Particle Acceleration in Accretion Flows and Related High-energy Signatures

Tohoku University

Shigeo S. Kimura

References:

Murase, SSK, Meszaros, 2020, PRL, 125, 011101
Kheirandish, Murase, SSK, 2021, ApJ, 922, 45
SSK, Murase, Meszaros, 2021, Nat. Comm., 12, 5615
SSK, Tomida, Murase 2019, MNRAS, 485, 163
SSK et al. in preparation

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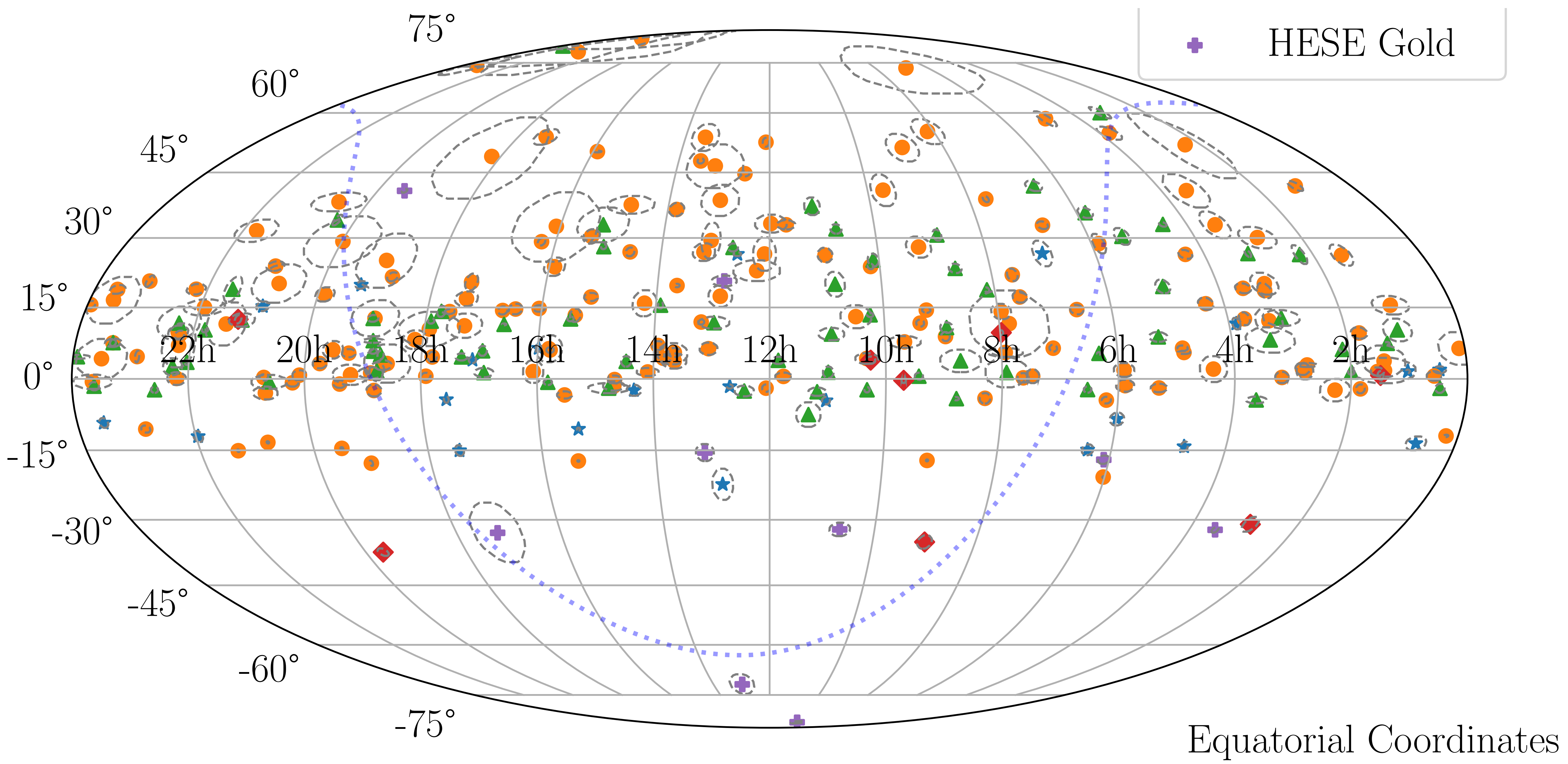
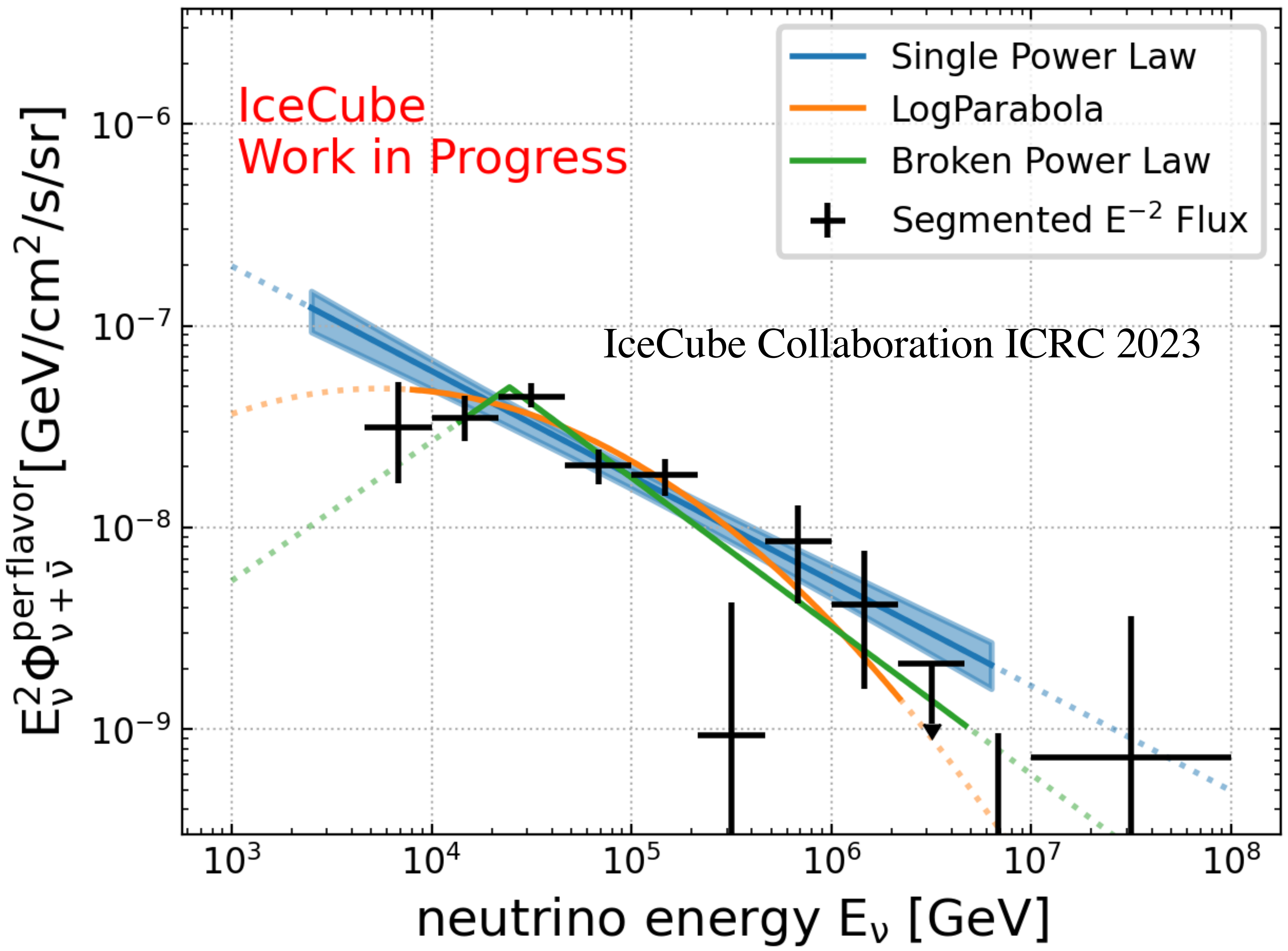
Cosmic Neutrino Background Spectrum

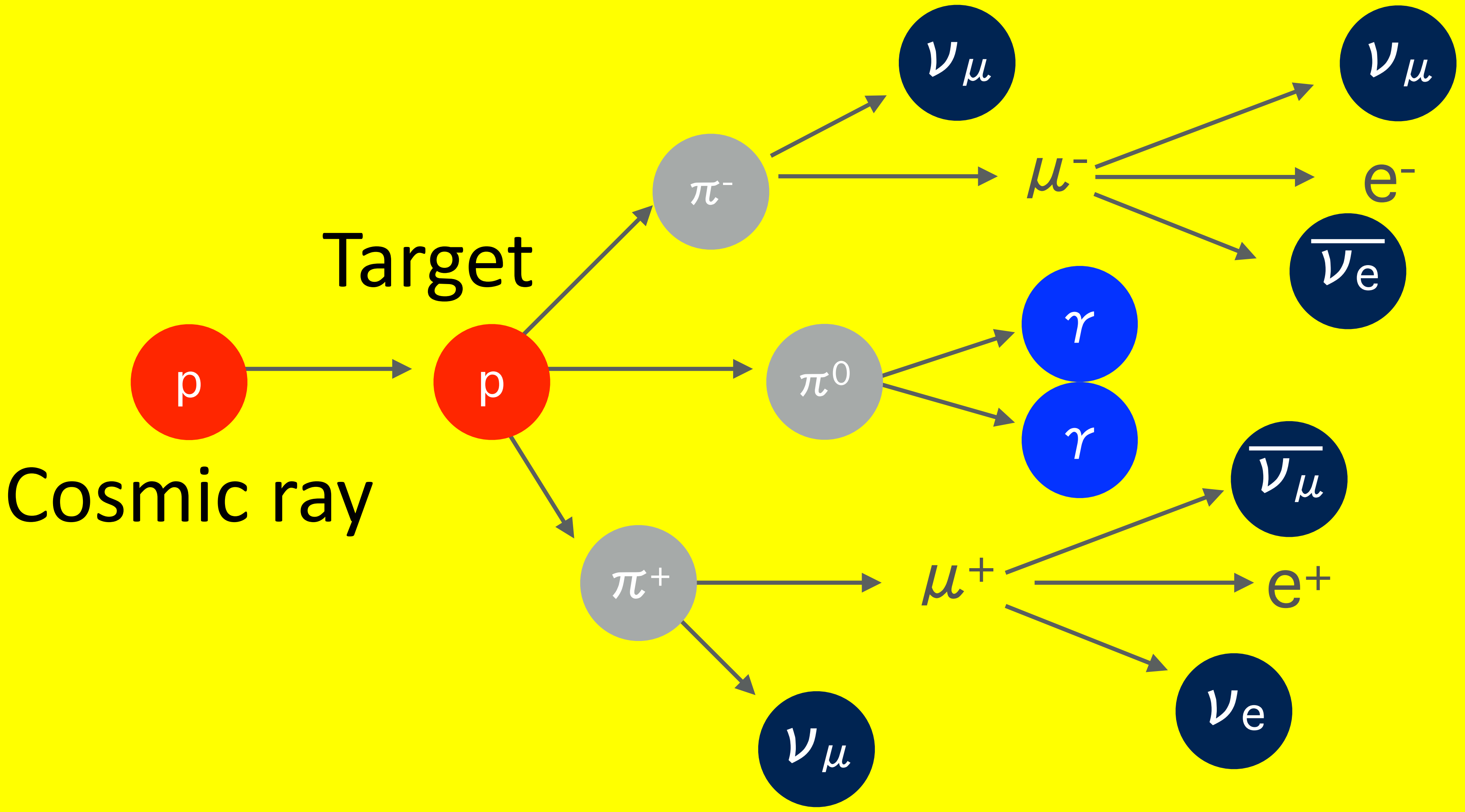




- IceCube has been detecting astrophysical neutrinos
- Arrival direction: consistent with isotropic —> cosmic HE neutrino background
- Soft spectrum: F_{E_ν} @ TeV > F_{E_ν} @ PeV
- **Origin of cosmic neutrinos are a new big mystery**

