Progress of theoretical modeling on high-energy neutrino emission

C01: Theoretical study on multimessenger signals from neutrino-emitting astrophysical objects

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High-energy Neutrino Astrophysics

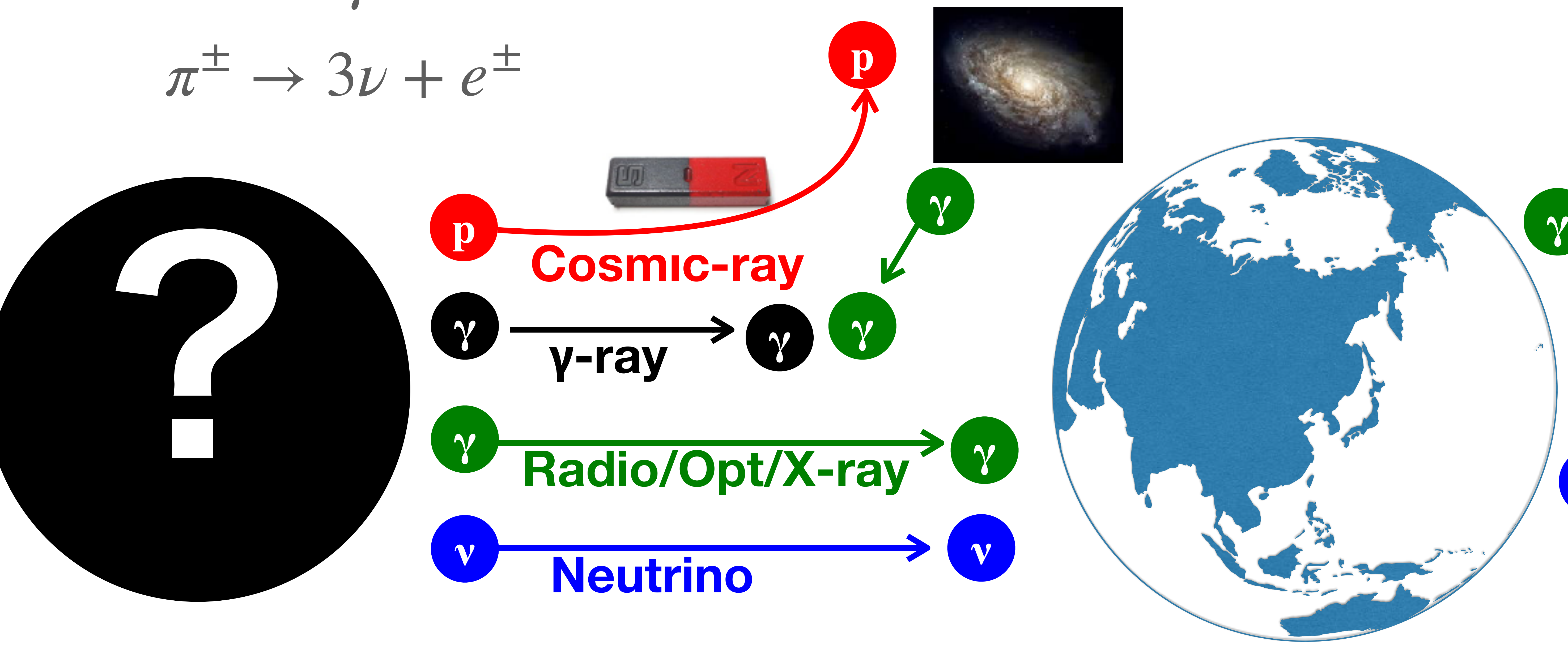
- Smoking-gun for hadronic cosmic rays

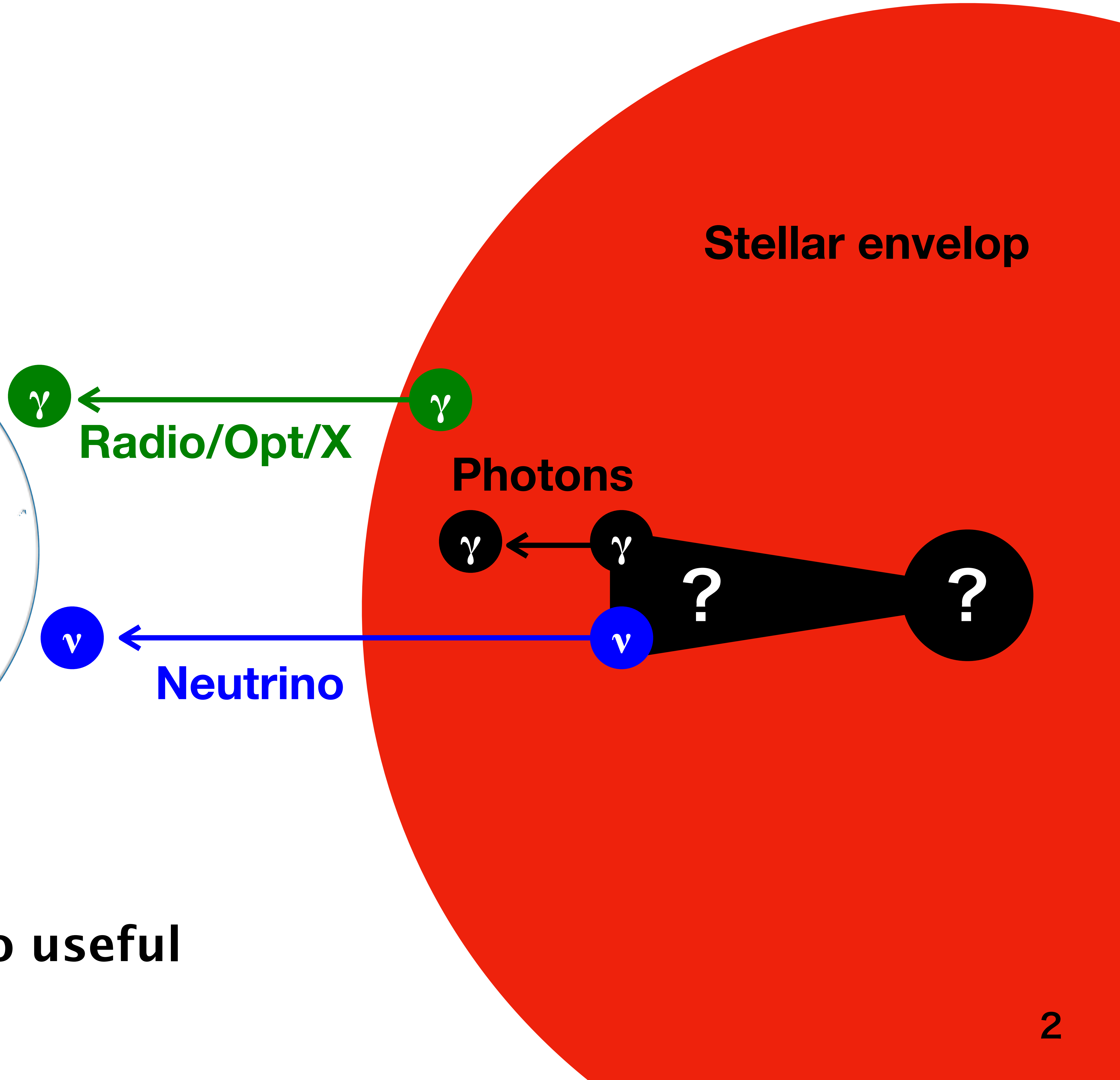
- Unique probe inside dense medium

$$p + p \to p + p + \pi$$

$$\pi^0 \to 2\gamma$$

$$\pi^\pm \to 3\nu + e^\pm$$





$$p + \gamma \to p + \pi$$

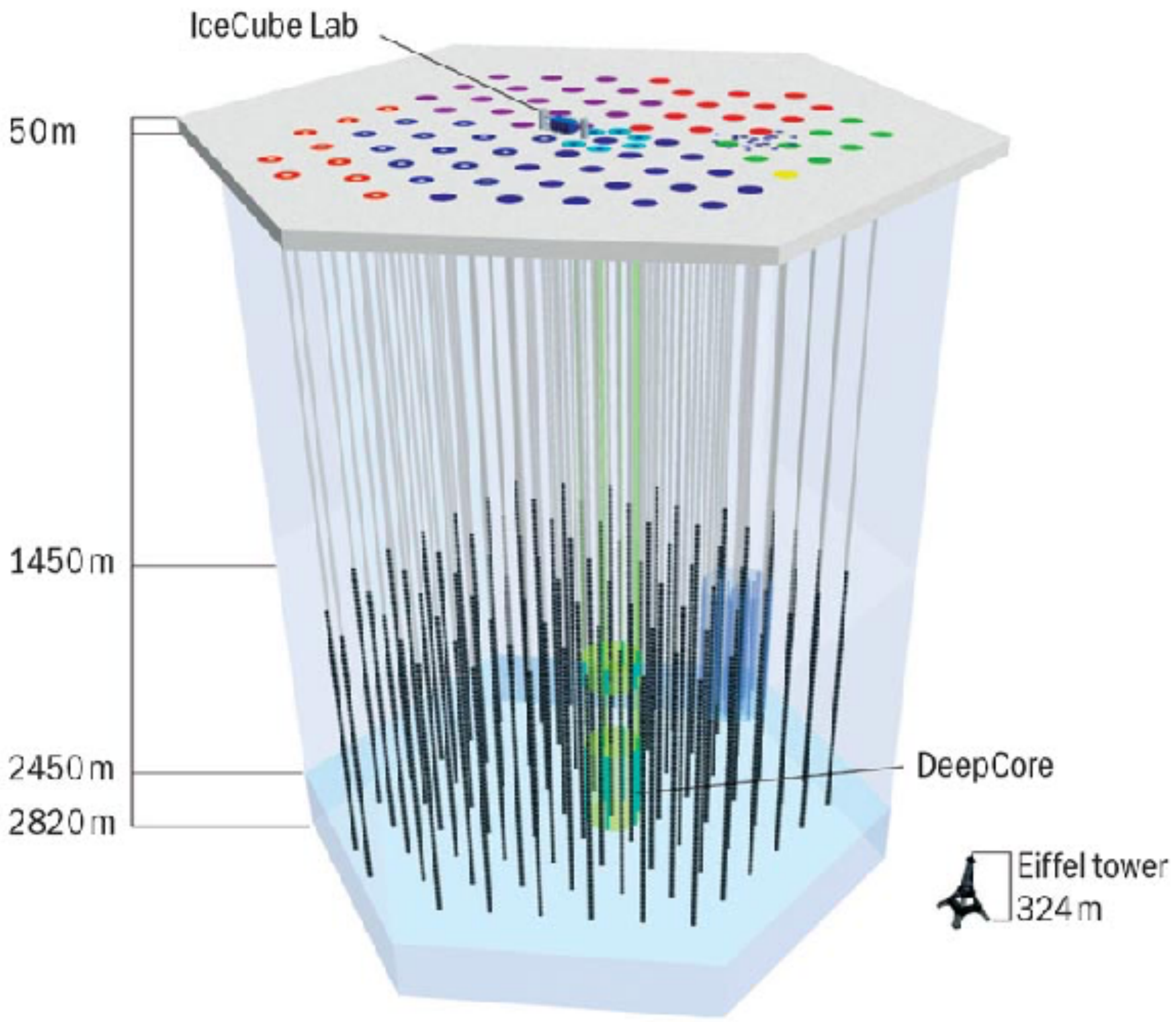
