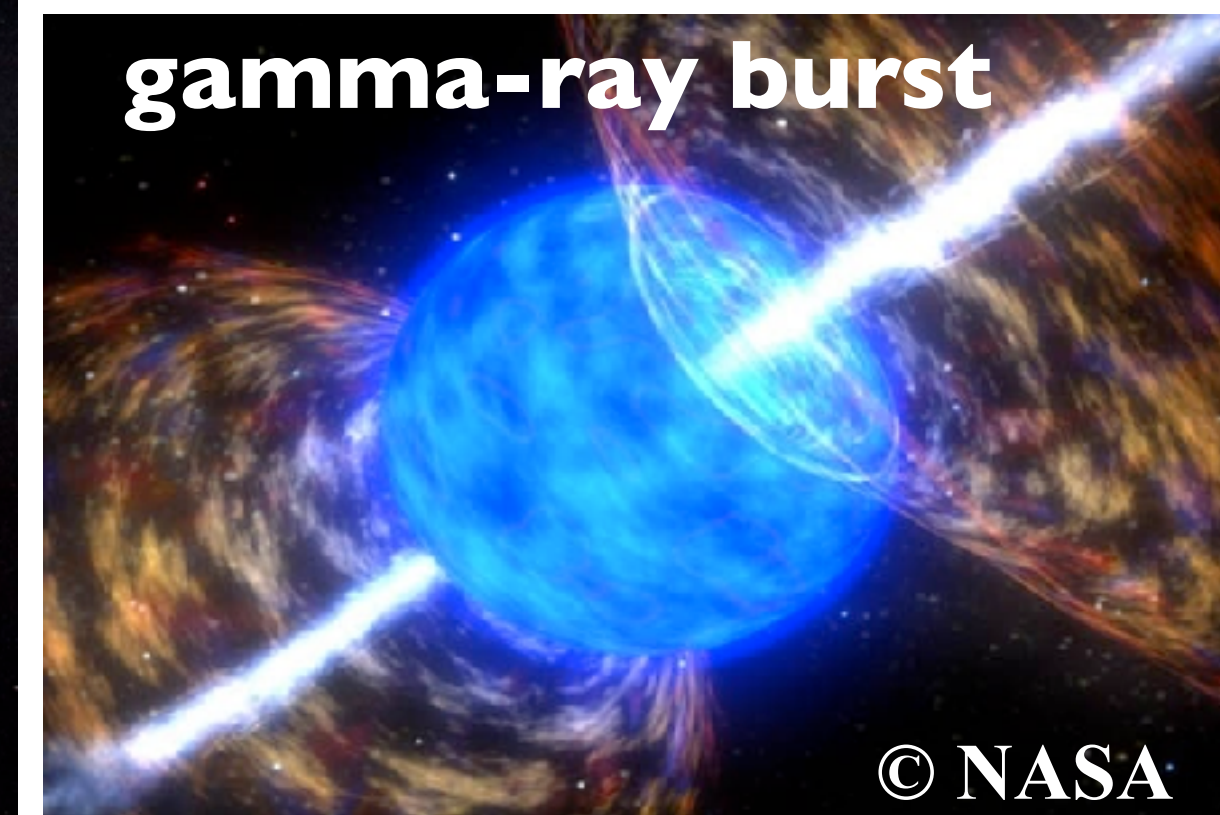
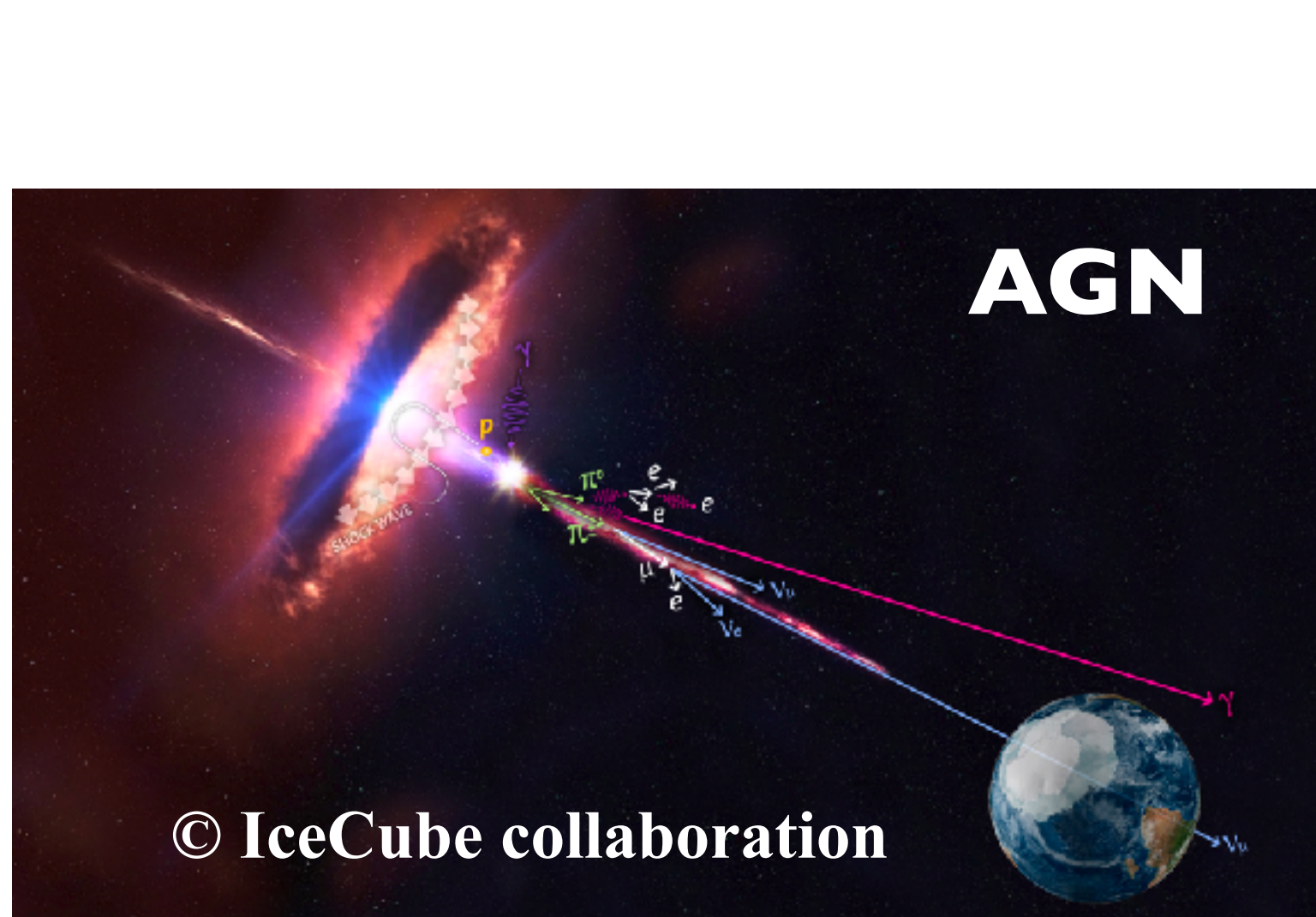
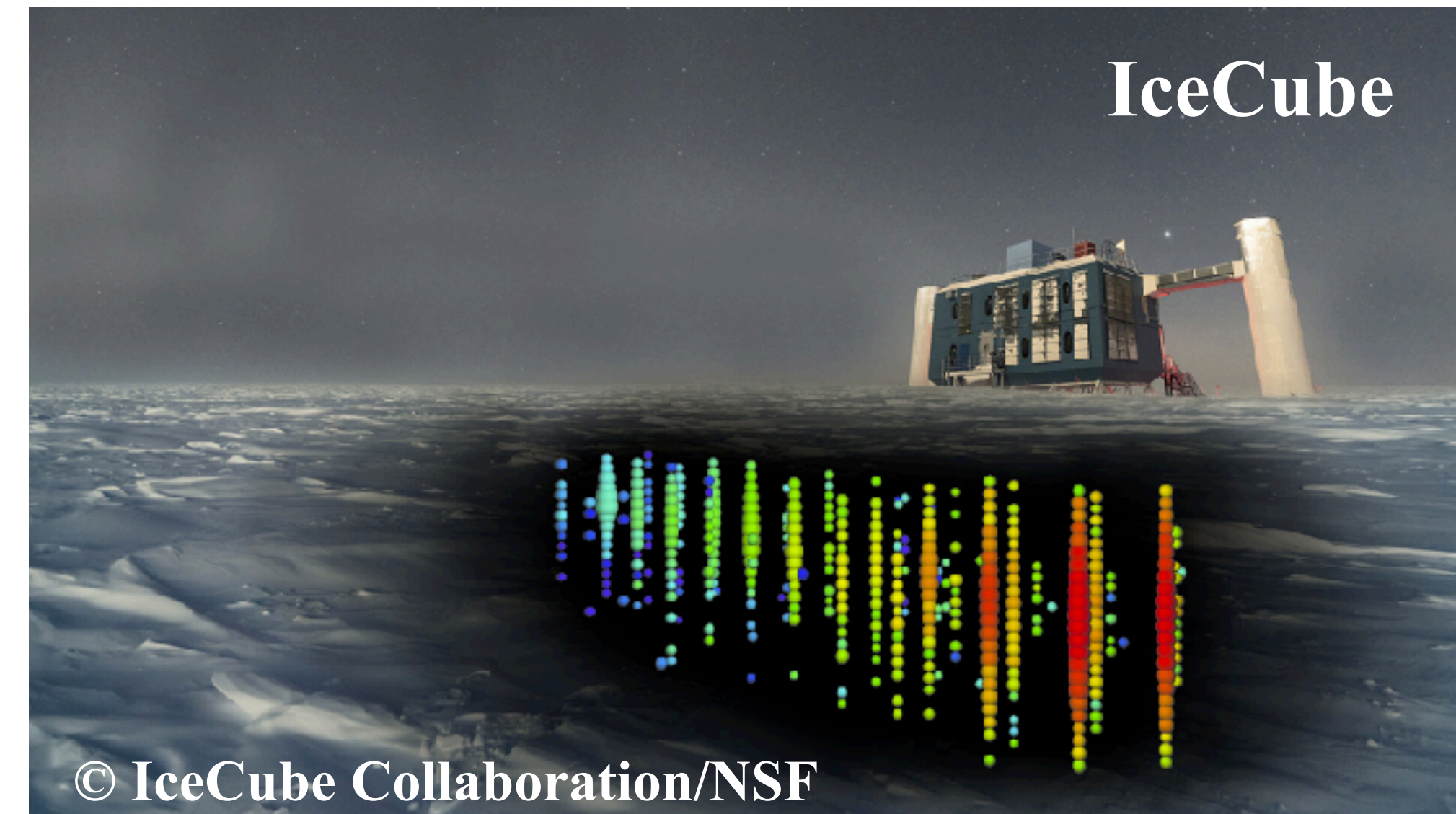
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# Importance of High Energy (HE) Neutrino