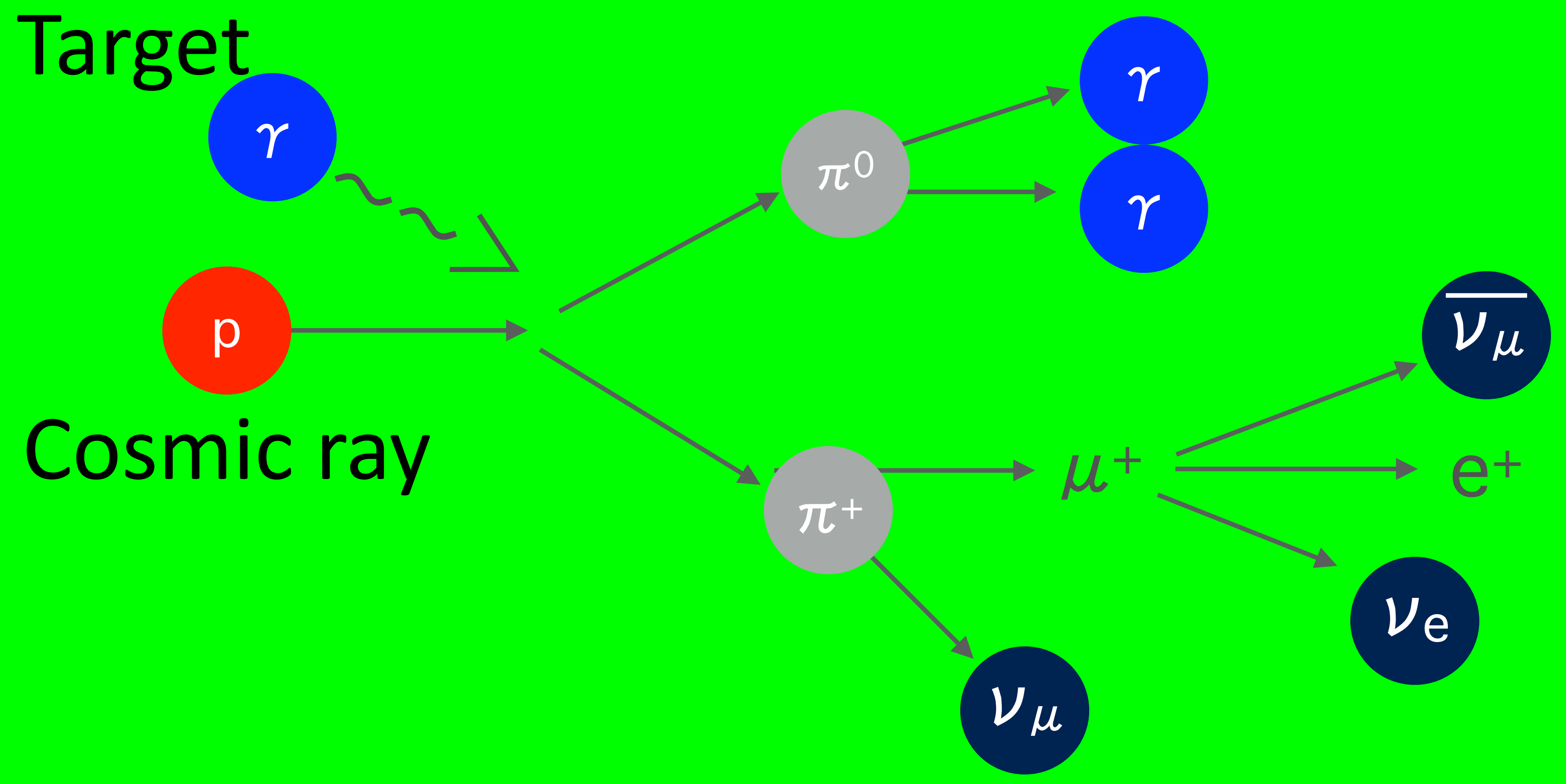
High-energy neutrino production

- pp inelastic collision



- p+p → p+p+π
- π± → 3ν+e
- π0→2γ

- Photomeson production (pγ)



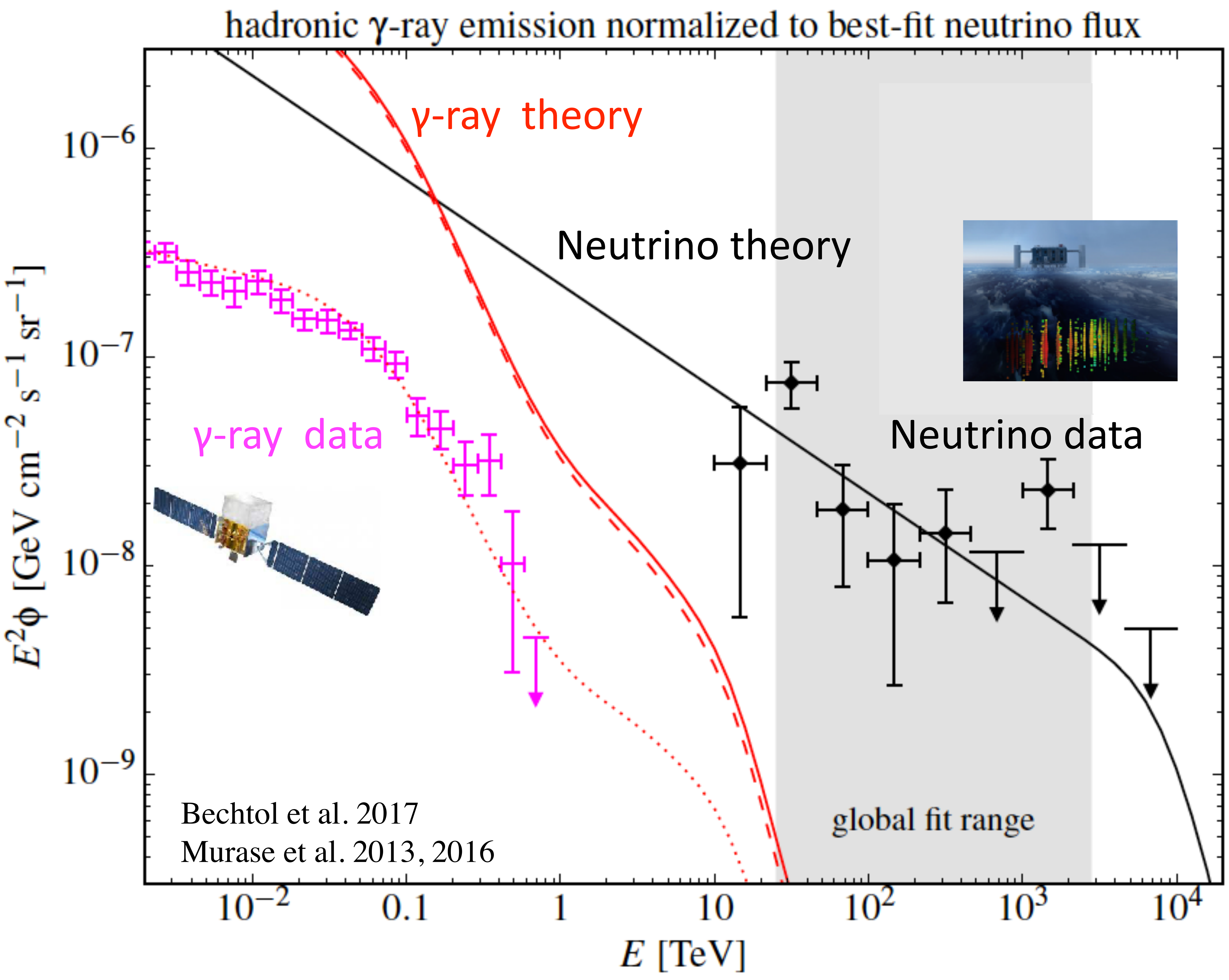
- p+γ → p+π
- π± → 3ν+e
- π0→2γ

Interaction between CRs & photons/nuclei → Neutrino production

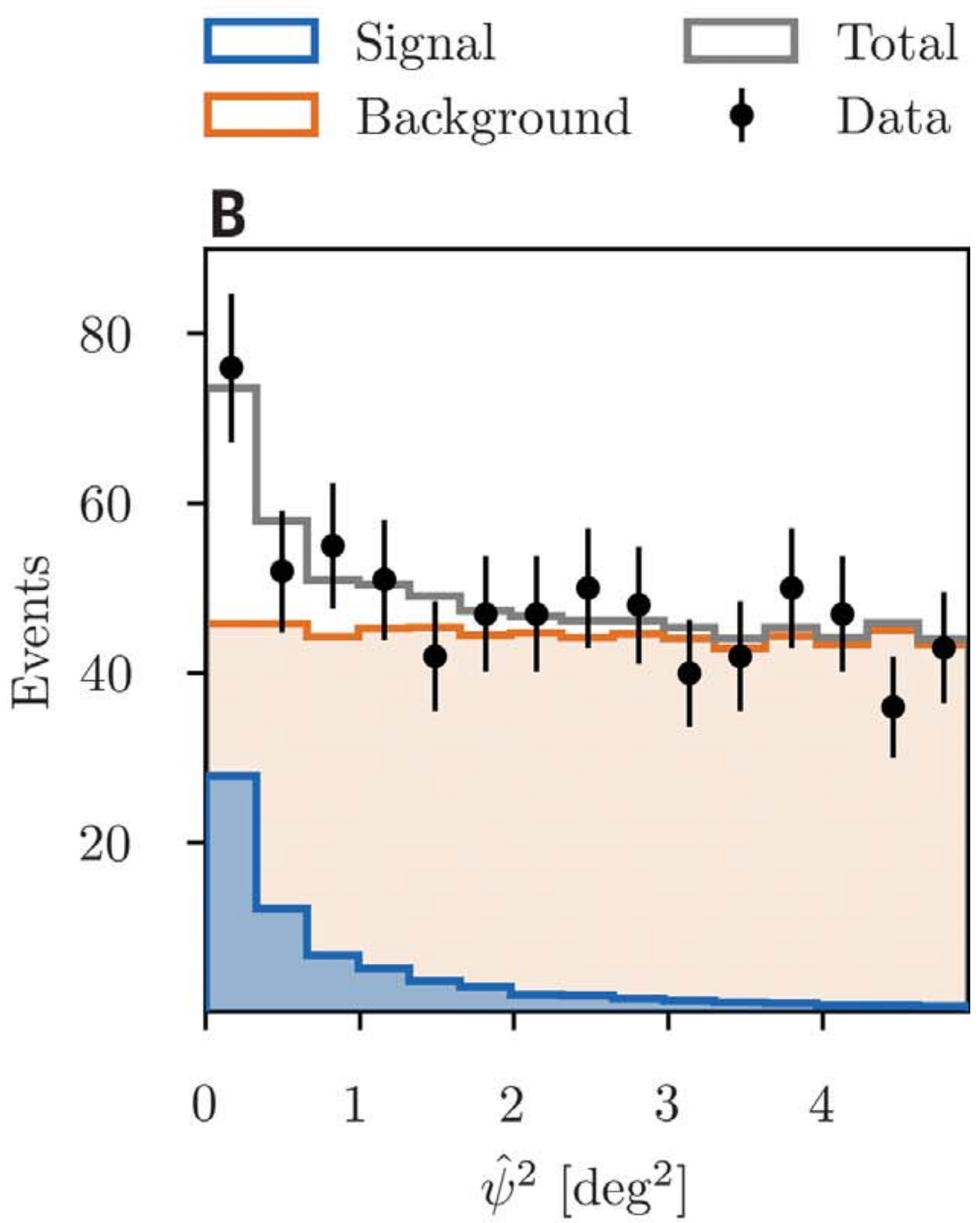
Gamma-rays inevitably accompanied with neutrinos