$$\pi^0 \to 2\gamma$$

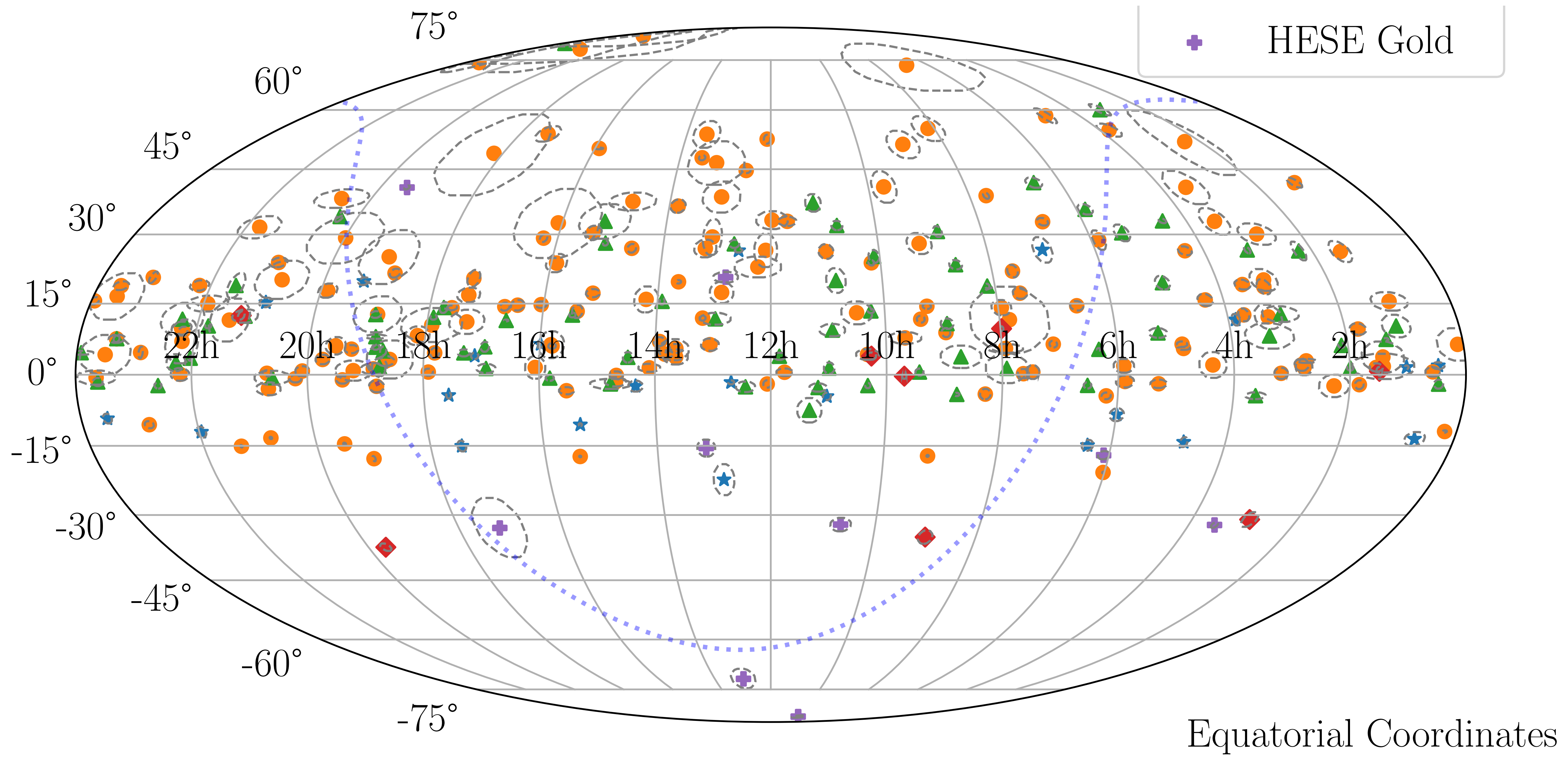
$$\pi^\pm \to 3\nu + e^\pm$$

*γ-rays with E >100 TeV are also useful
to probe hadronic cosmic rays

Astrophysical Neutrino Observations

IceCube 2013 PRL





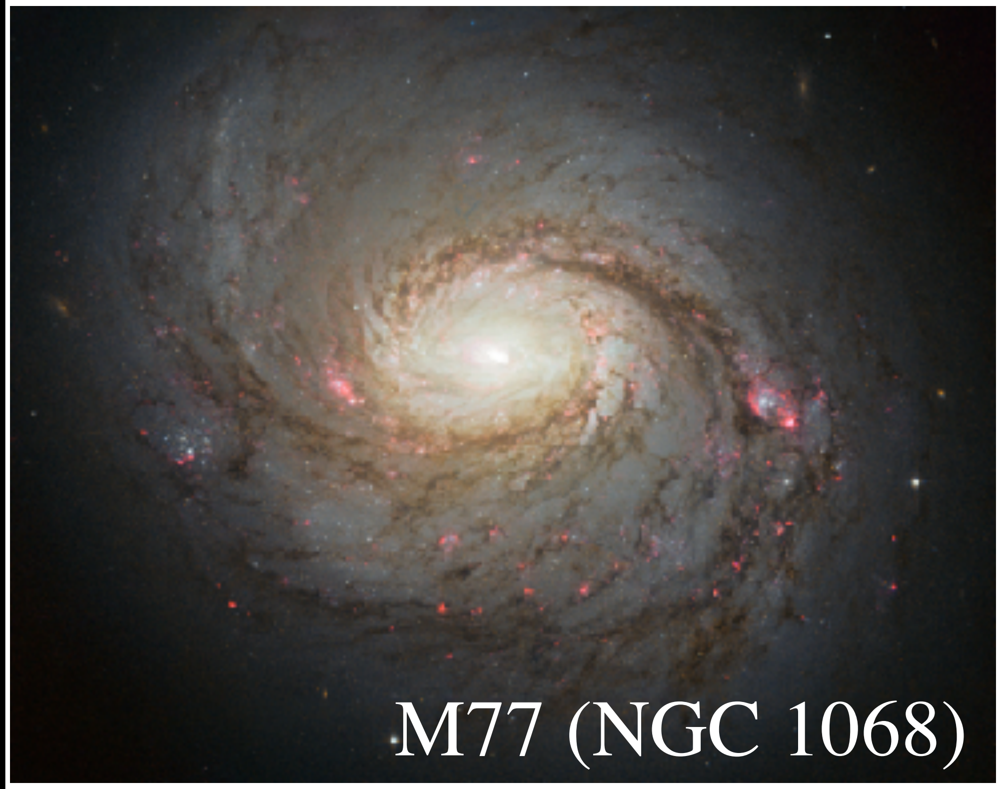
IceCat-1 2023

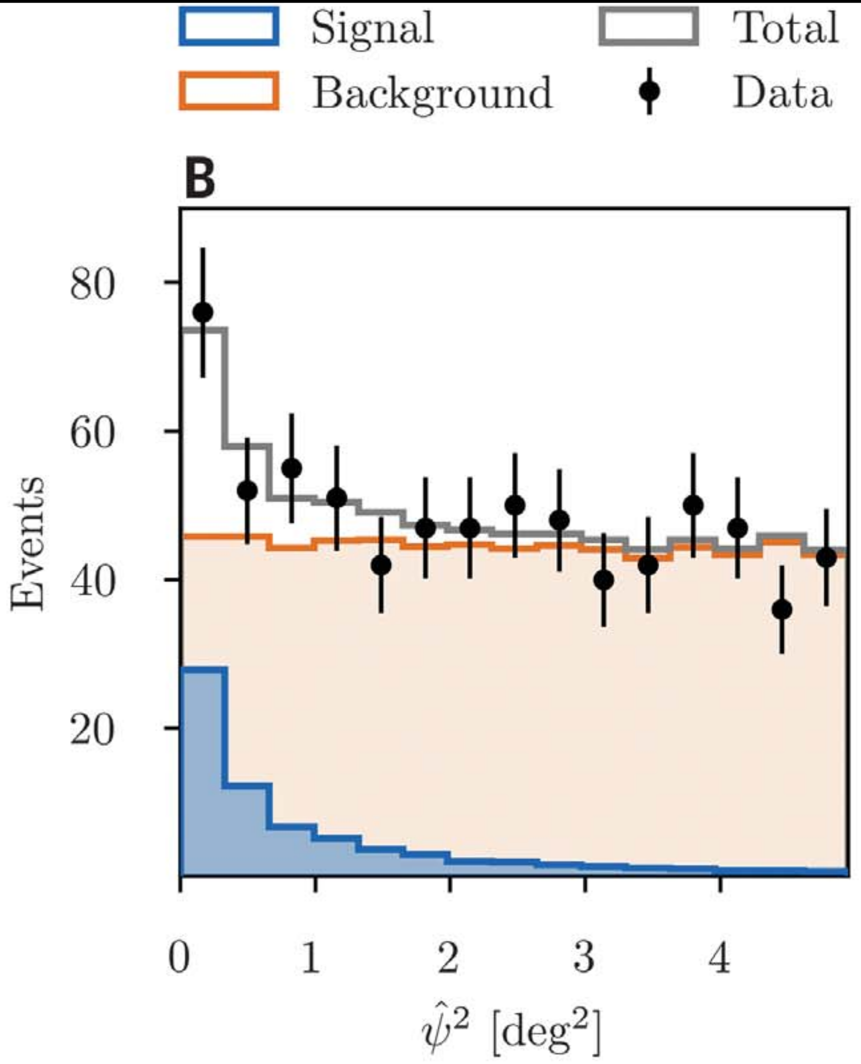
- IceCube has been detecting astrophysical neutrinos
- Arrival direction: consistent with isotropic —> cosmic HE neutrino background
- Soft spectrum: F_{E_ν} @ TeV > F_{E_ν} @ PeV
- **Origin of cosmic neutrinos are a new big mystery**