- HE neutrinos are crucial messenger to explore the origin of cosmic-ray accelerations.
- IceCube has detected astrophysical neutrinos, but has not yet fully constraint the neutrino sources.
  - ✓ Active Galactic Nuclei (AGN)
  - ✓ Galaxy Clusters
  - ✓ Starburst Galaxies
  - ✓ Low Luminosity Gamma-Ray Bursts

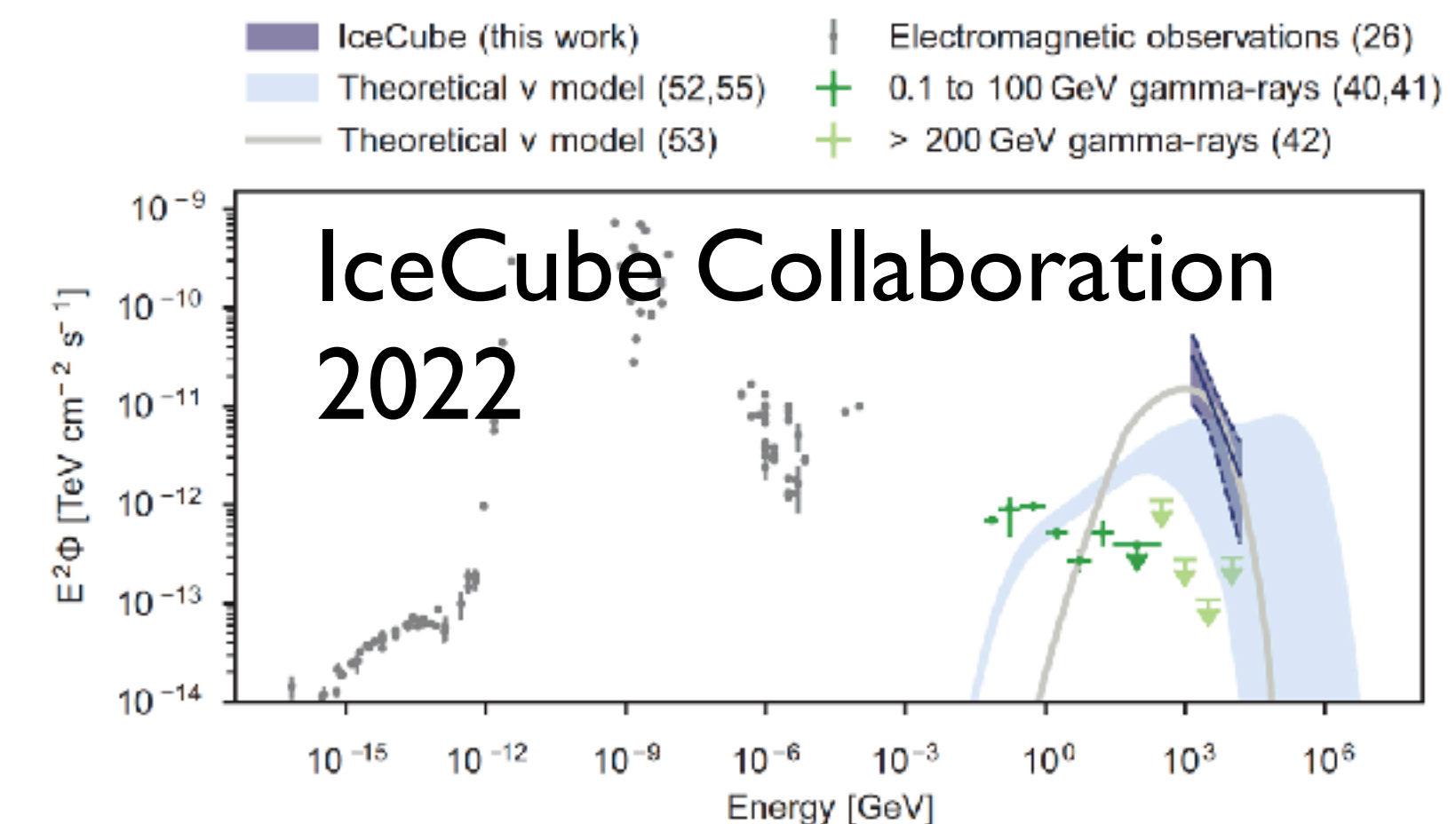
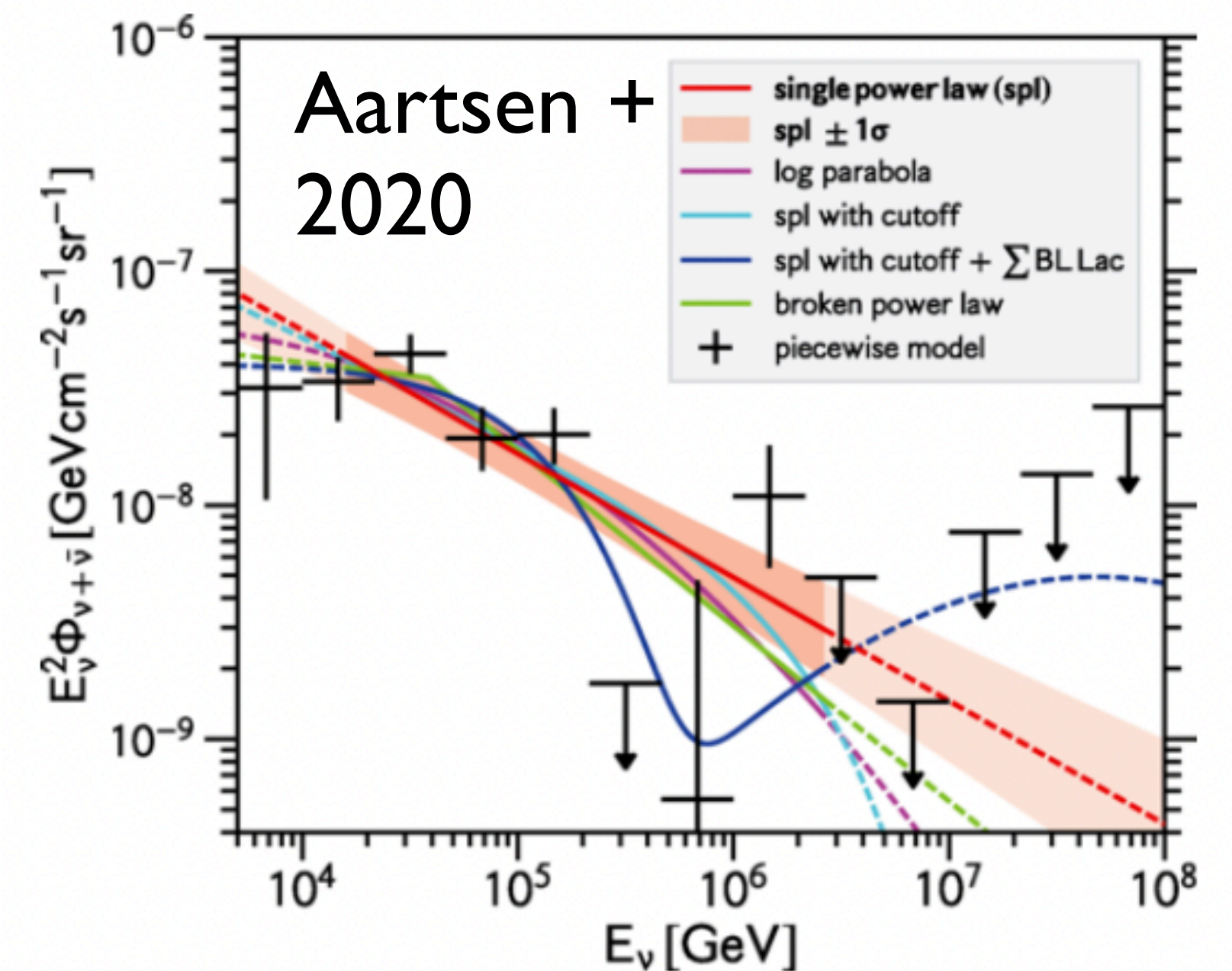