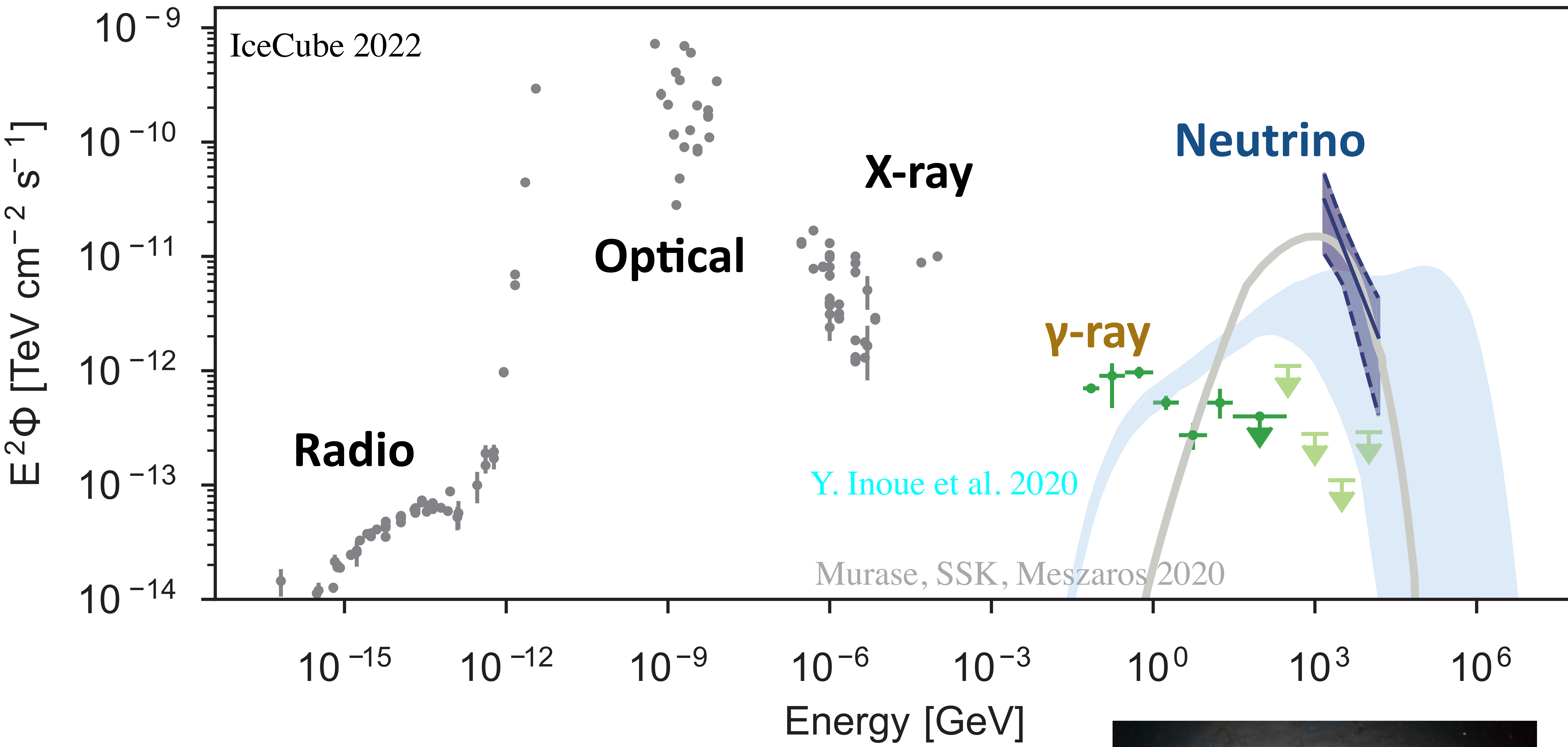
Gamma-ray Constraint on Neutrino Sources

- Fermi Satellite is measuring cosmic gamma-ray backgrounds
- ν flux@10 TeV > γ-ray flux@100 GeV
- Consider sources from which both γ & ν can easily escape
  → fit theory to neutrino data
  → γ-ray theory >> γ-ray data
- **γ-ray needs to be absorbed inside the sources (hidden source)**
  $\gamma + \gamma \to e^+ + e^-$
- X-rays efficiently absorbs GeV γ-rays

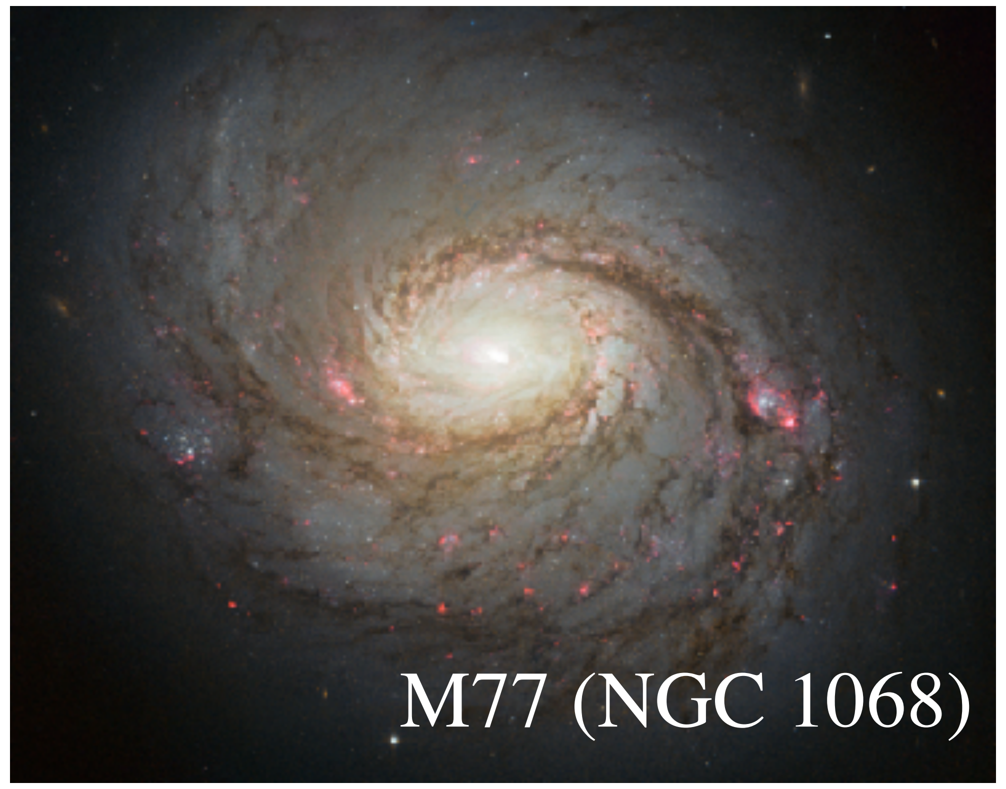


Evidence of Neutrinos from Seyferts





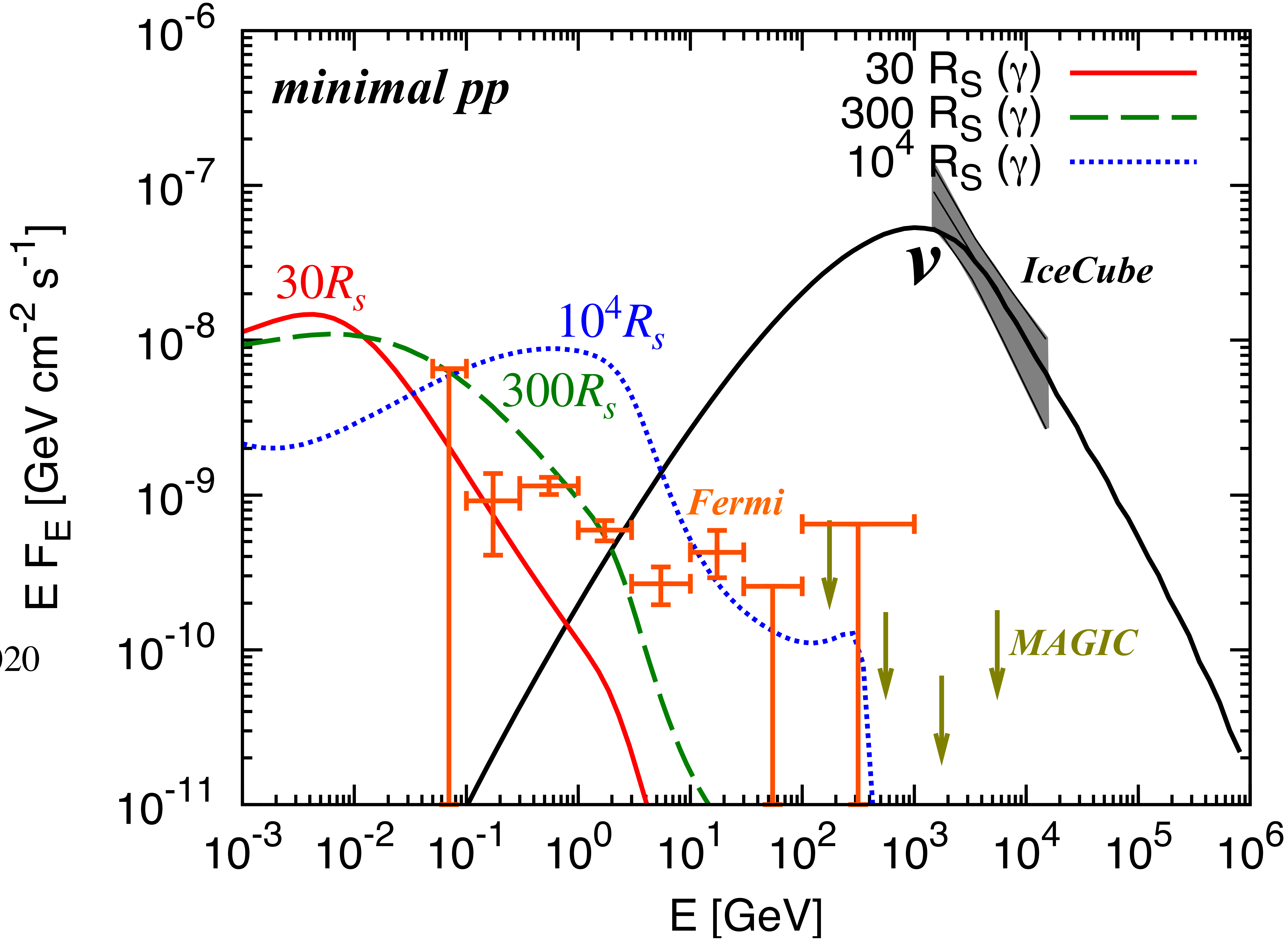
- Point source search with 10-year data set with an improved analysis method
- Cataloged source search result: 2.9σ (2020) —> 4.2σ (2022)
- $F_\nu \gg F_\gamma$ —> Hidden neutrino source
- **γ-ray, CR & ν production sites are under debates. Let's discuss possibilities.**



γ-ray constraints

Murase 2022

- NGC 1068 should be hidden sources
  —> demands compact emission sites
- EM cascade modeling with γ-ray data:
  —> Emission region: $R \lesssim 100 R_S$
- Possible regions of neutrino emission:
  - **magnetized accretion flows (coronae)** Murase, SSK+ 2020
  - Accretion shocks Inoue+ 2020
  - disk winds Inoue+ 2022