Recent Progresses in Neutrino/γ-ray Observations

- IceCube TeV–PeV Neutrinos

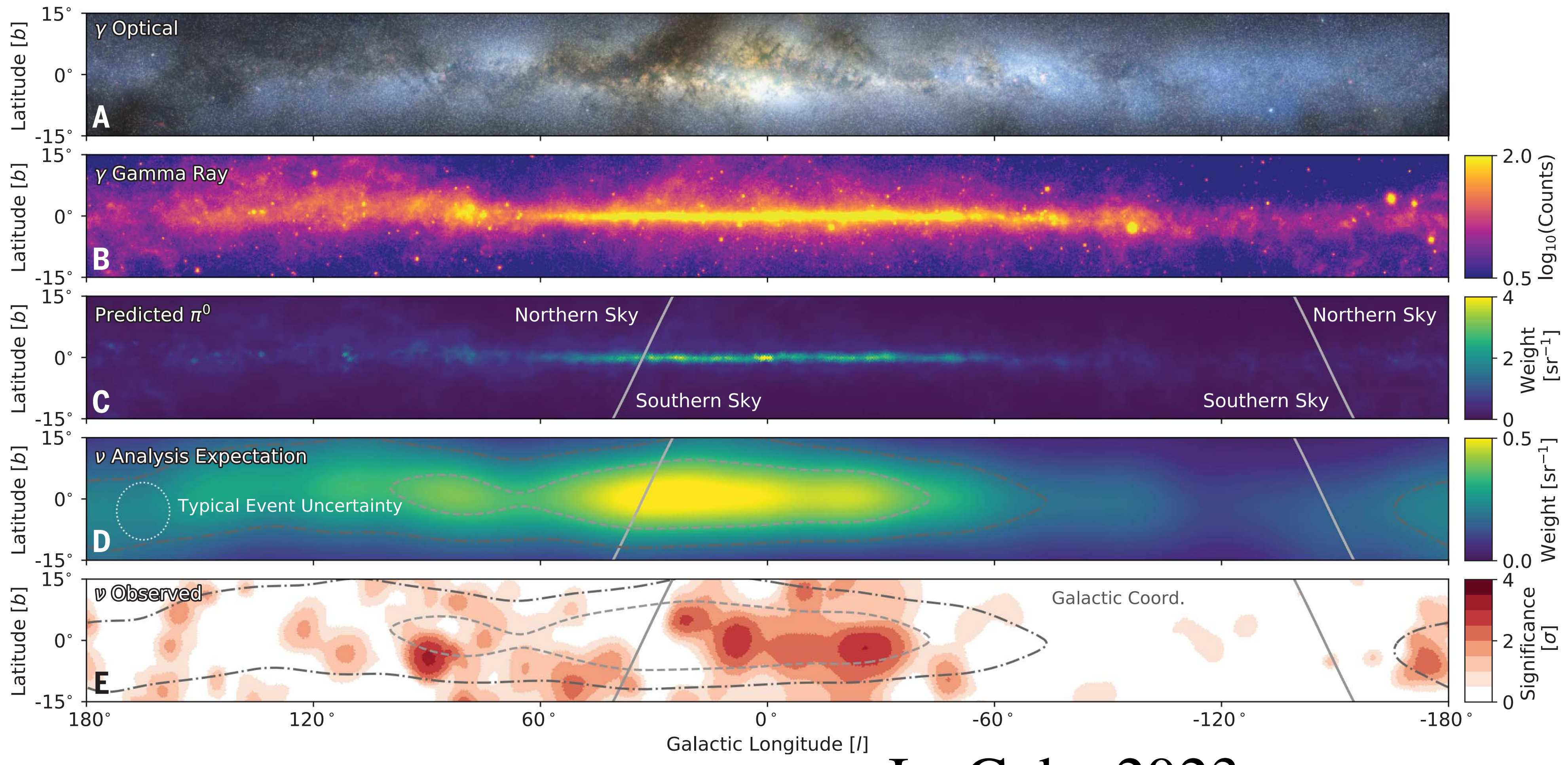
- Seyfert Galaxies





IceCube 2022; see also Y.Inoue+2020, S. Inoue+2022

- Milky Way Galaxy

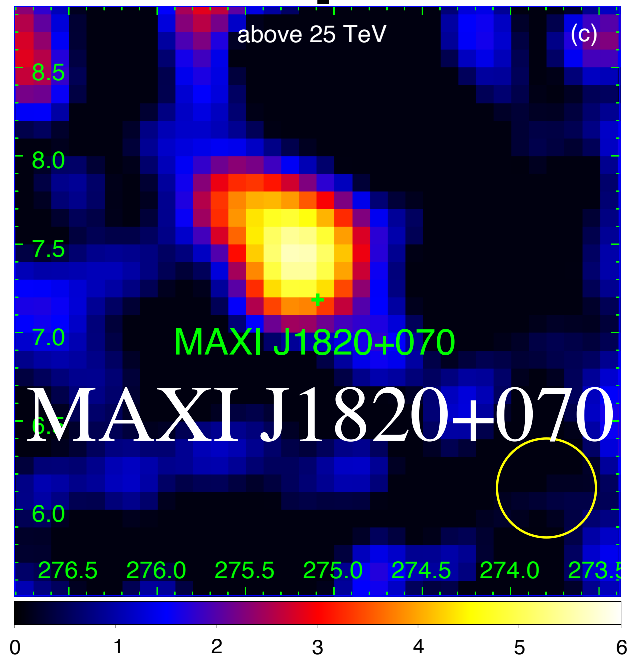


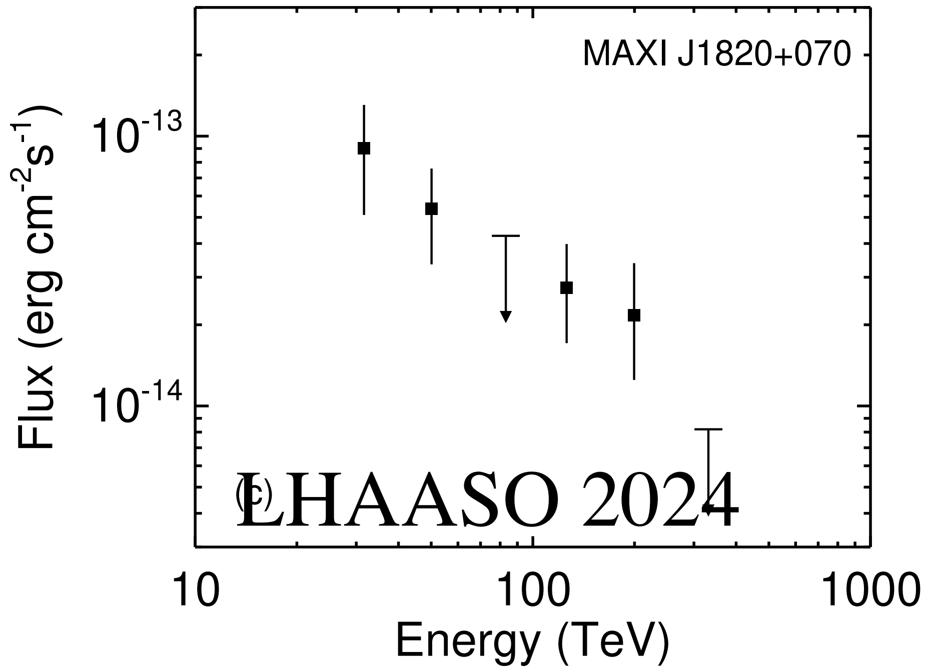
IceCube 2023

- LHAASO TeV–PeV gamma-rays

- Micro-quasars

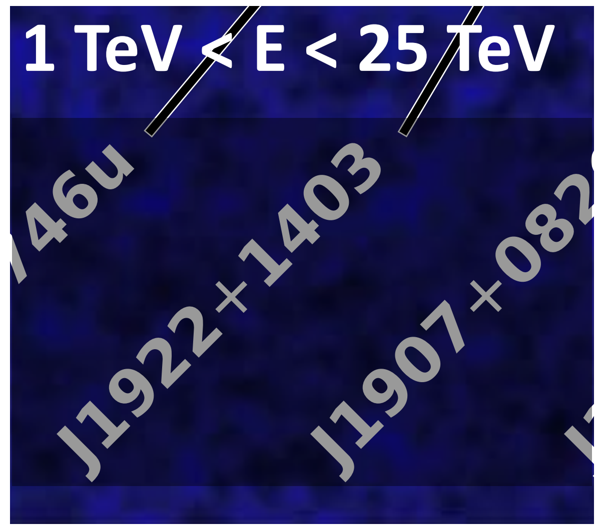
Cf.) Talk by Shidatsu-san

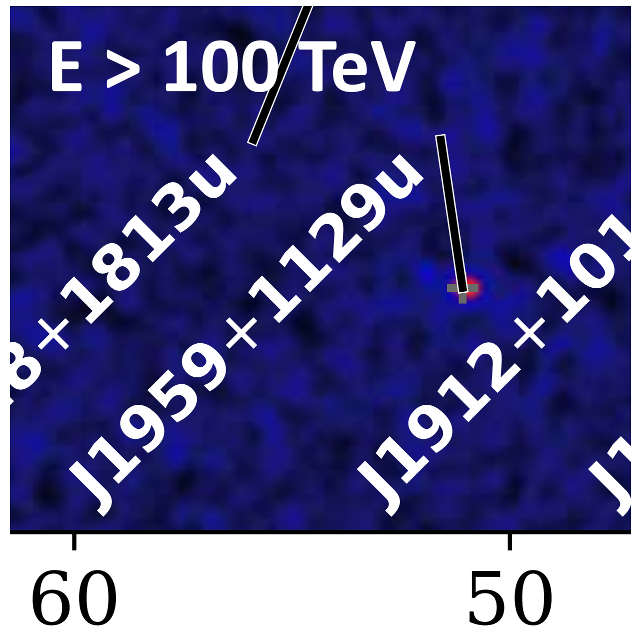


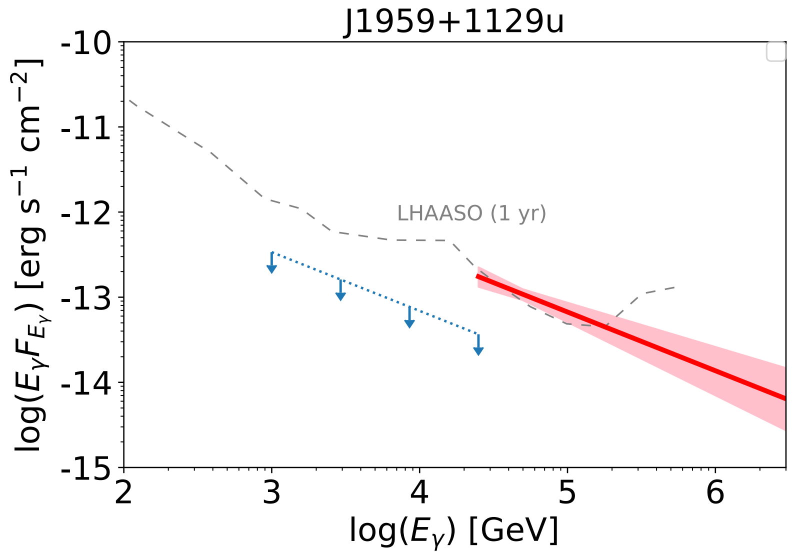


- Dark Sources

LHAASO 2024

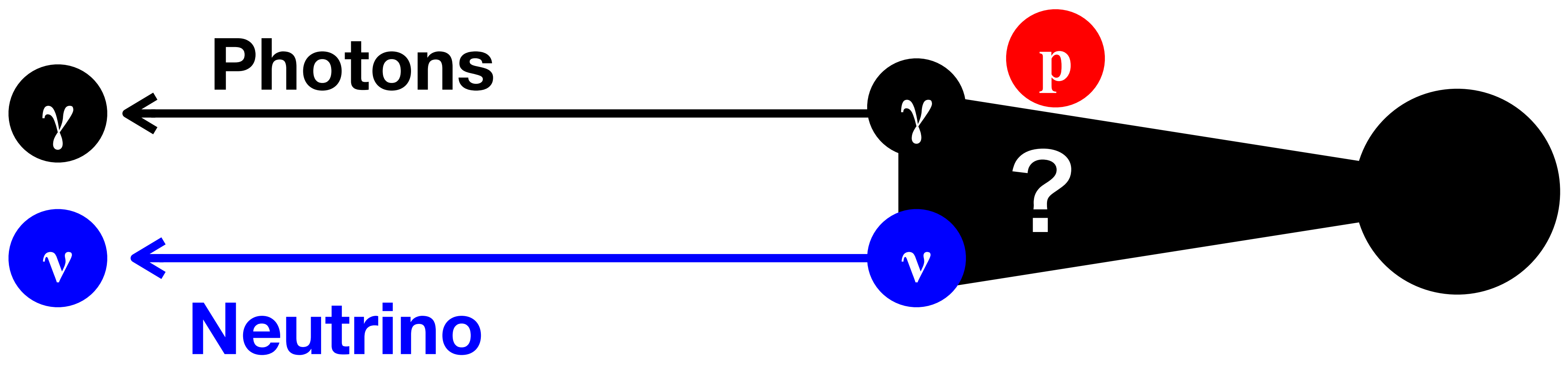




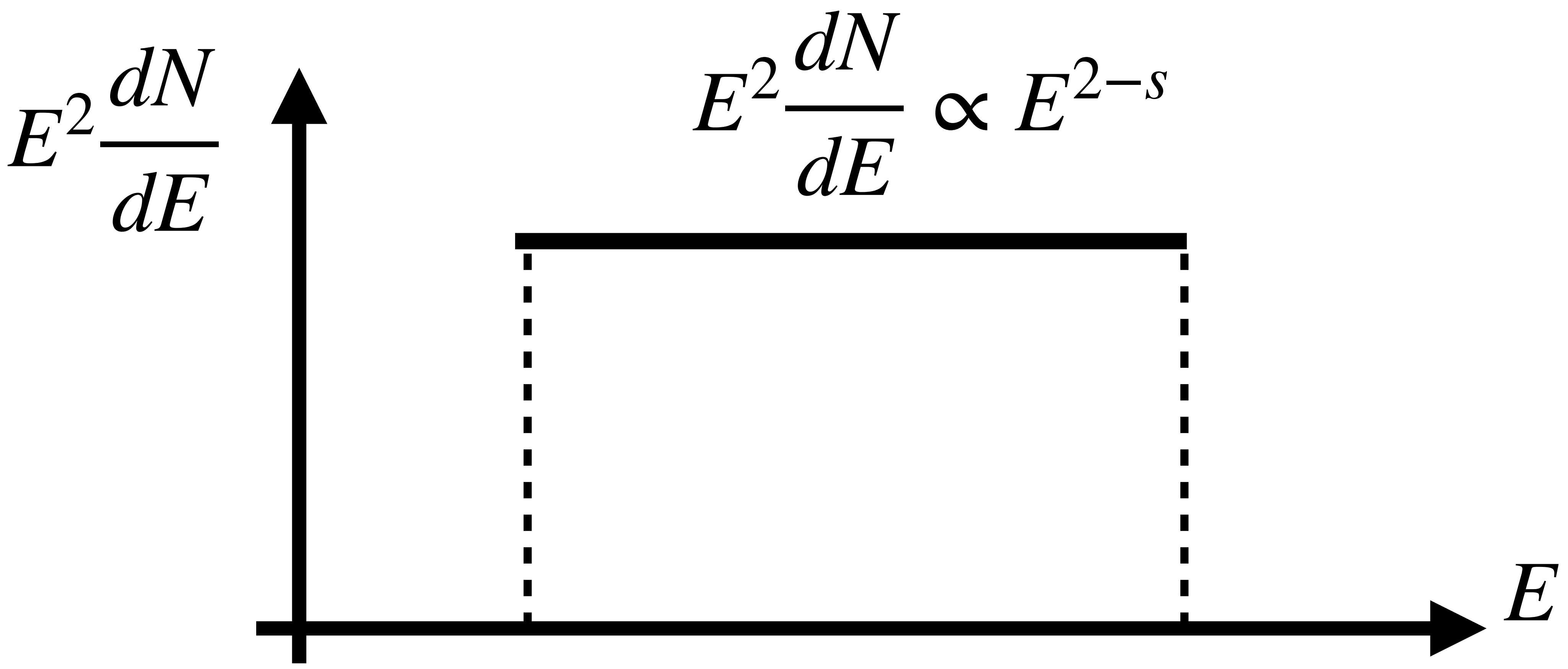


Main-stream Model Assumptions

- One-zone approximation
  - Ignore spacial structure for simplicity



- Single power-law proton distribution with index $s \sim 2$