# IceCube Neutrino Spectral Energy Distribution (SED)

- Diffuse neutrino: moderately flat SEDs (e.g., Aartsen + 2020)
- A neutrino hotspot NGC 1068 detected by a decadal survey: steep(power law index  $\sim 3$ ) SED (Aartsen + 2020, IceCube Collaboration 2022)
  - Variety 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)

**We consider an accretion flow model, in this work.**





# Cosmic Ray (CR) Acceleration Model in Accretion Flow

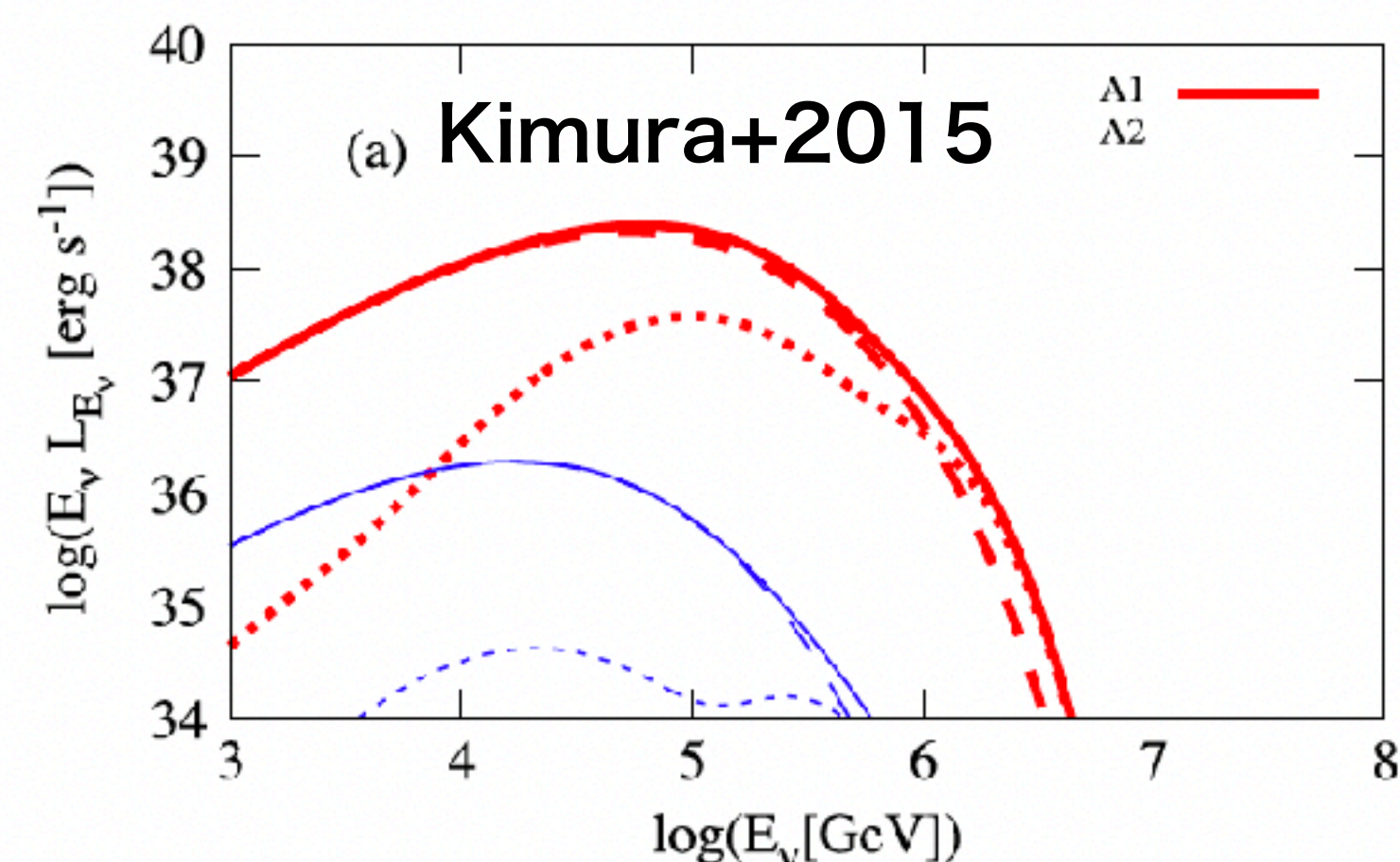
- Magnetic Reconnection (e.g., Hoshino + 2013 PIC sim.)
- Turbulence in kinetic scale based on a single-zone approximation (e.g., Kimura + 2015).

Q: What is the global effect of the accretion flows on the neutrino SEDs?