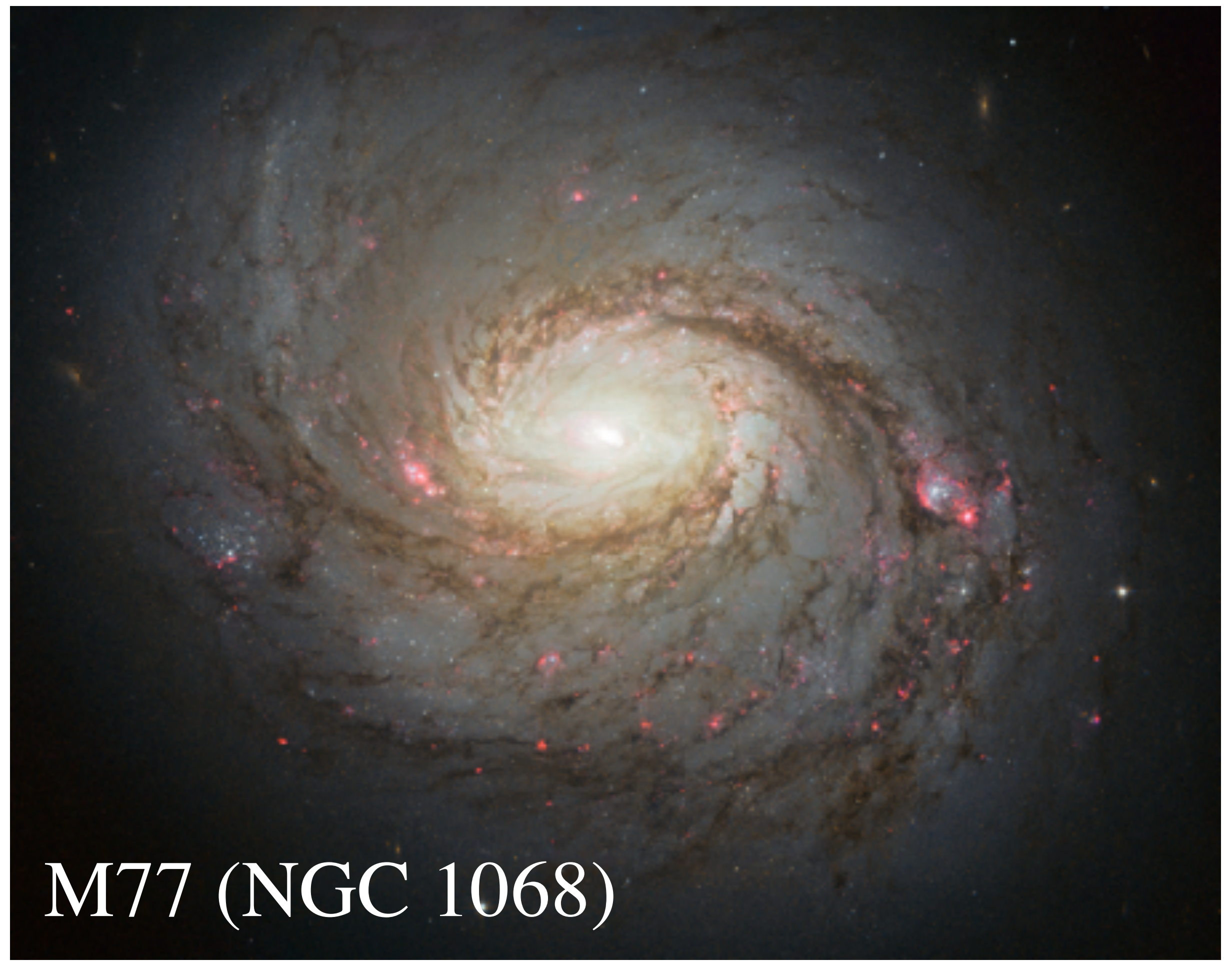


SANE & MAD

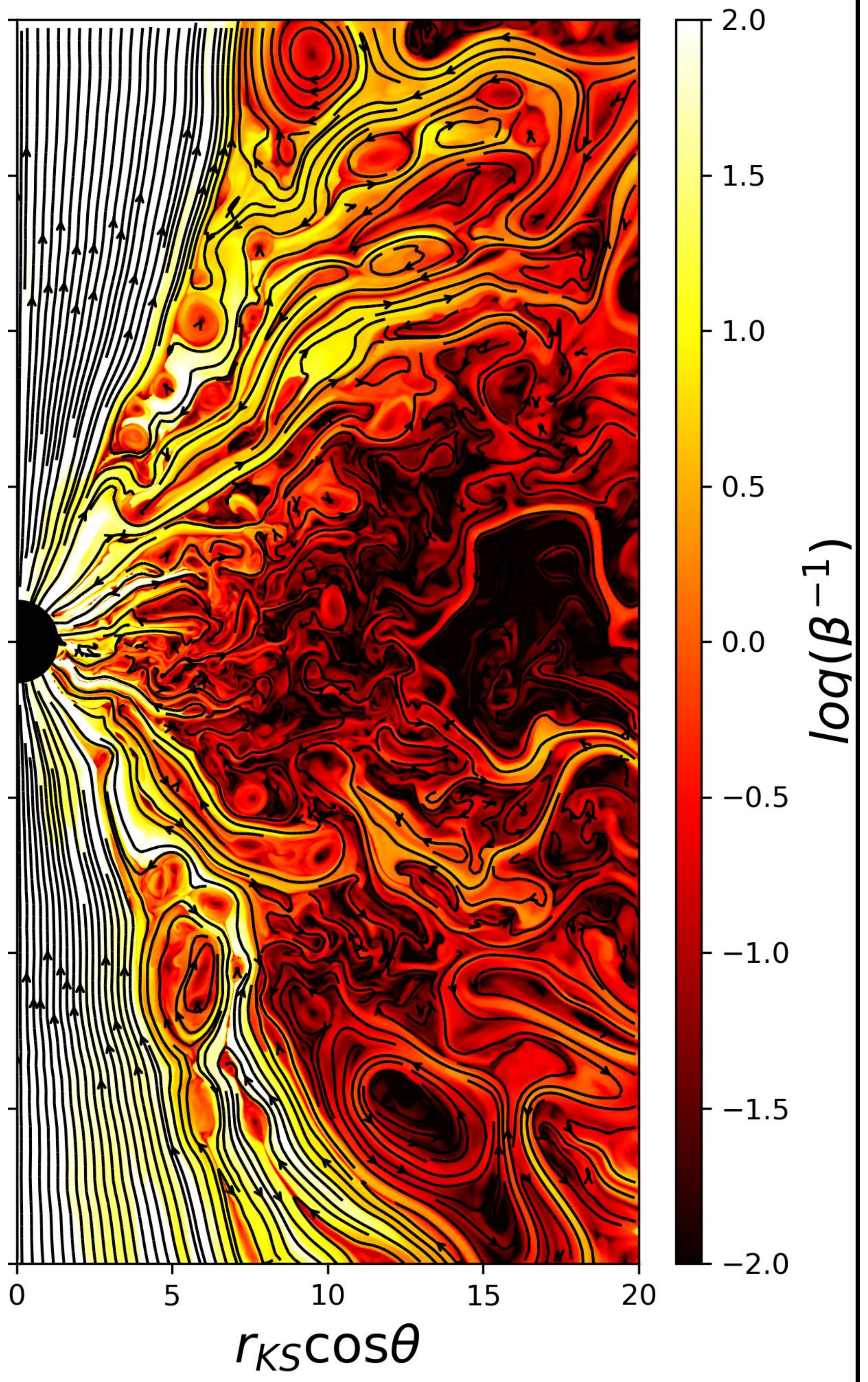
Narayan et al. 2012

- Standard and Normal Evolution (SANE)

Ripperda et al. 2020



M77 (NGC 1068)