  - Ignore cosmic-ray acceleration process for simplicity



Our strategy: beyond one-zone & single power-law

- One-zone approximation
  - Ignore spacial structure for simplicity

- **Multi-emission regions**
  - **Multi-zone modeling**
  - **1D hydro-simulations + neutrino emission calculation**
  - **3D hydro-simulations + neutrino emission calculation**

- Single power-law proton distribution with index $s \sim 2$
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- **Considering cosmic-ray acceleration & diffusion**
  - **Semi-analytic treatment**
  - **MHD + test particle simulations**
  - **MHD + transport equations**

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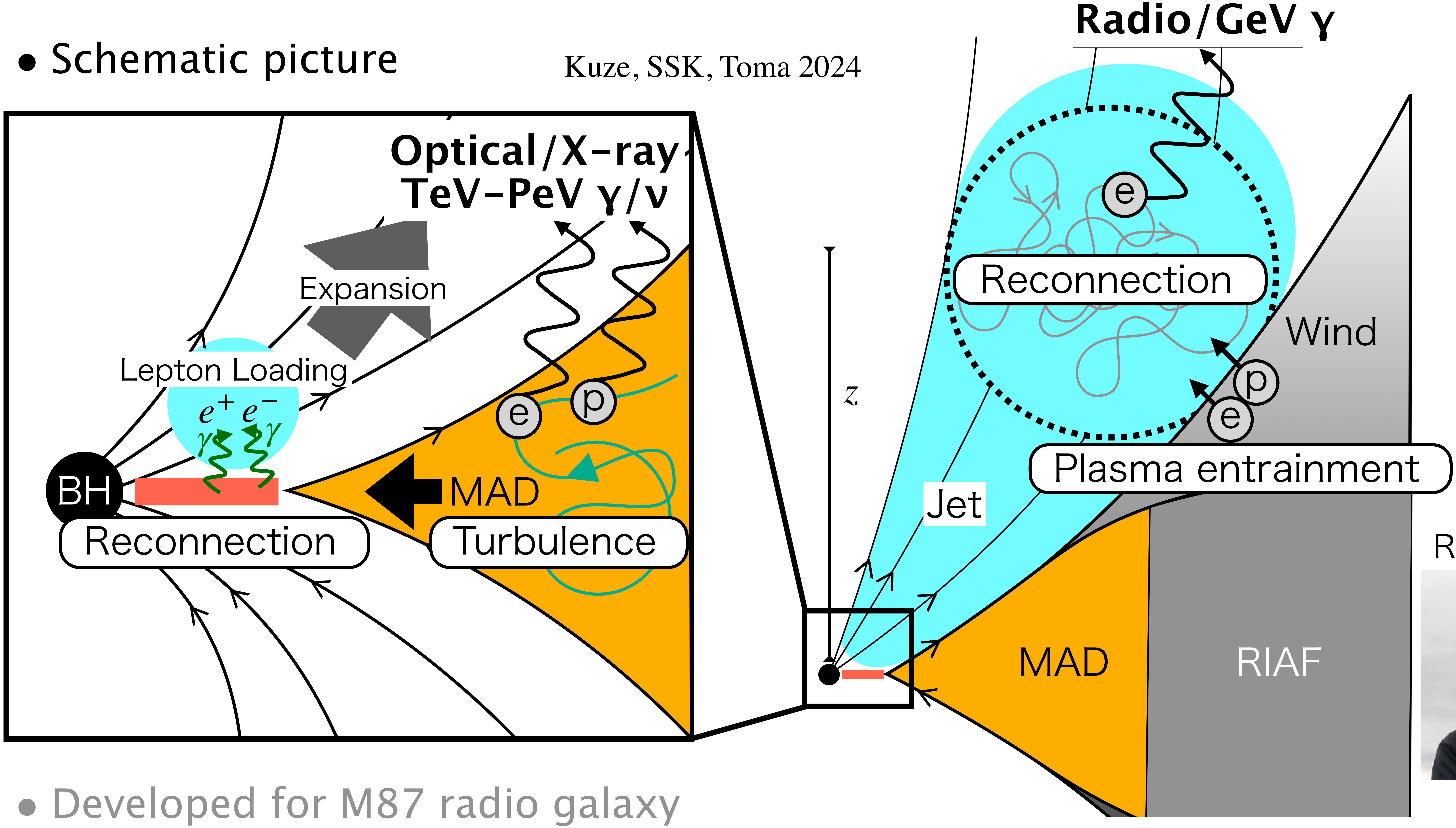
Neutrino & γ-rays from Micro-quasars