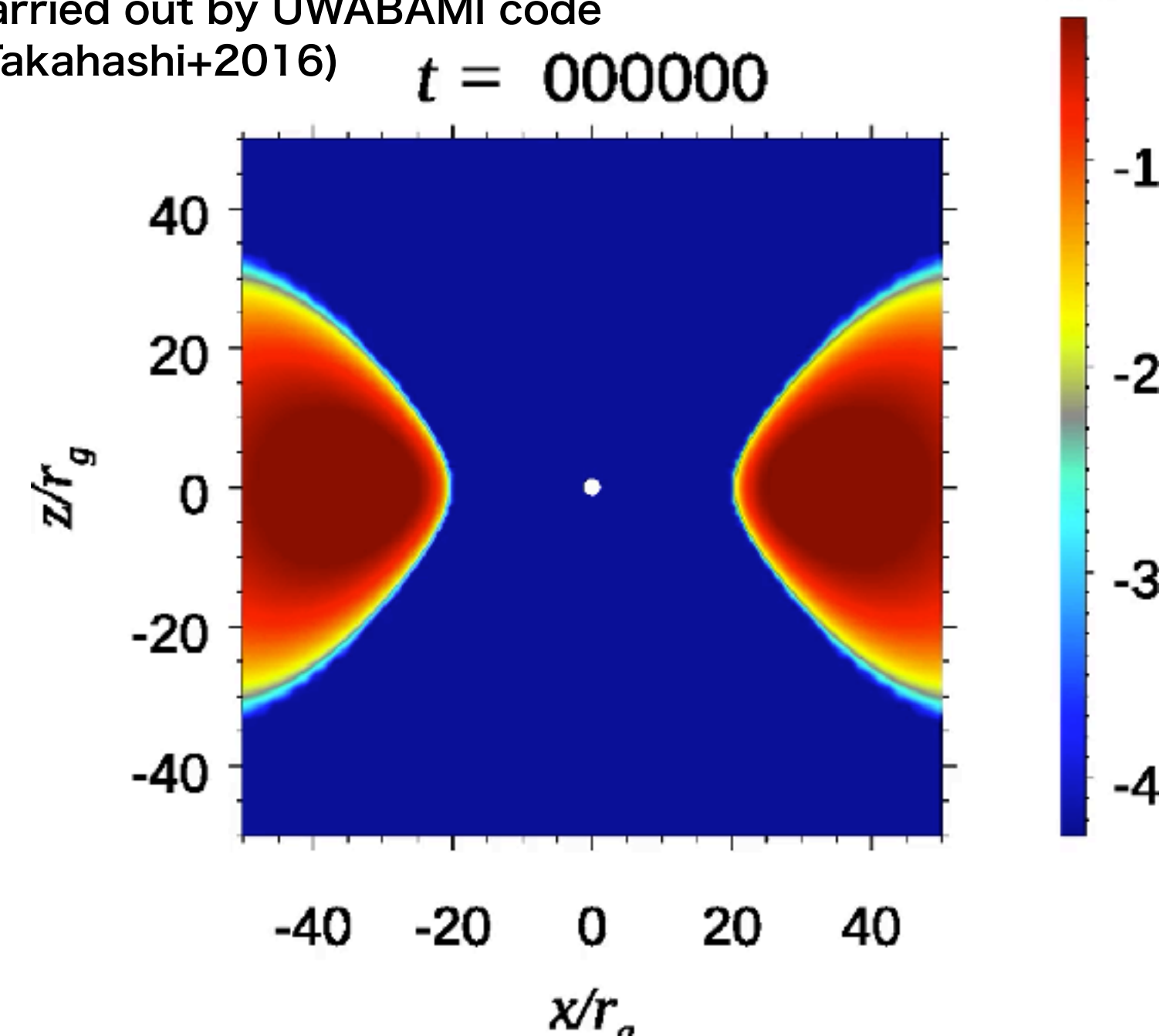
Purpose of this work :

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 general relativistic MHD (GRMHD) simulations of accretion flows + CR acceleration & neutrino emission computation [a new code  $\nu$ -RAIKOU ( $\nu$ -来光) code]



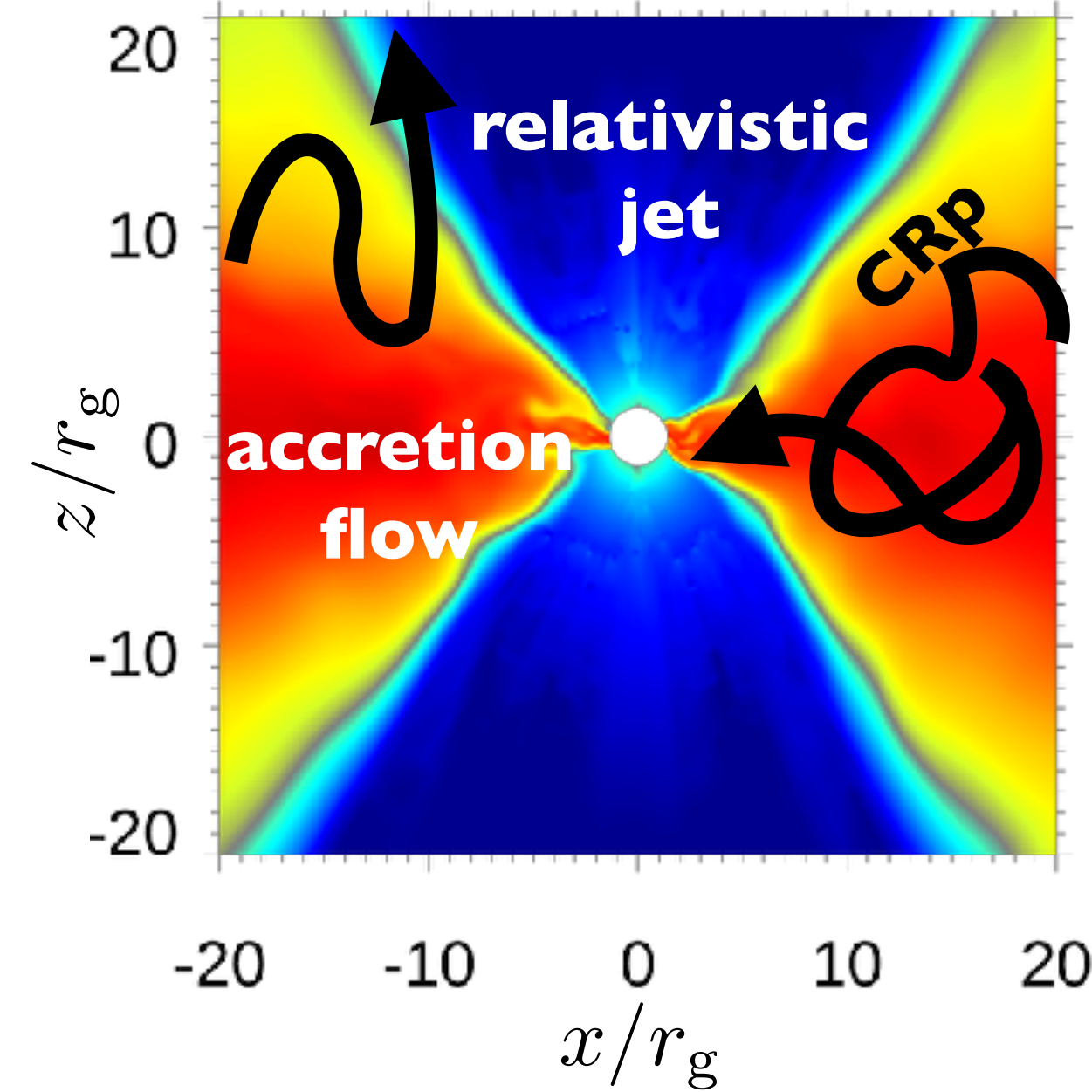
GRMHD simulation of accretion flow (TK +2023) carried out by UWABAMI code (Takahashi+2016)  $t = 000000$



# Method

## (1) Trajectory of tracer particles of CRp based on 3D GRMHD data

- Assumption: CRps moves along the streamlines.  
# we are interested in acceleration upto  $\sim \text{PeV}$  (gyro radii  $<$  mesh size)
- GRMHD dataset of semi-MAD (moderately magnetized state) (TK+2023) simulated using GR(R)MHD code UWABAMI (Takahashi + 2016).