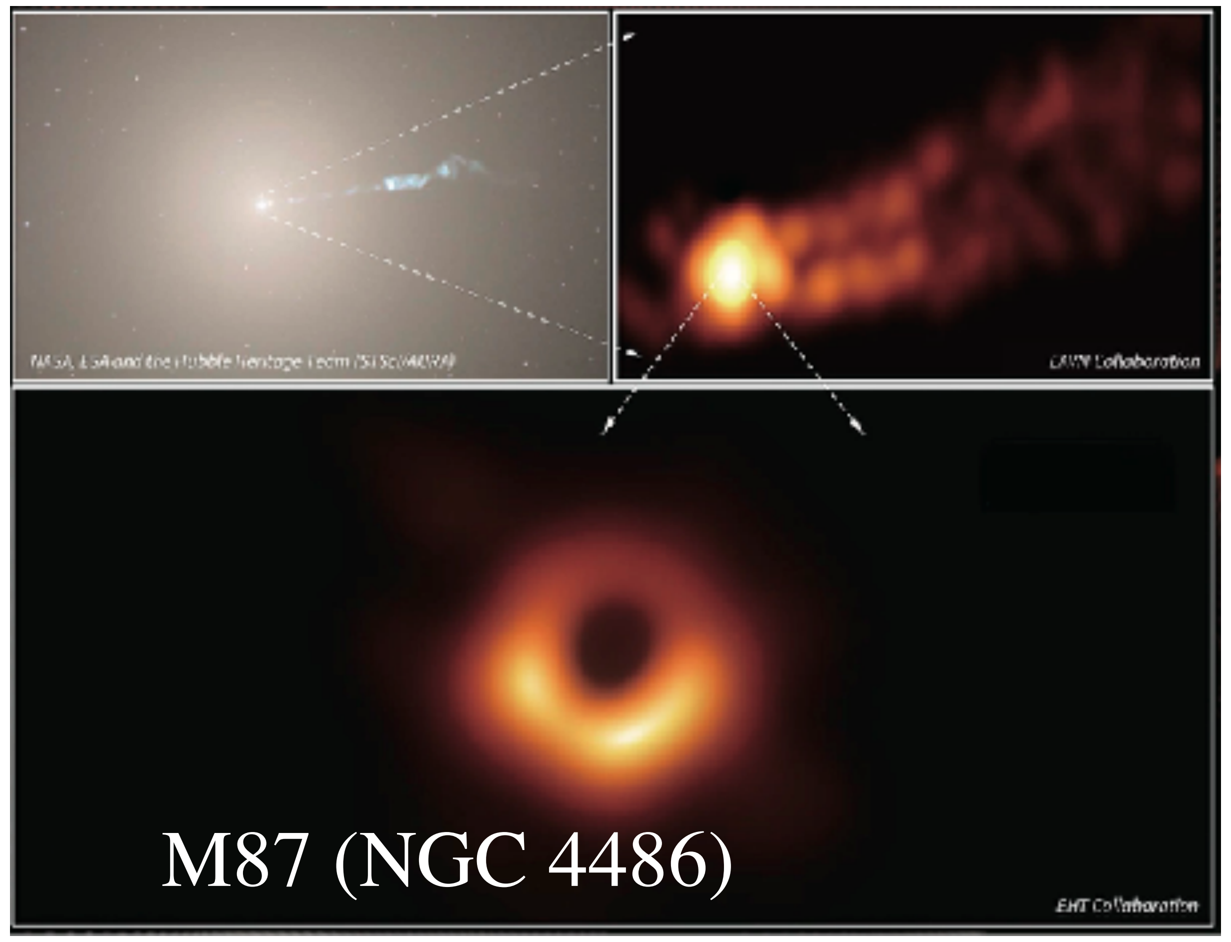


- Turbulence driven by MRI
- Weaker jets are launched

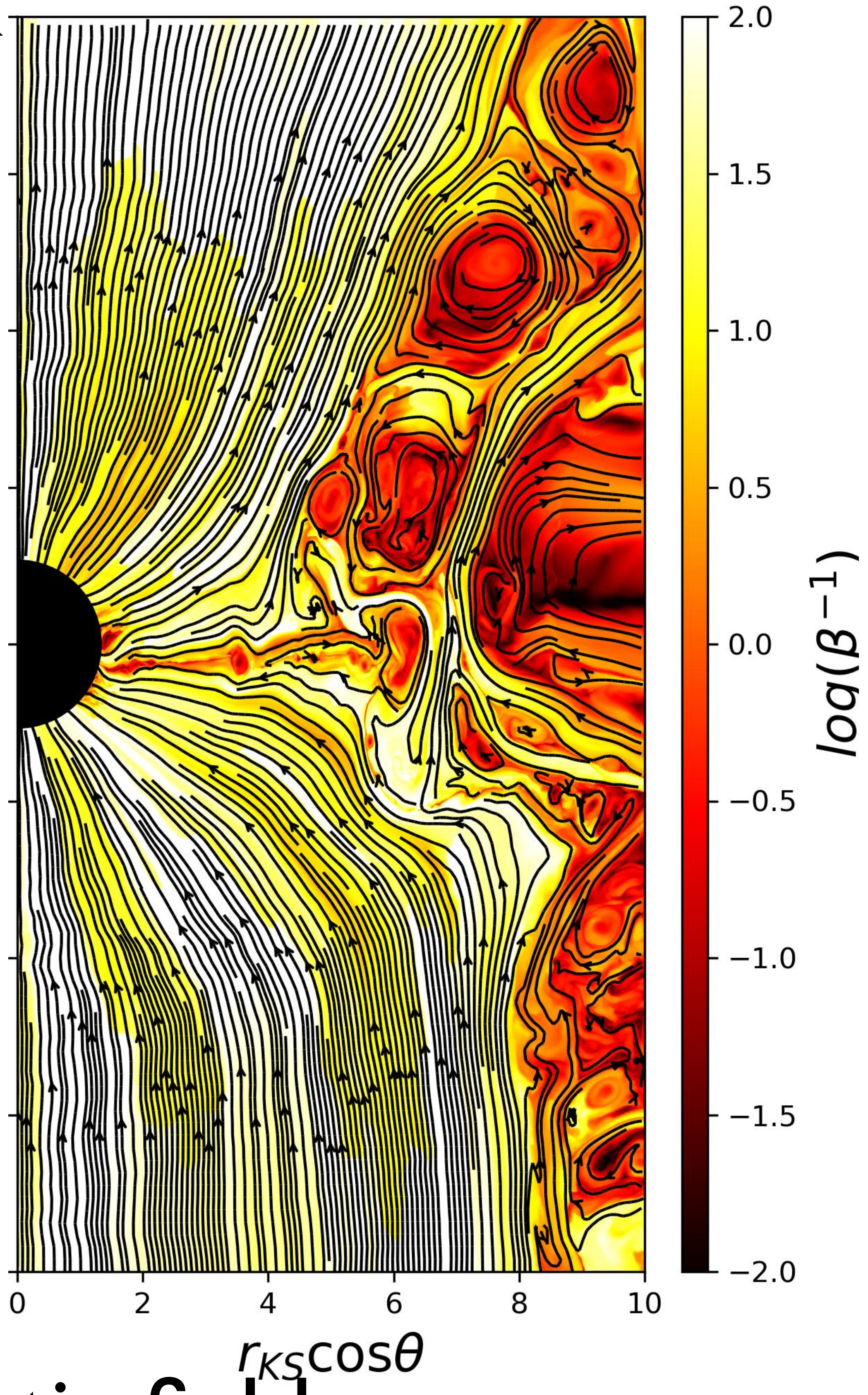
→ related to **radio-quiet AGNs**

- Magnetically Arrested Disk (MAD)

Ripperda et al. 2020



M87 (NGC 4486)



- Strong and ordered magnetic fields
- Powerful jet can be launched

→ related to **radio-loud AGN**

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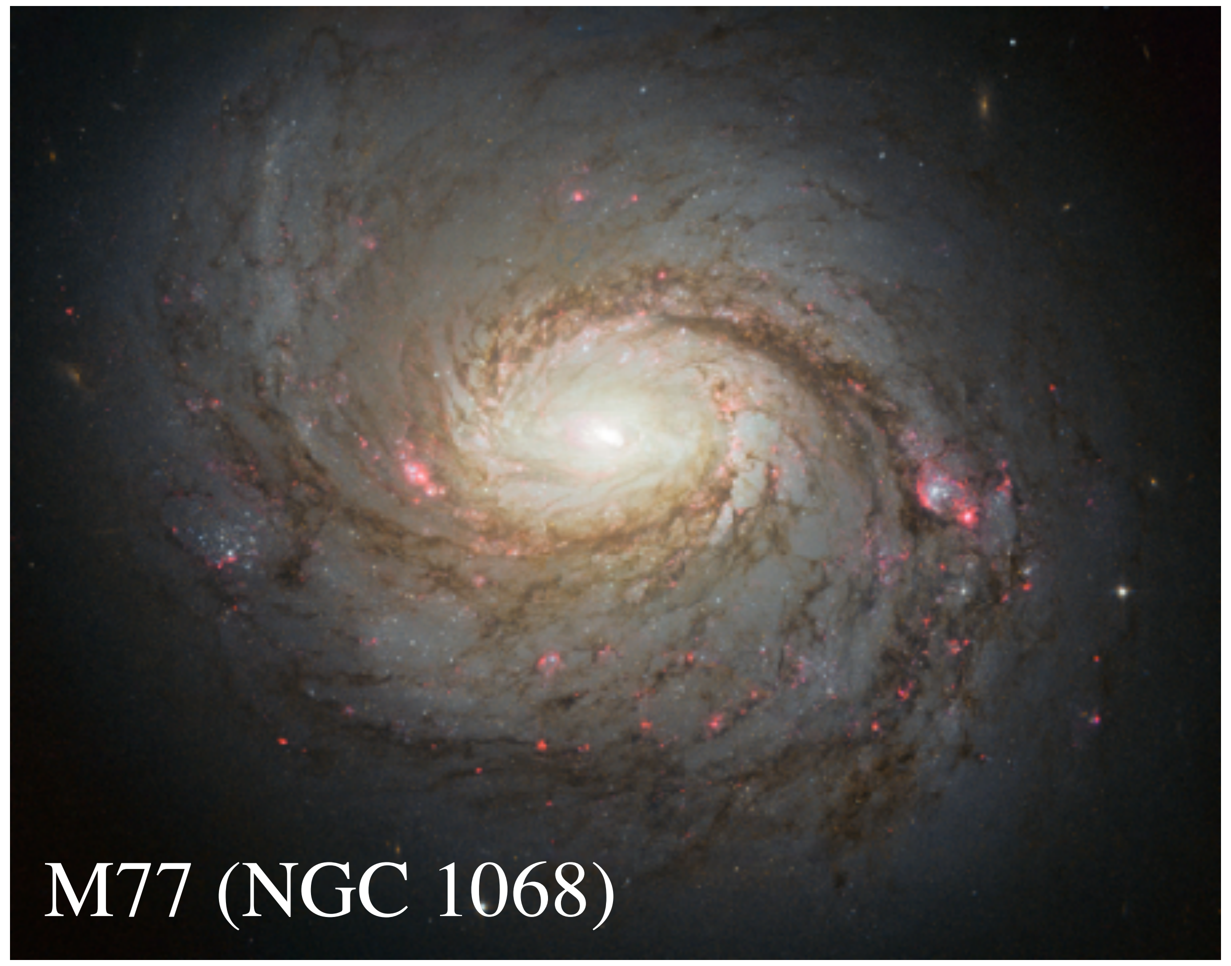
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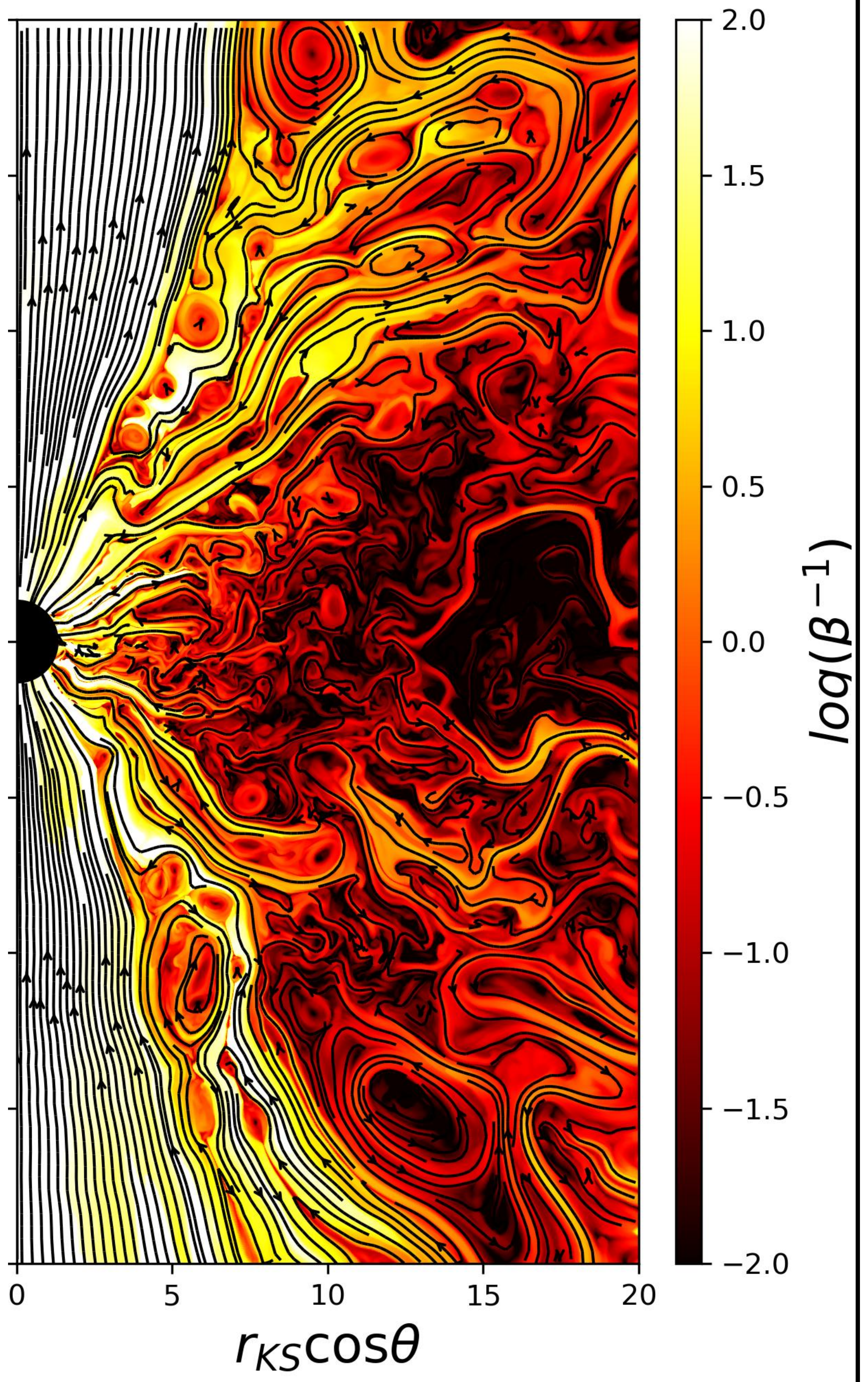