- Schematic picture

Kuze, SSK, Toma 2024

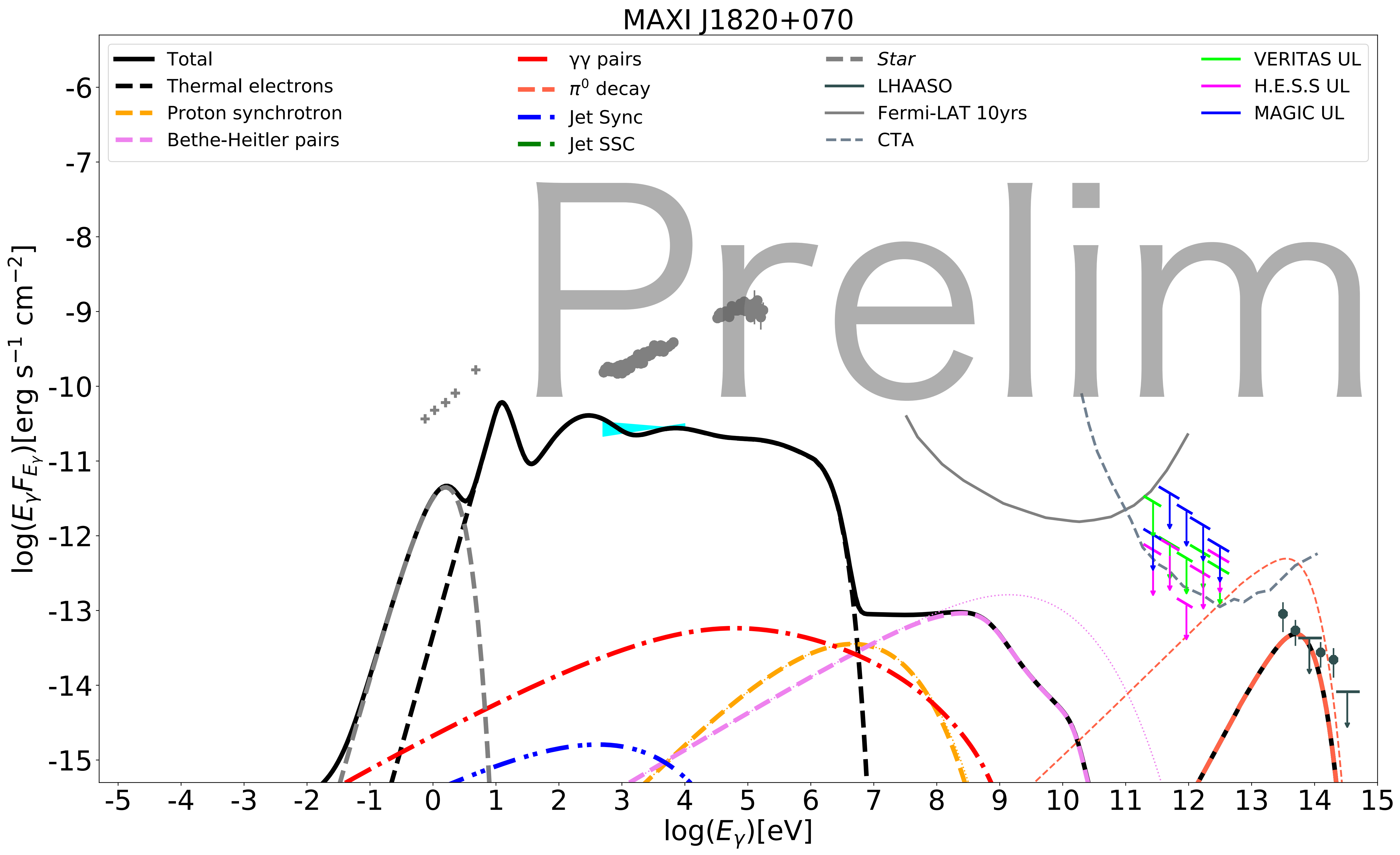


Riku Kuze

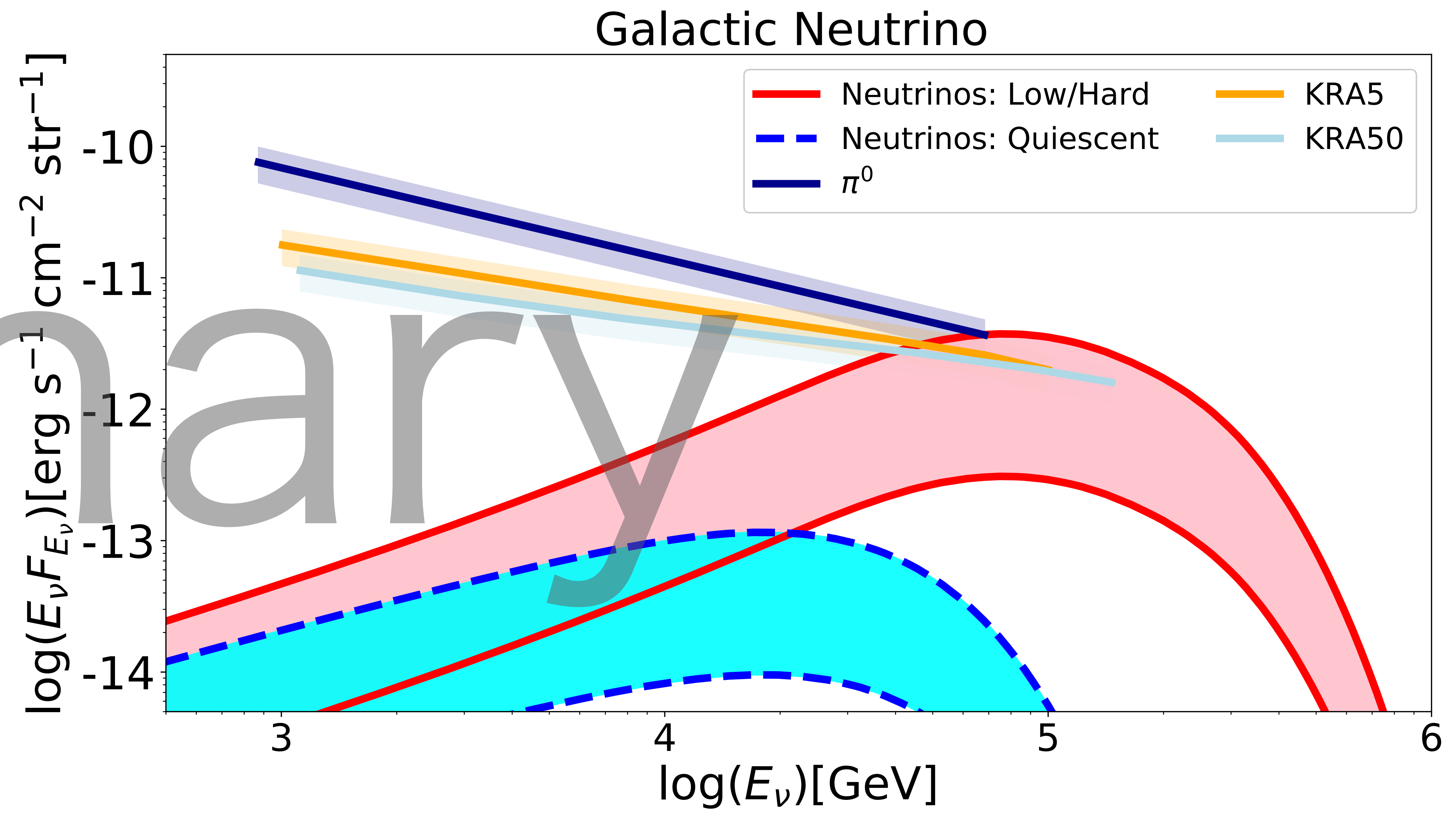
- Developed for M87 radio galaxy

Neutrino & γ-rays from Micro-quasars

- Our model can explain multi-wavelength data for MAXI J1820 & Cyg X-1



- Micro-quasars could potentially contribute to Galactic neutrinos?