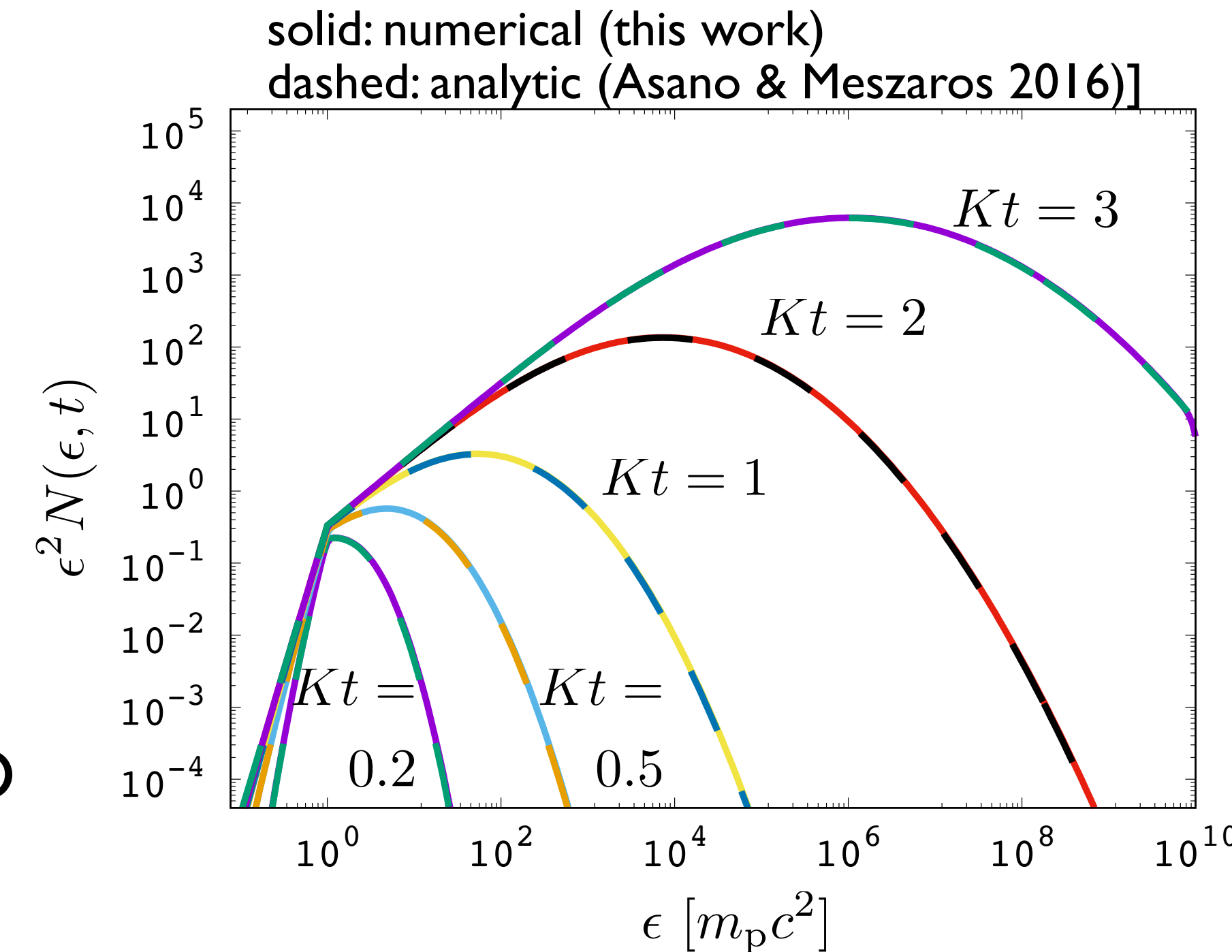


## (2) Computation of SED of CRp

- Fokker-Planck Eqs. are solved at each point of tracer particle in the fluid-rest frame.
- Diffusion and Injection terms in the energy space is solved using Green func.(Becker+2006) with the hard sphere approximation ( $D(\epsilon) = K\epsilon^2$ ).
- Compression/expansions effects are also included.