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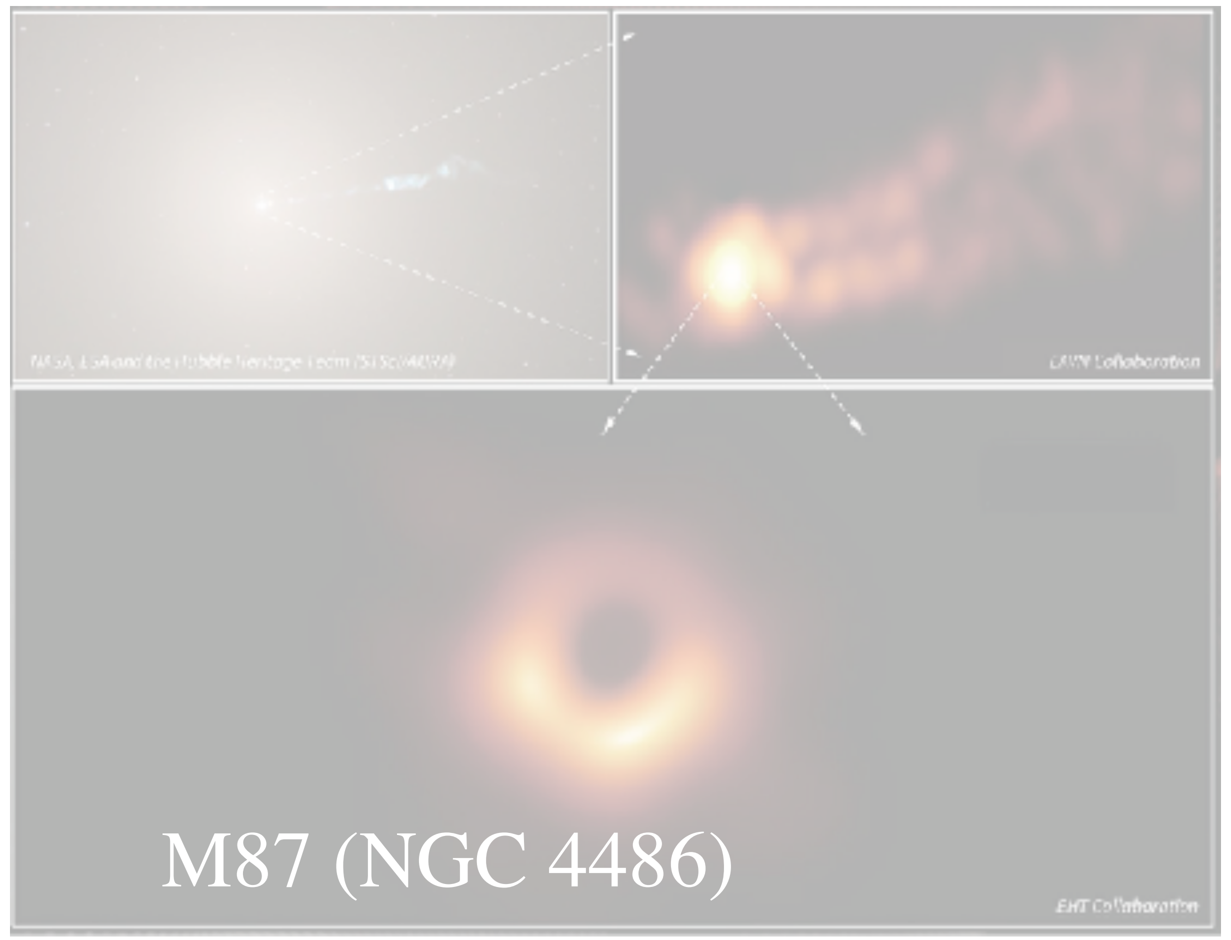
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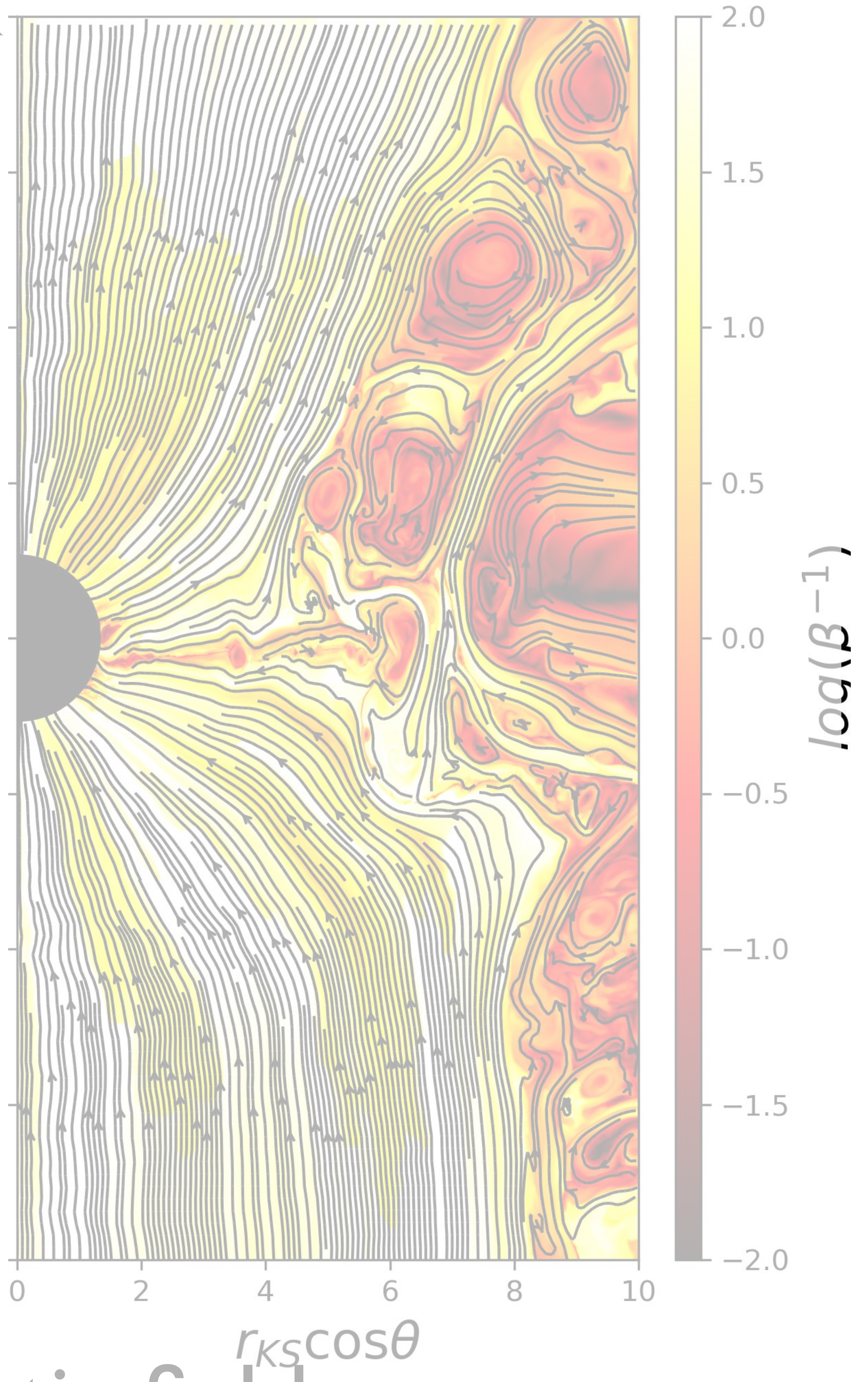
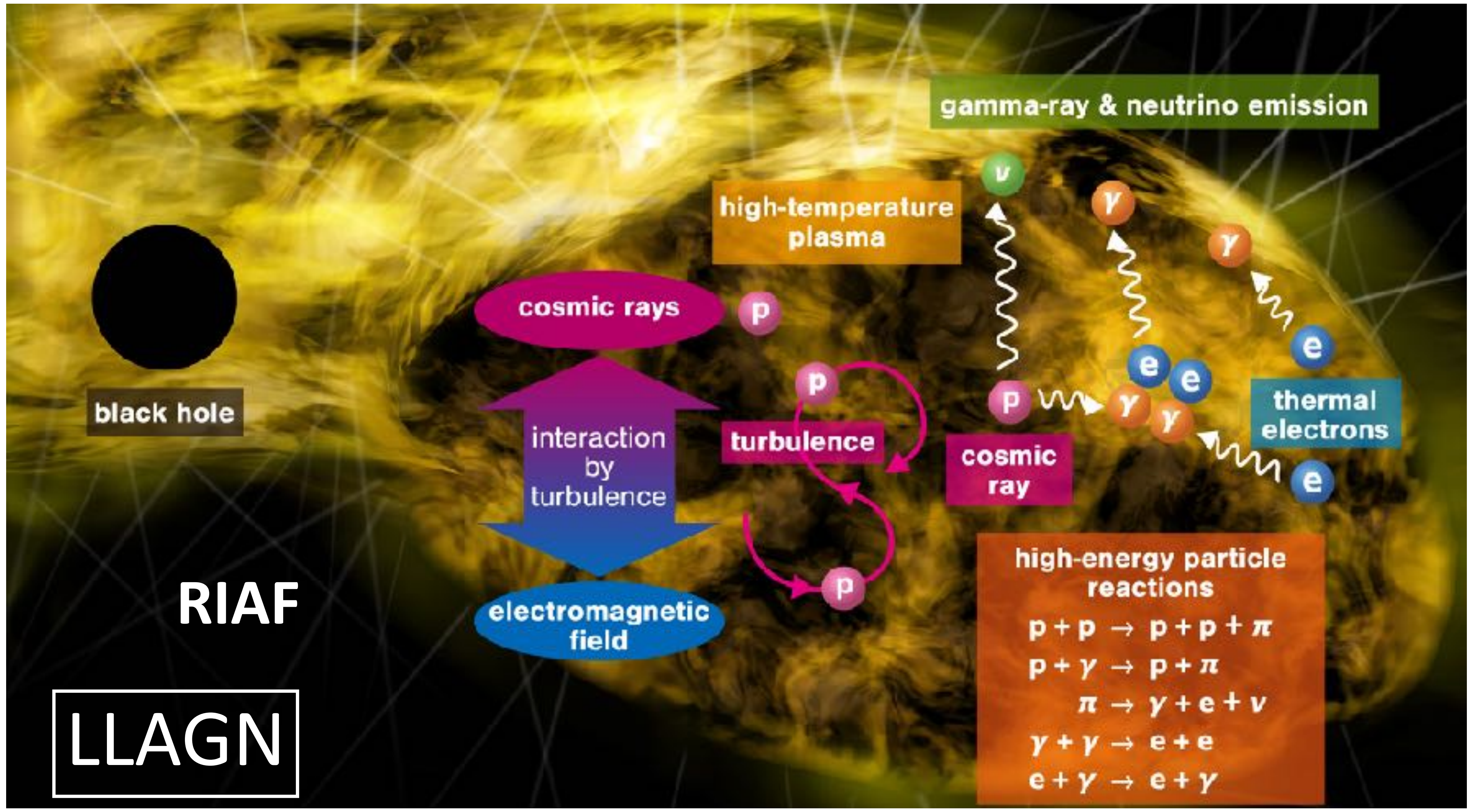
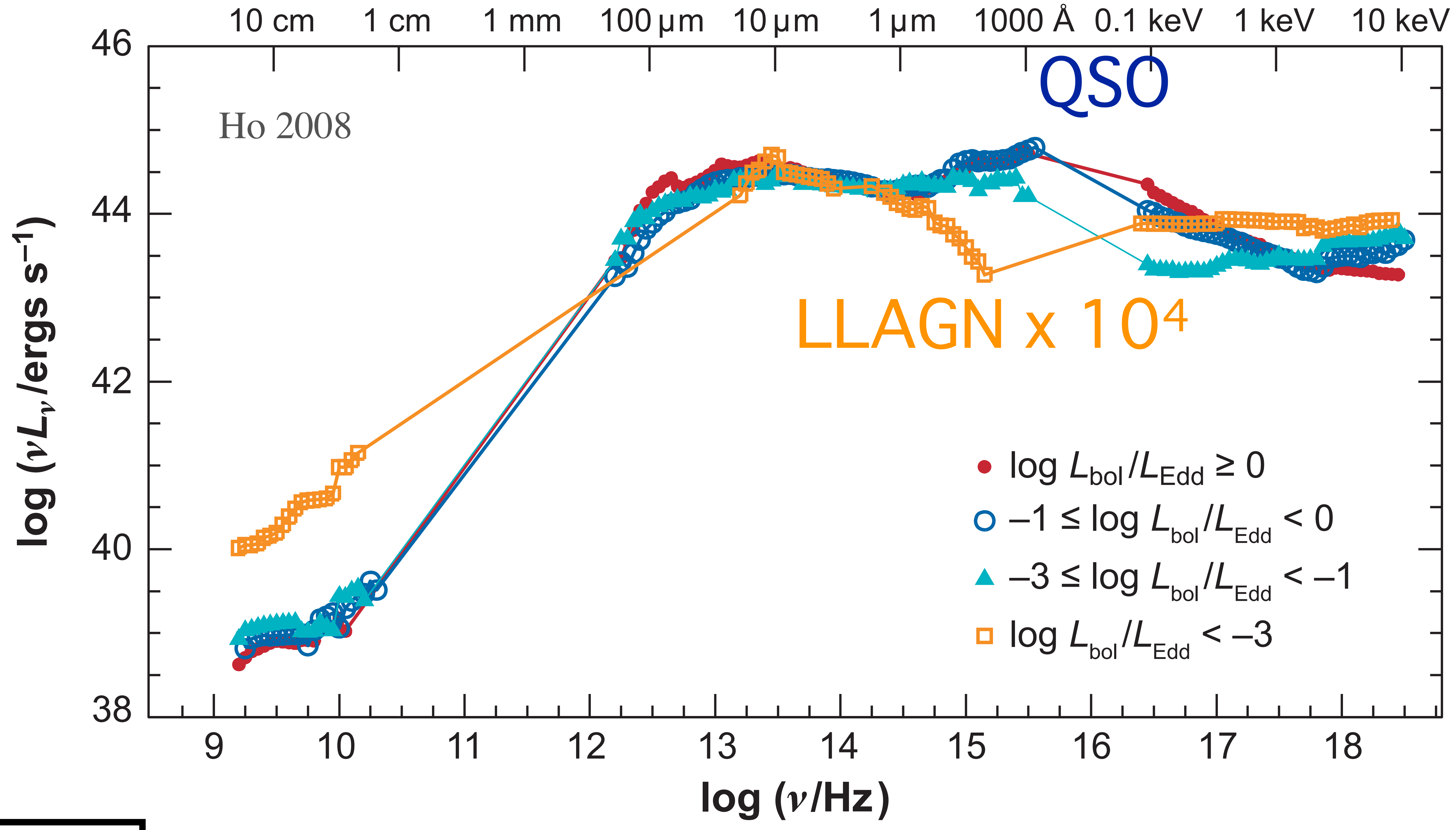