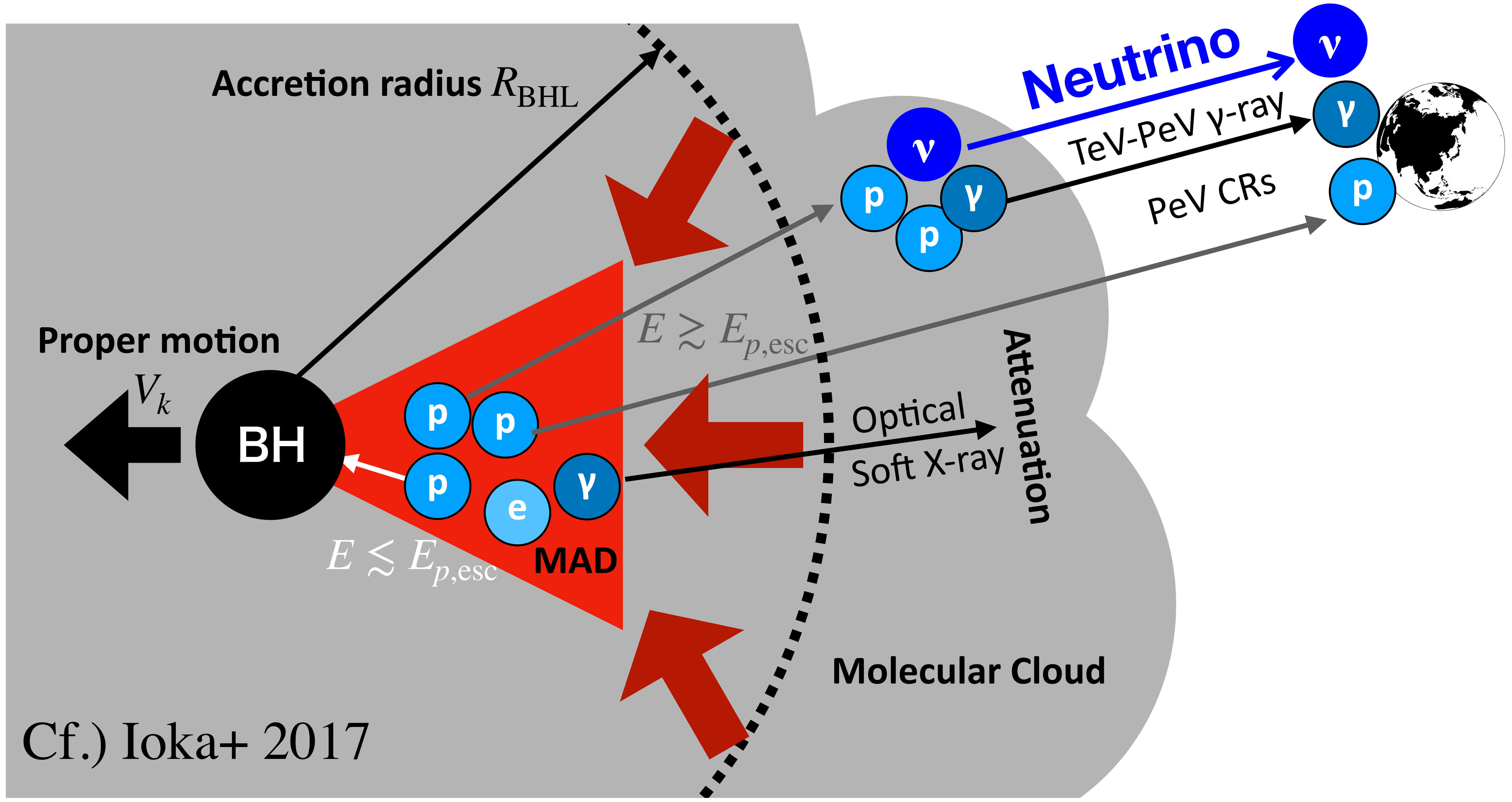


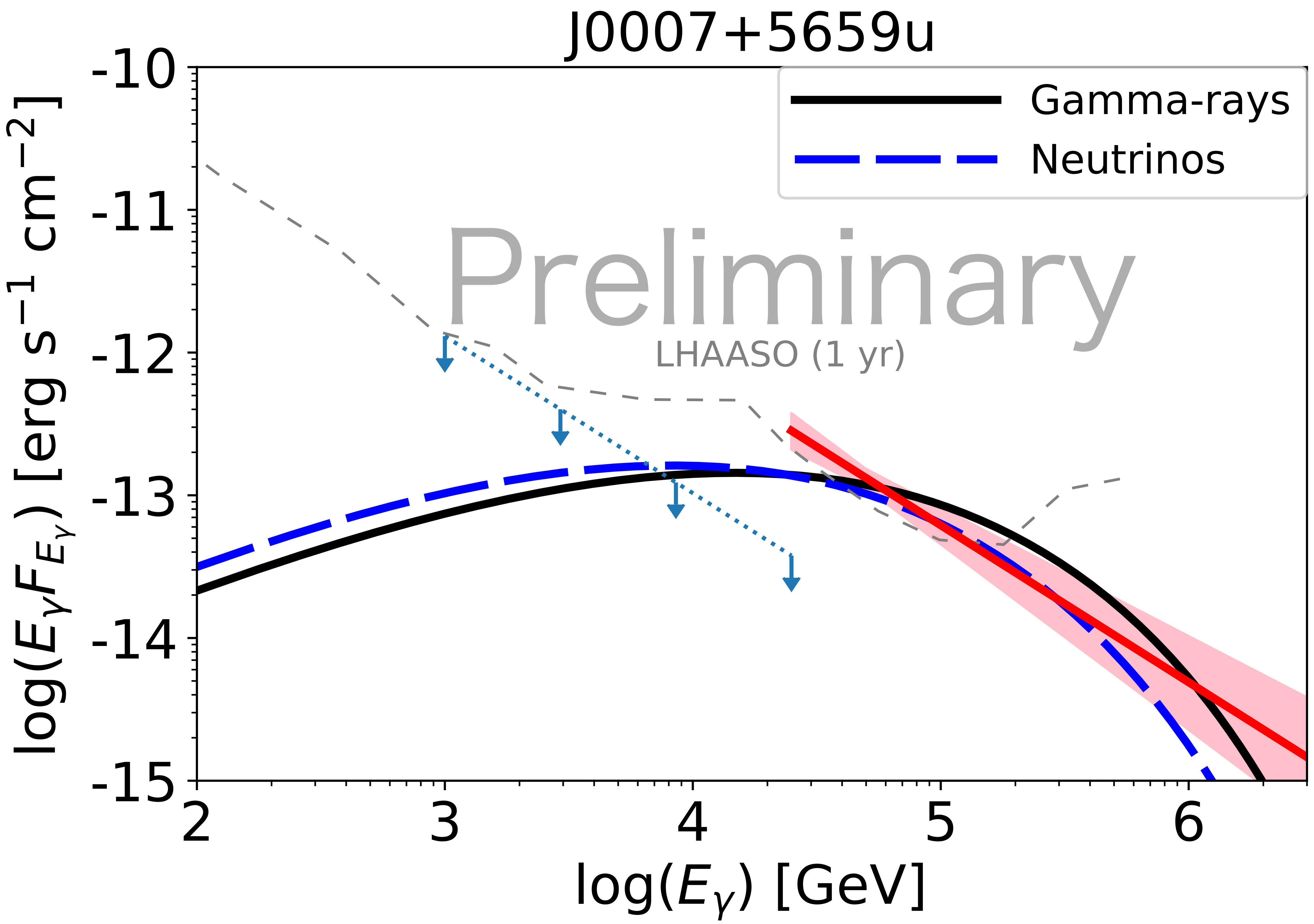
Kuze, SSK, Fang in prep.

Riku Kuze

Neutrino & γ-rays from Isolated black holes

- ~ 10^8-10^9 isolated black holes in our Galaxy   SSK, Tomida, Kobayashi, Kin, Zhang in prep.
- Some of them are in molecular clouds
  => high accretion rate => PeV CR acceleration
  => Neutrino & γ production by interaction with molecular gas





- IceCube-Gen2 might be able to detect them if we stack ~ 10 objects
- IBHs can emit GeV-TeV γ from their magnetosphere   Poster by Kin-san

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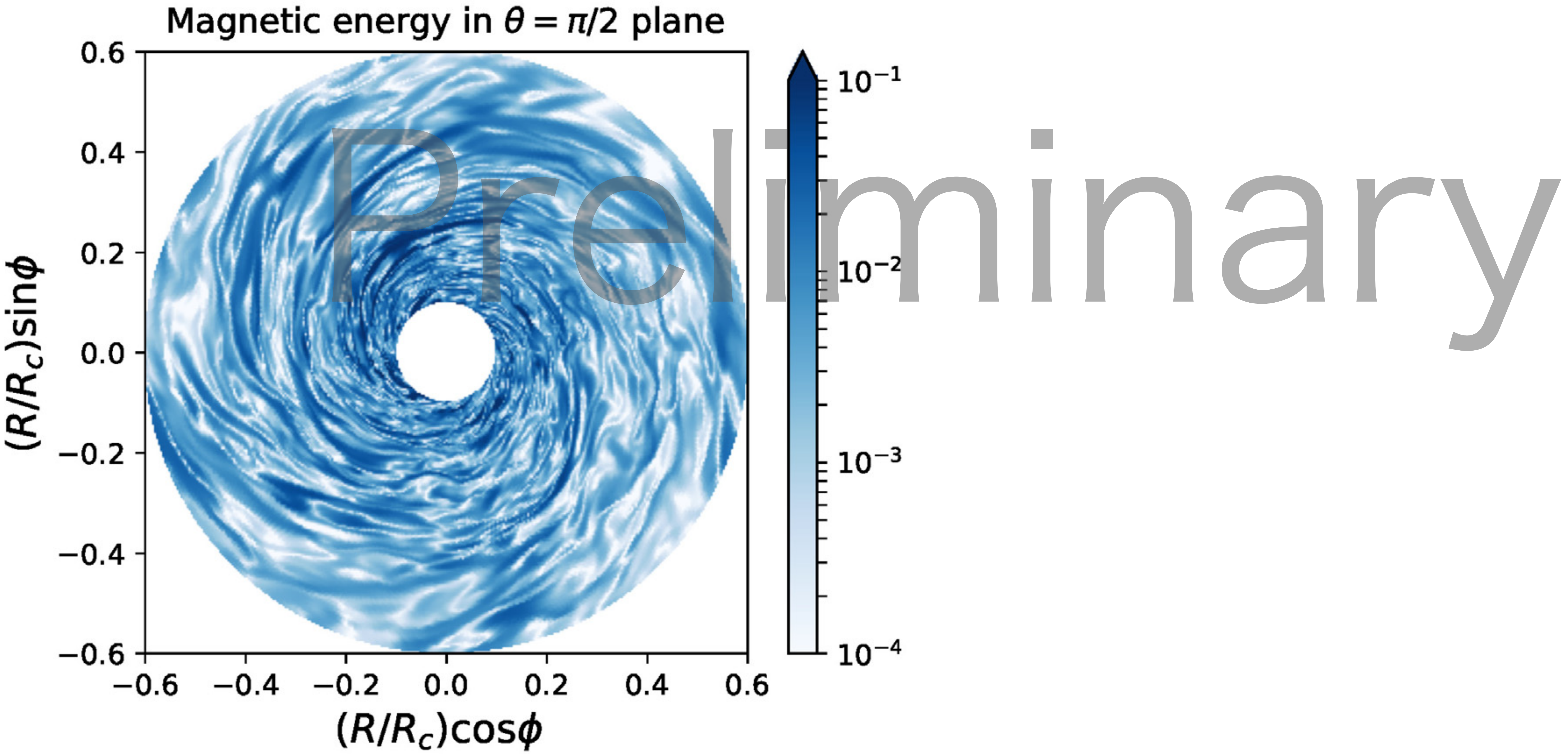
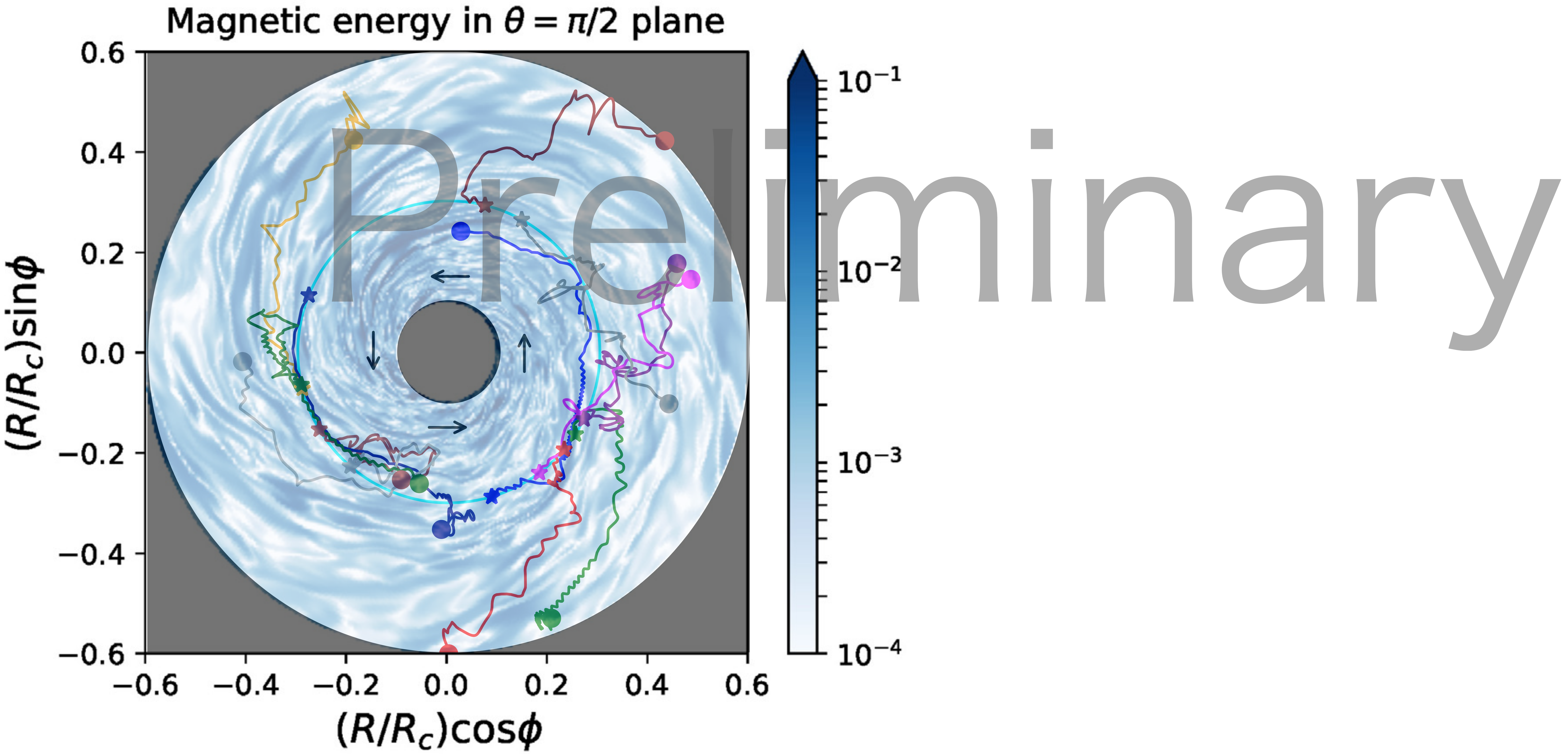
MHD + Test particles