## (3) Neutrino SED

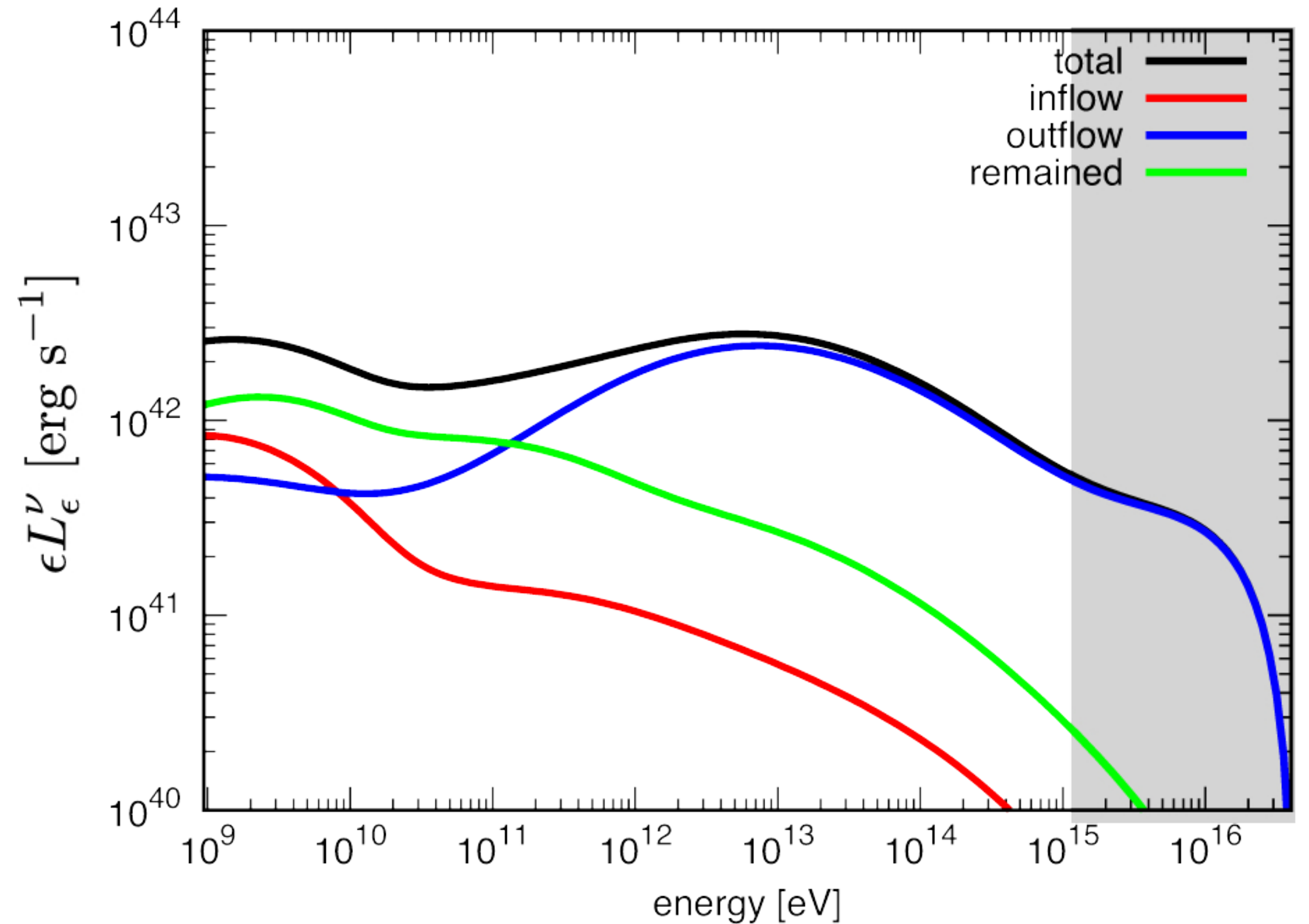
- pp collisions of tracer particle of CRps with thermal protons of GRMHD simulation data.
- Gravitational redshift





# Time-Averaged Neutrino SEDs

- **SEDs flatter than single-zone models appear (This may be consistent with diffuse neutrino)**
- Neutrino SEDs decomposed into origin of CRps in **inflow**, **outflow**, **others (remaining)**
- Neutrinos originated from inflow CRp ~ those from (eventual) outflow CRp.

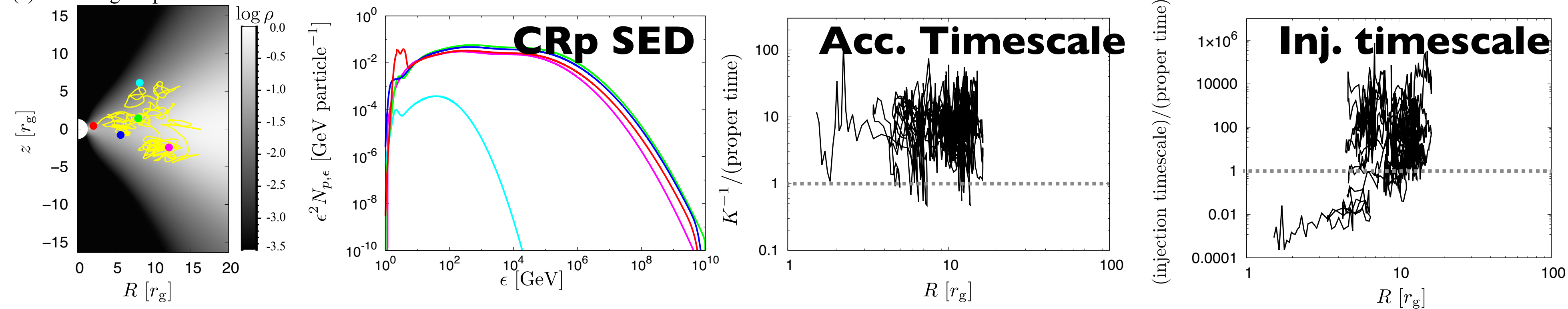


$$t_{\text{acc}} = v/\dot{v} \quad K = 4\eta/t_{\text{acc}}(U_{\text{th}}/U_{\text{CR}}) \quad \eta = 3 \times 10^{-4}$$

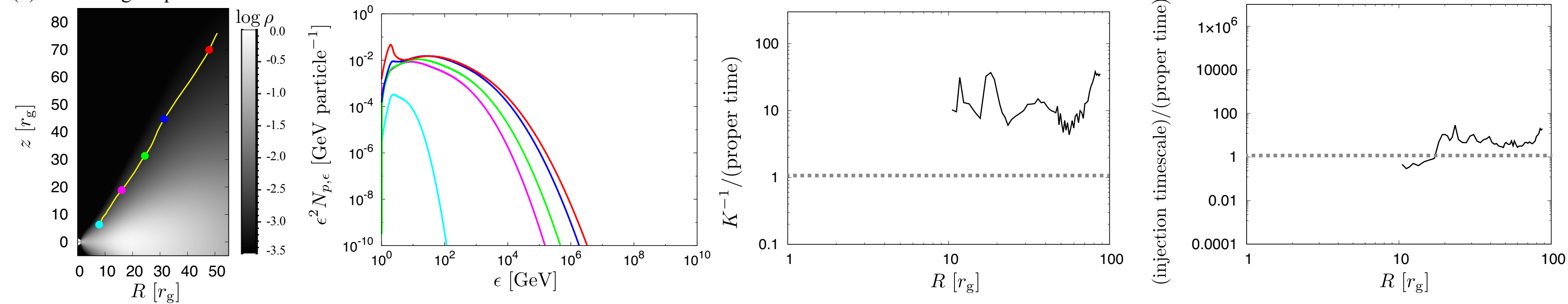
$$t_{\text{inj}} = B/\dot{B} \quad \dot{n}_{\text{inj}} = f_{\text{inj}}/(\beta t_{\text{inj}}) \quad f_{\text{inj}} = 1.5 \times 10^{-3}$$