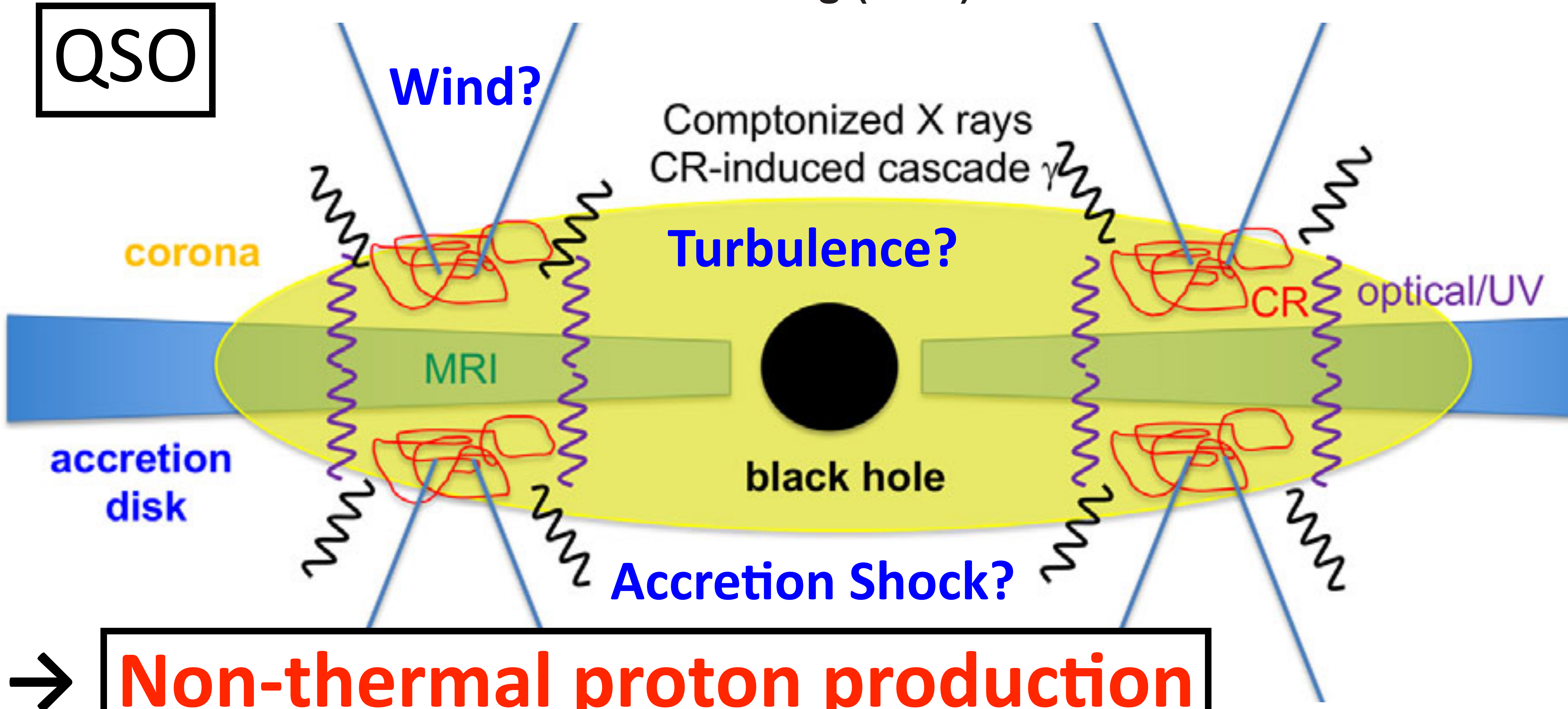
- Strong and ordered magnetic fields
- Powerful jet can be launched
  → related to **radio-loud AGN**

AGN Accretion Flows

- QSO: Blue bump & X-ray
  →Optically thick disk + coronae
- LLAGN: No blue bump & X-ray
  →Optically thin flow
  Radiatively Inefficient Accretion Flow (RIAF)







Protons in coronae & RIAFs are collisionless → Non-thermal proton production

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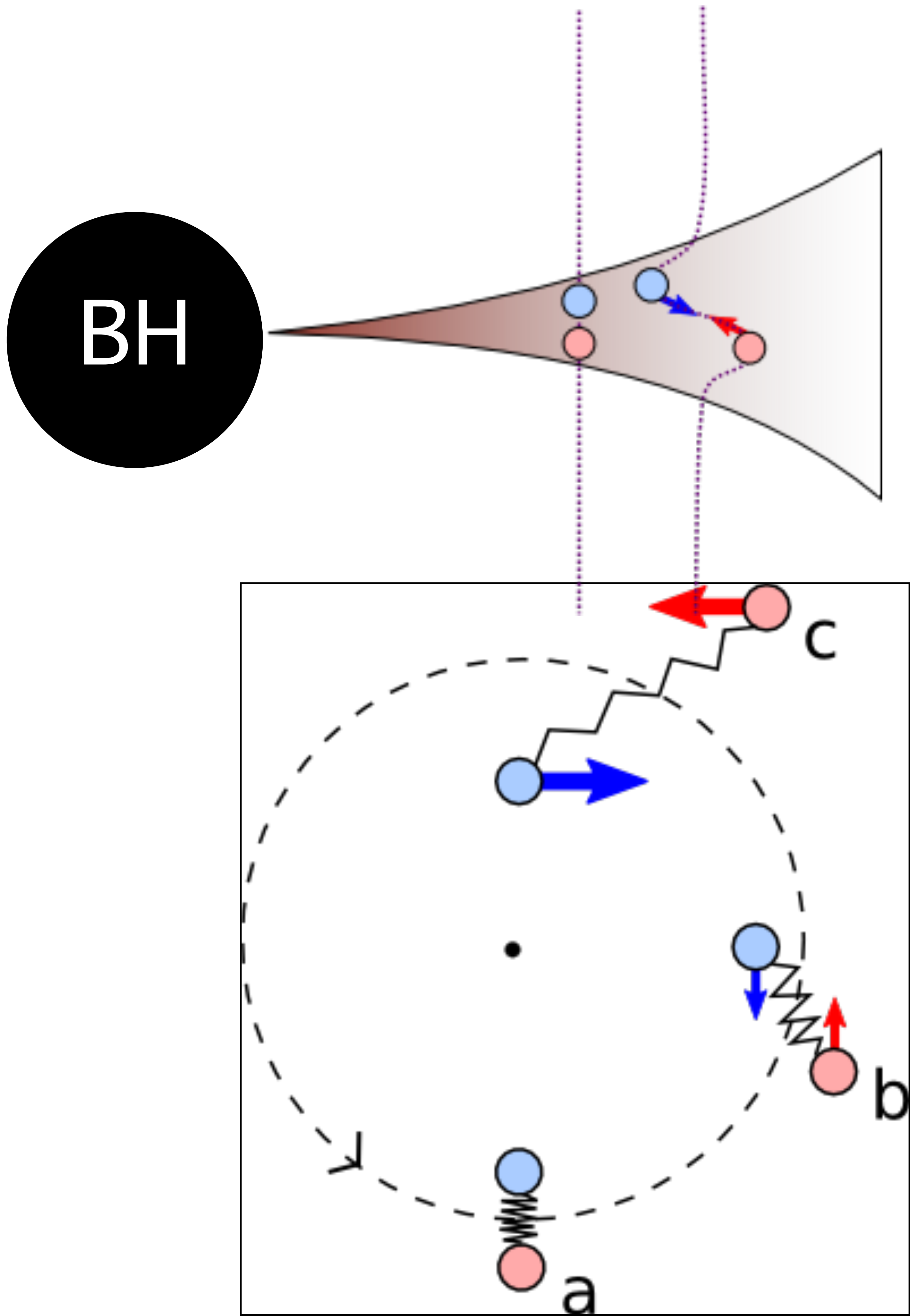
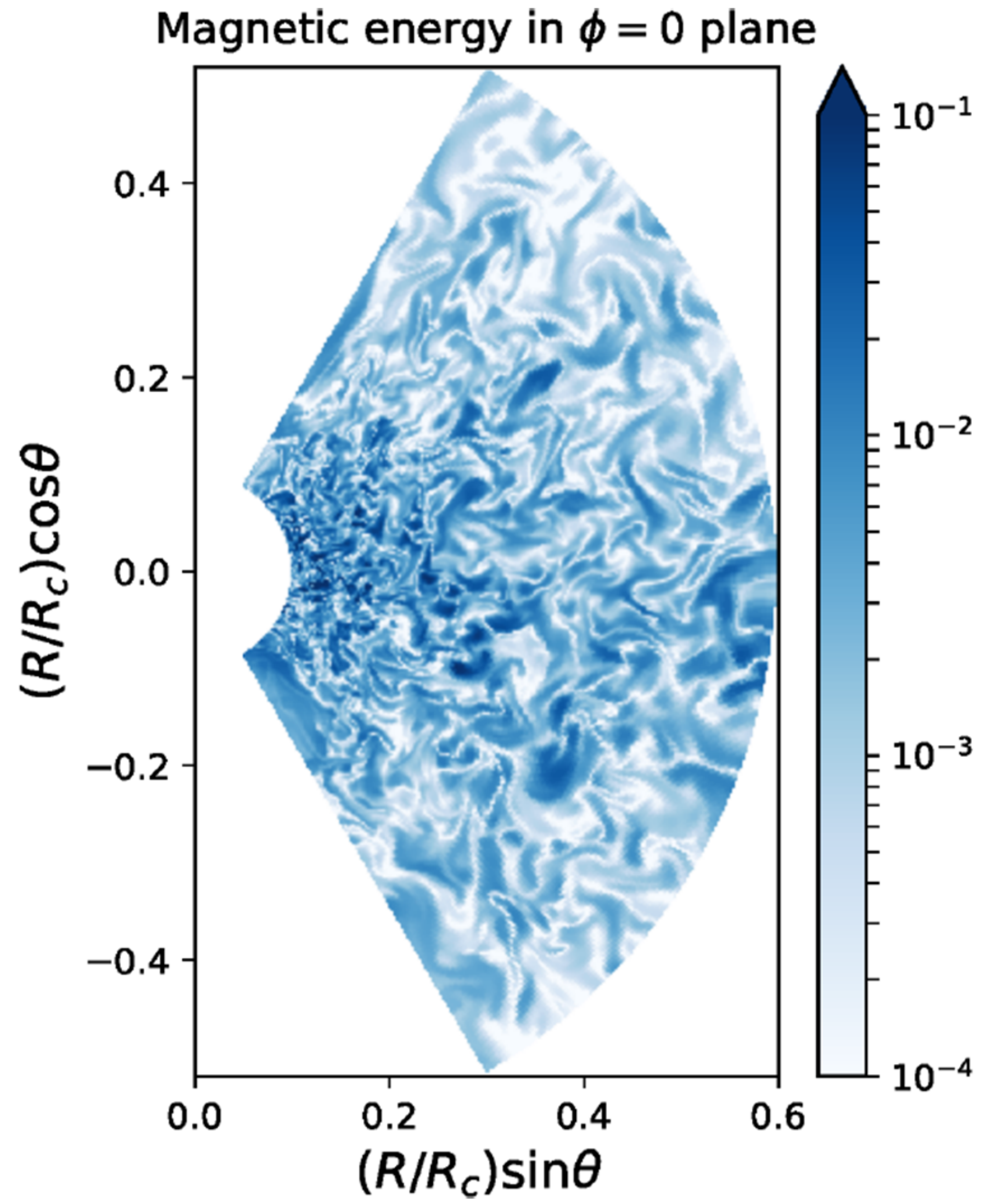
Magneto-Rotational Instability (MRI)