- MHD: turbulence field in large scales
-

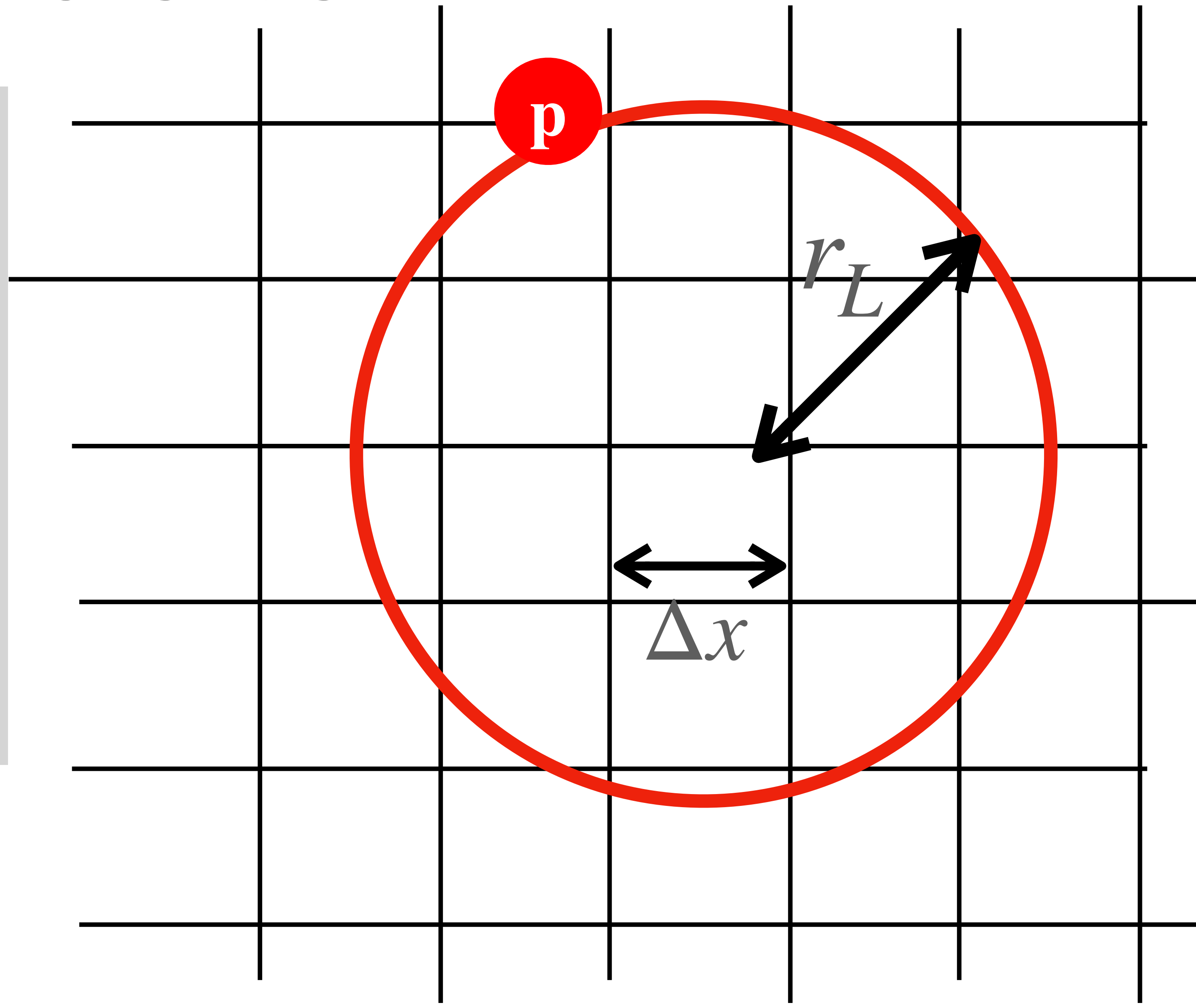


MHD + Test particles

- MHD: turbulence field in large scales
- Particles: orbits & energy evolution



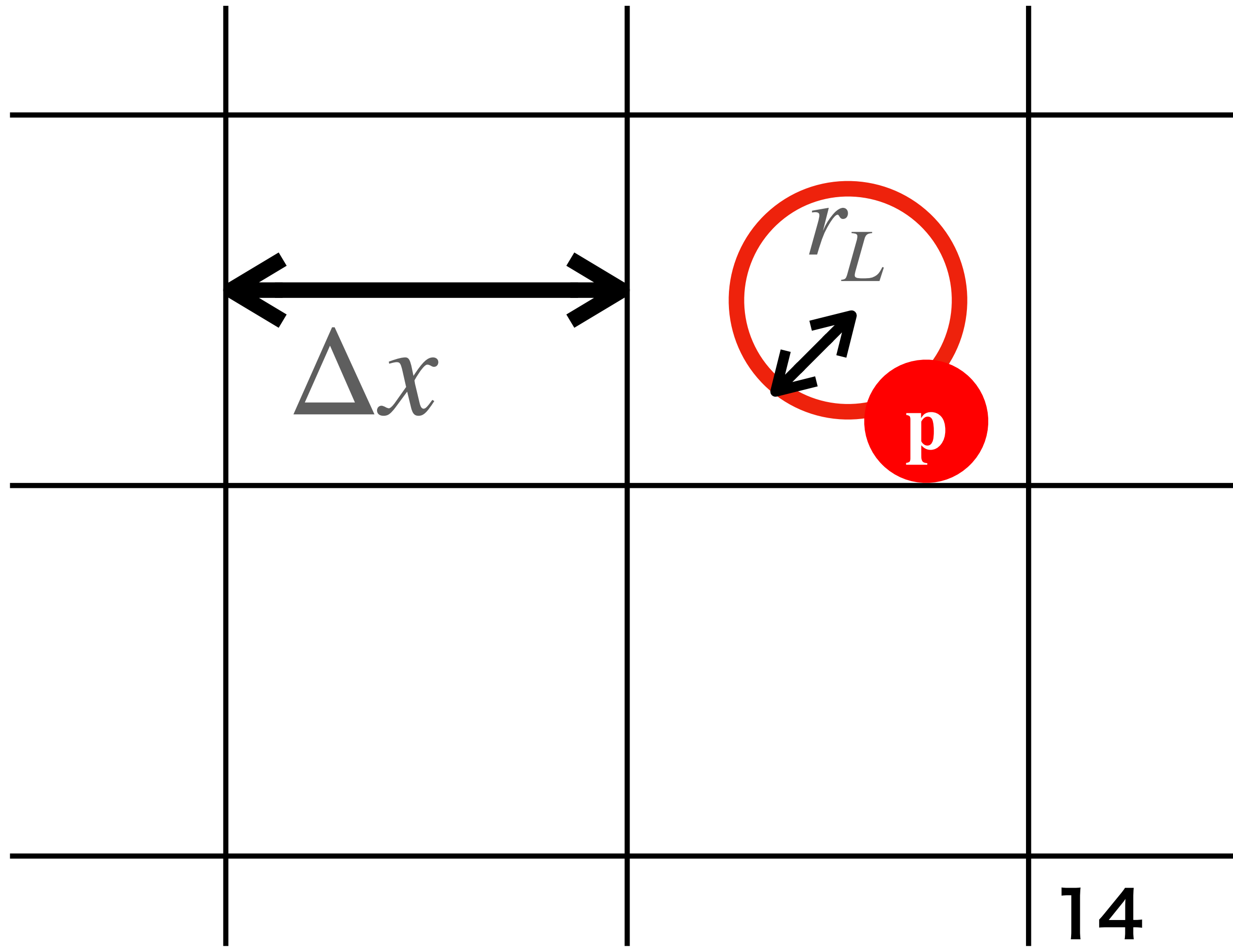
Particle Acceleration Simulations & CR transports in MHD simulation data



- MHD Simulation + Test Particle Simulation
  - Solve orbits of CR particles using MHD data sets
  - Enable us to obtain diffusion coefficients
  - limited to CRs with $r_L > \Delta x$