# CR trajectory and timescale

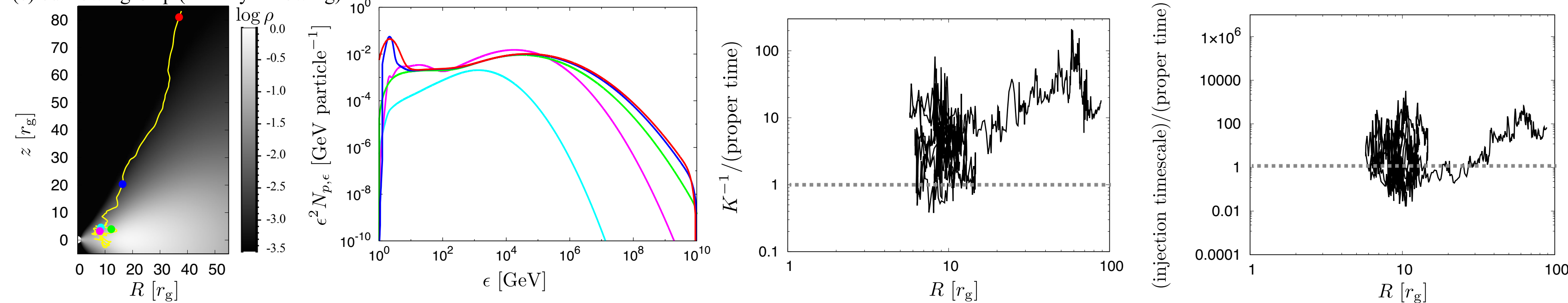
(a) inflowing CRp



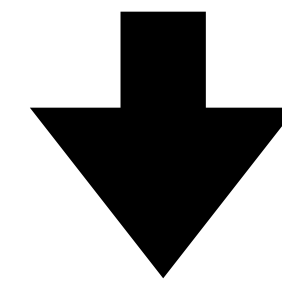
(b) outflowing CRp



(c) outflowing CRp (initially inflowing)



• Summation of various CRp

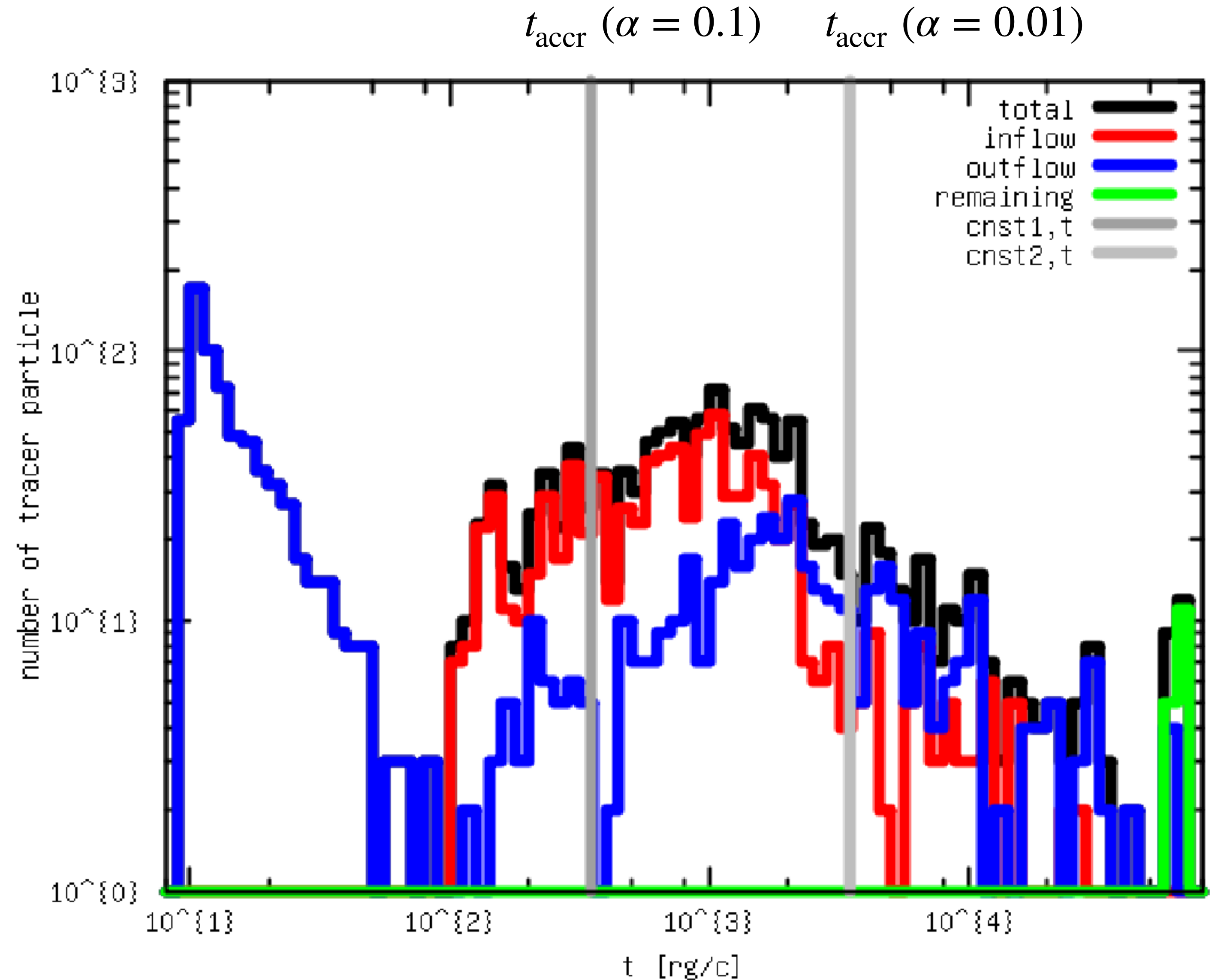


Superposition results in flatter SED.

# Escape (stay) timescale from the simulation region

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

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





# Summary

- **CRp acceleration & Neutrino emission of global accretion flows based on 3D GRMHD simulation data.**
- **Due to the global effect (superposition of various injection of acceleration of CRp) → flatter SEDs (maybe consistent with diffuse neutrino SEDs)**
- **Remarkable neutrino originated from outflows accelerated in inflow.**
- **Computations of neutrino with MAD models and MWL photon SED will be shown soon.  $p-\gamma$  processes will be incorporated in near future.**