SSK et al. 2016, 2019, in prep

Model for diffusion coefficient

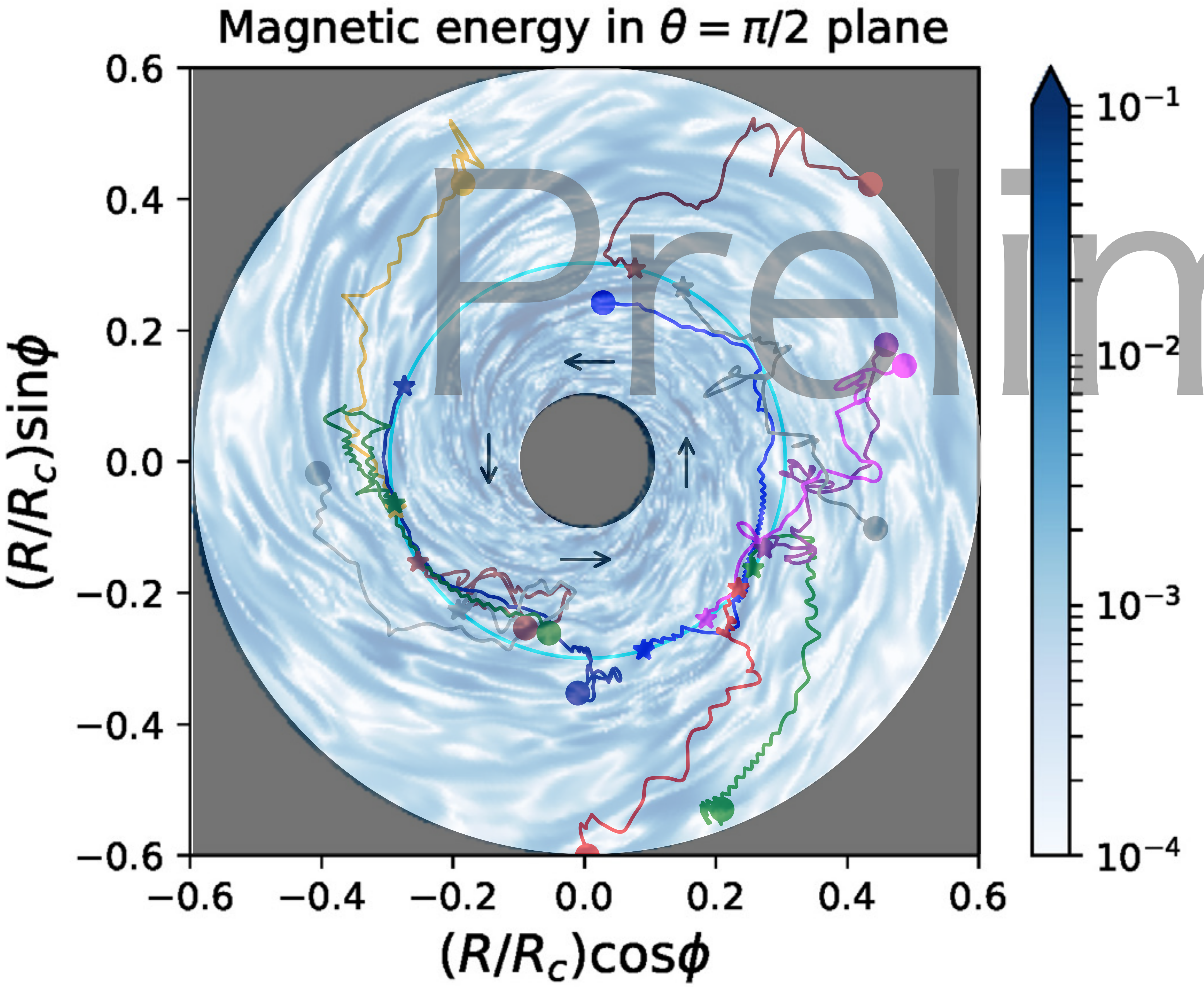


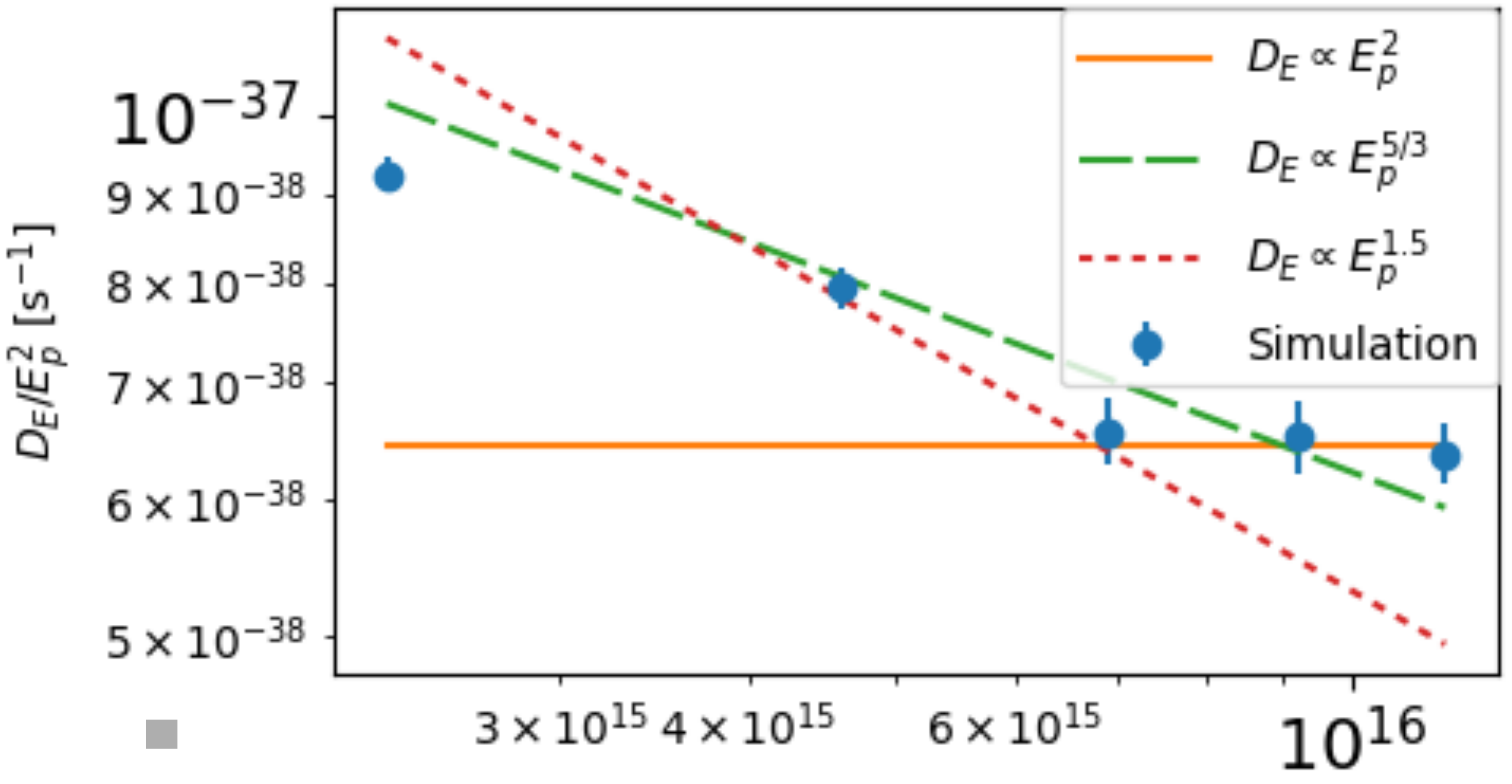
- MHD Simulation + CR Transport simulation
  - Solve CR transport equation using MHD data sets
  - We need a model for diffusion coefficients
  - We can obtain useful info for CRs with $r_L < \Delta x$

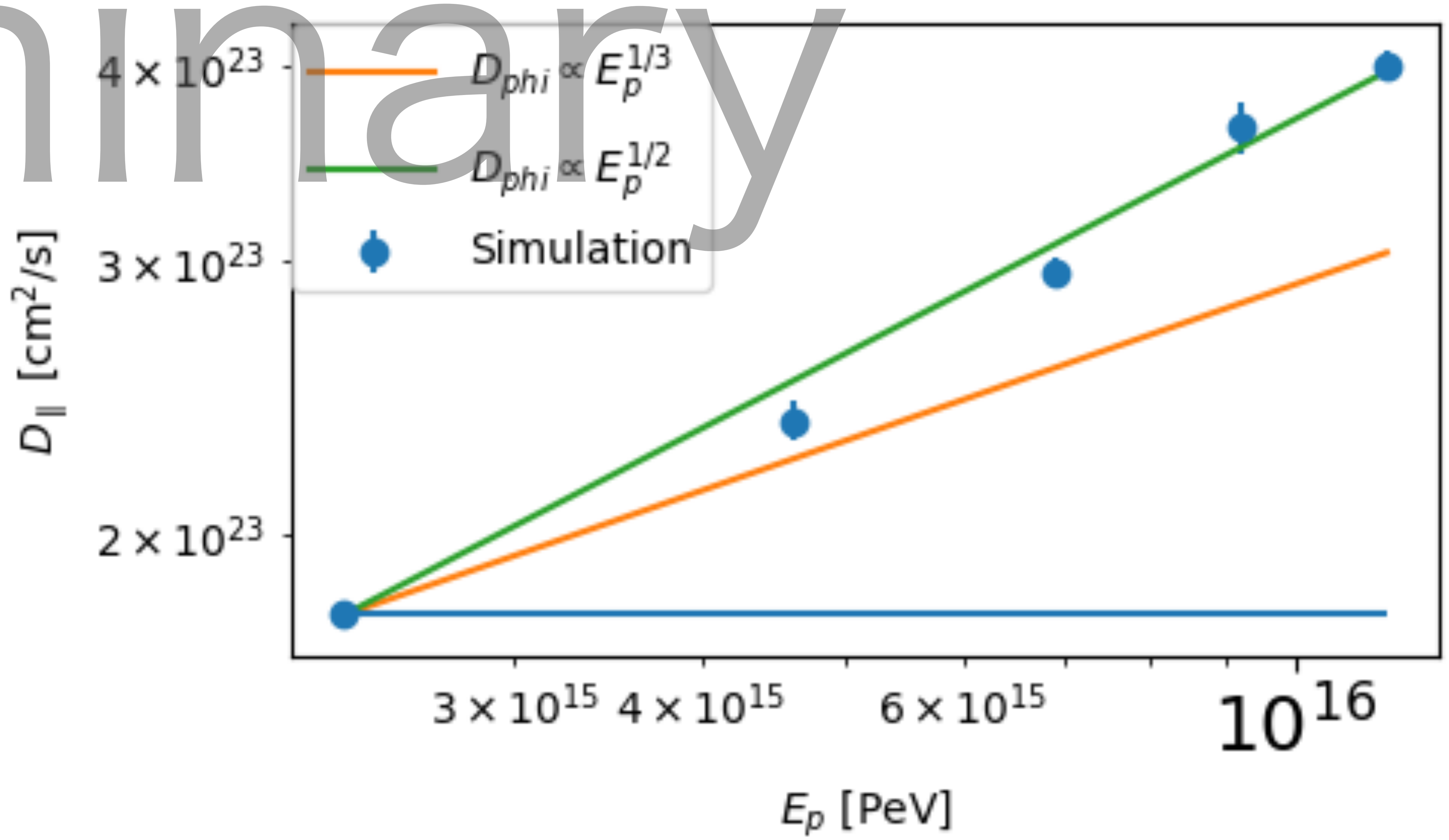
Talk by Ishizaki-san; Poster by Kawashima-san

MHD + Test particles

- MHD: turbulence field in large scales
- Particles: orbits & energy evolution
  => **Diffusion coefficients in configuration & energy spaces**







Summary

- High-energy Neutrinos are unique signals
  to probe hadronic cosmic rays & dense medium
- Our strategy: **beyond one-zone & single power-law**
- We are constructing neutrino emission models

- Steady Sources
  - Seyfert Galaxies (Radio-quiet AGN)
    Talk by Murase-san; Poster by Sakai-san
  - Low-luminosity AGN
    Poster by Kawashima-san
  - **Galactic Black Hole**
    This talk; Poster by Kin-san
  - Pulsar Wind Nebulae (PWN)
    Talk by S. Tanaka-san
  - Galactic Wind
    Talk by Shimoda-san

- Transient Sources
  - Pulsar-powered Supernovae
    Talk by Ekanger-san
  - Interaction-powered Supernovae
    Talks by Moriya-san & Ekanger-san
  - Afterglows of Gamma-ray Bursts
    Posters by Obayashi-san, Kusafuka-san
  - Internal dissipation of GRBs
    Talk by Nakama-san; Posters by Matsui-san, Wada-san
  - Tidal Disruption Events
    Talk by Murase-san