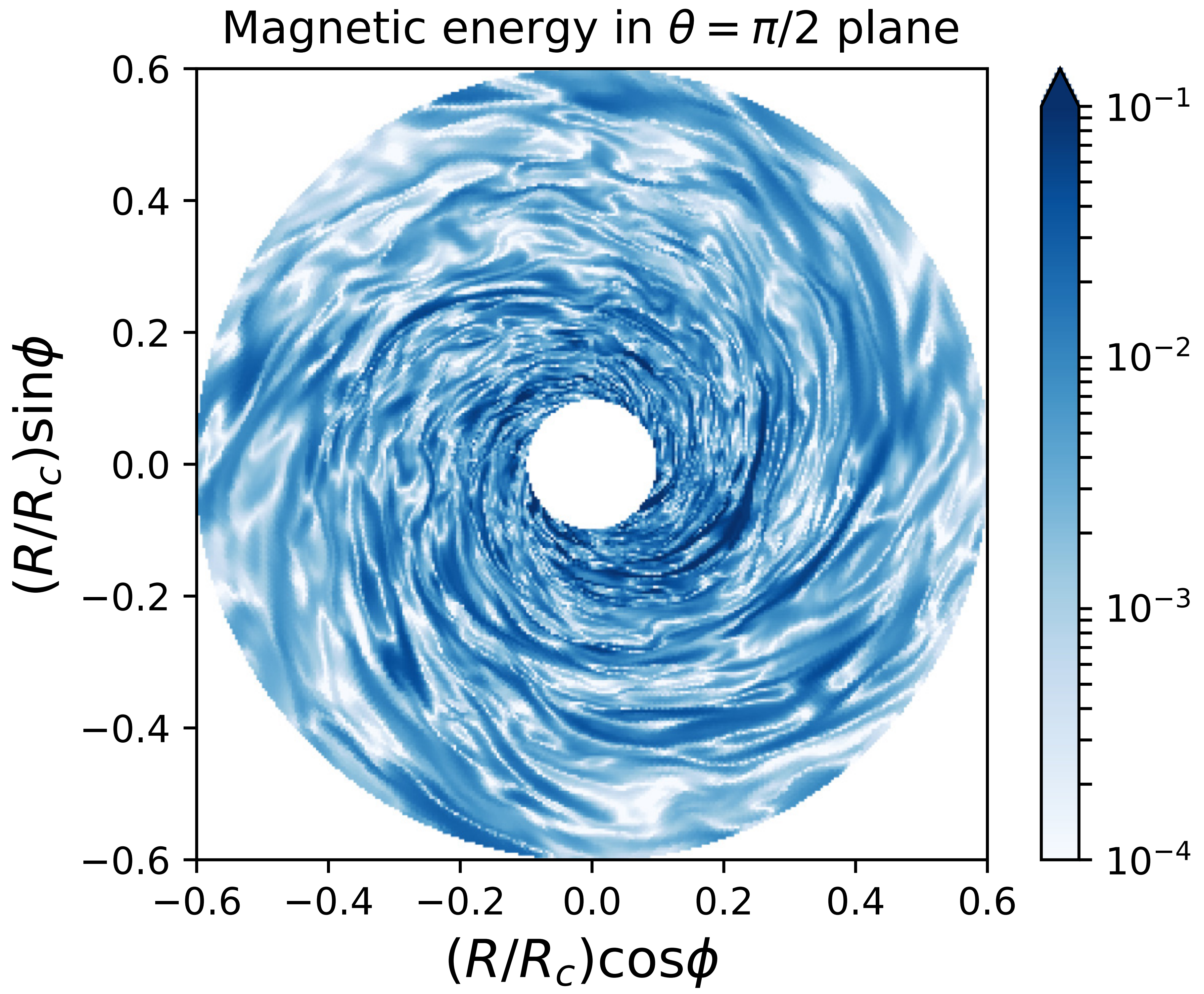
Gas accretion with angular momentum
→ formation of rotationally supported disks

Velikhov ’59; Balbus & Hawley ‘91



SSK et al. 2019, MNRAS



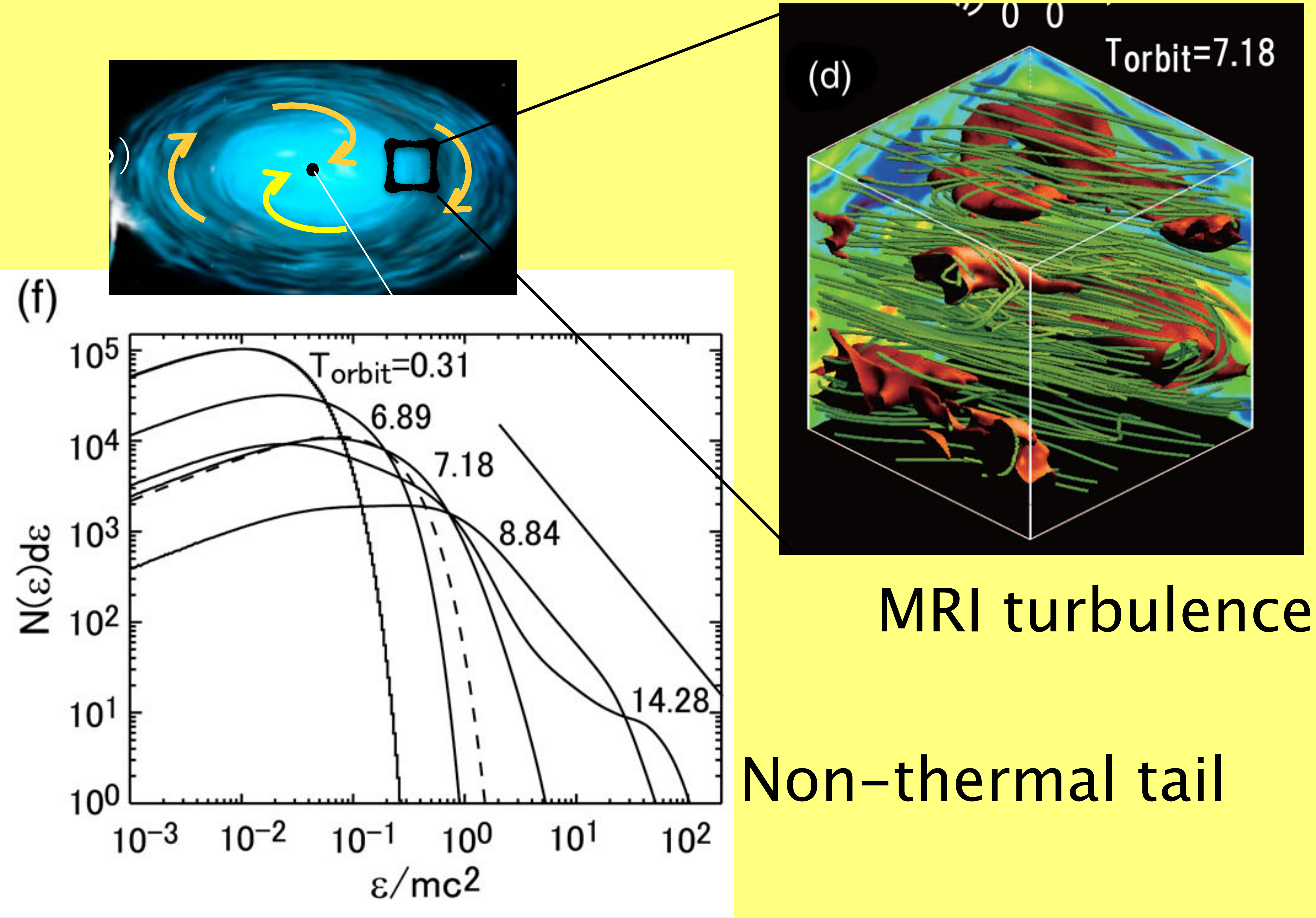


Accretion flows develop MHD turbulence by MRI

Particle Acceleration in Accretion Flows

Particle-In-Cell Simulations in shearing box

Hoshino 2013, 2015; Riquelme et al. 2012; Kuntz et al. 2016

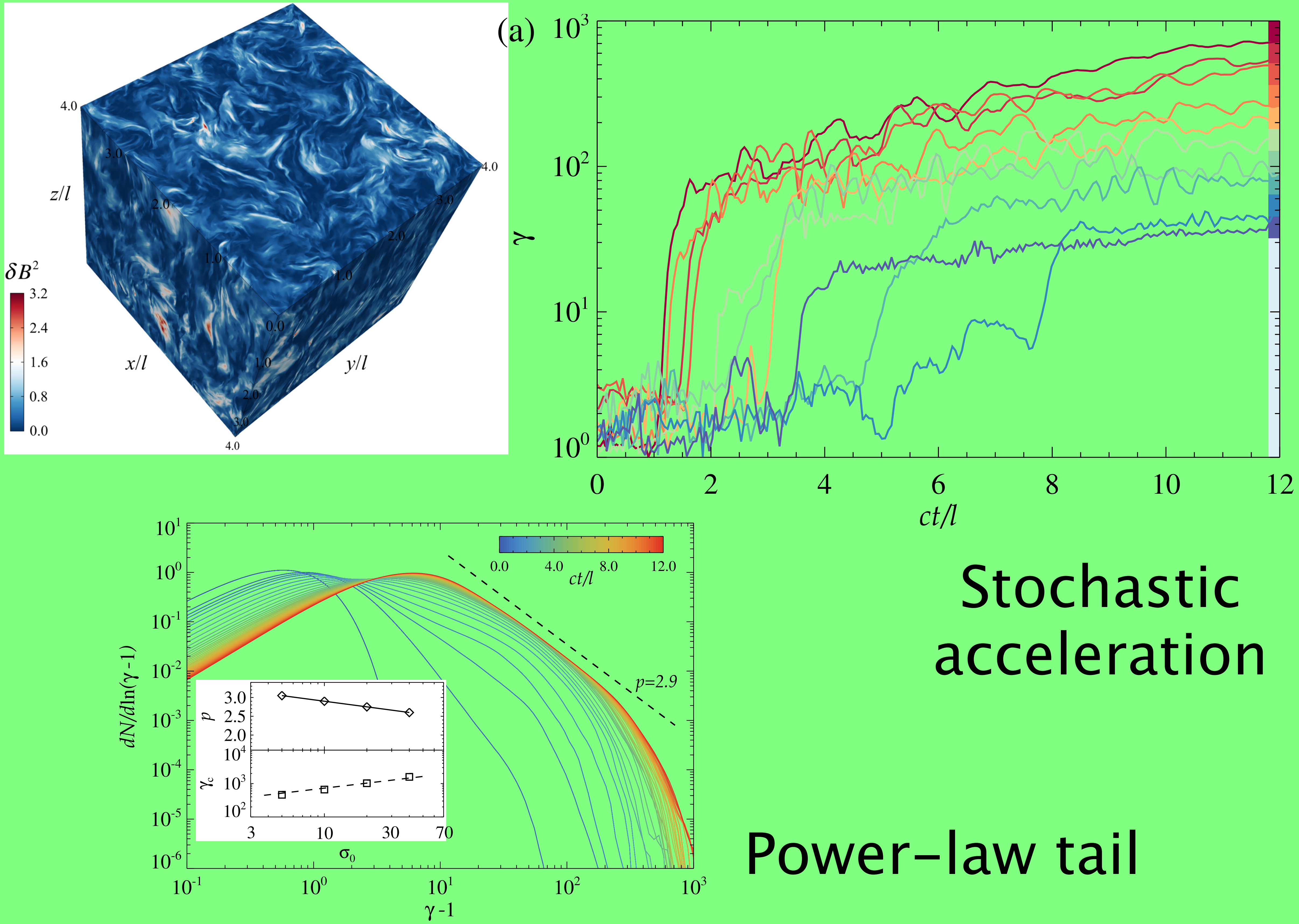


MRI turbulence

Non-thermal tail

Particle-In-Cell Simulations with turbulence

Comisso & Sironi 2018, 2019; Zhdankin et al. 2018



Stochastic acceleration

Power-law tail

Magnetic reconnection → relativistic particle production

Interaction with Turbulence → further energization

Particle Acceleration in Accretion Flows

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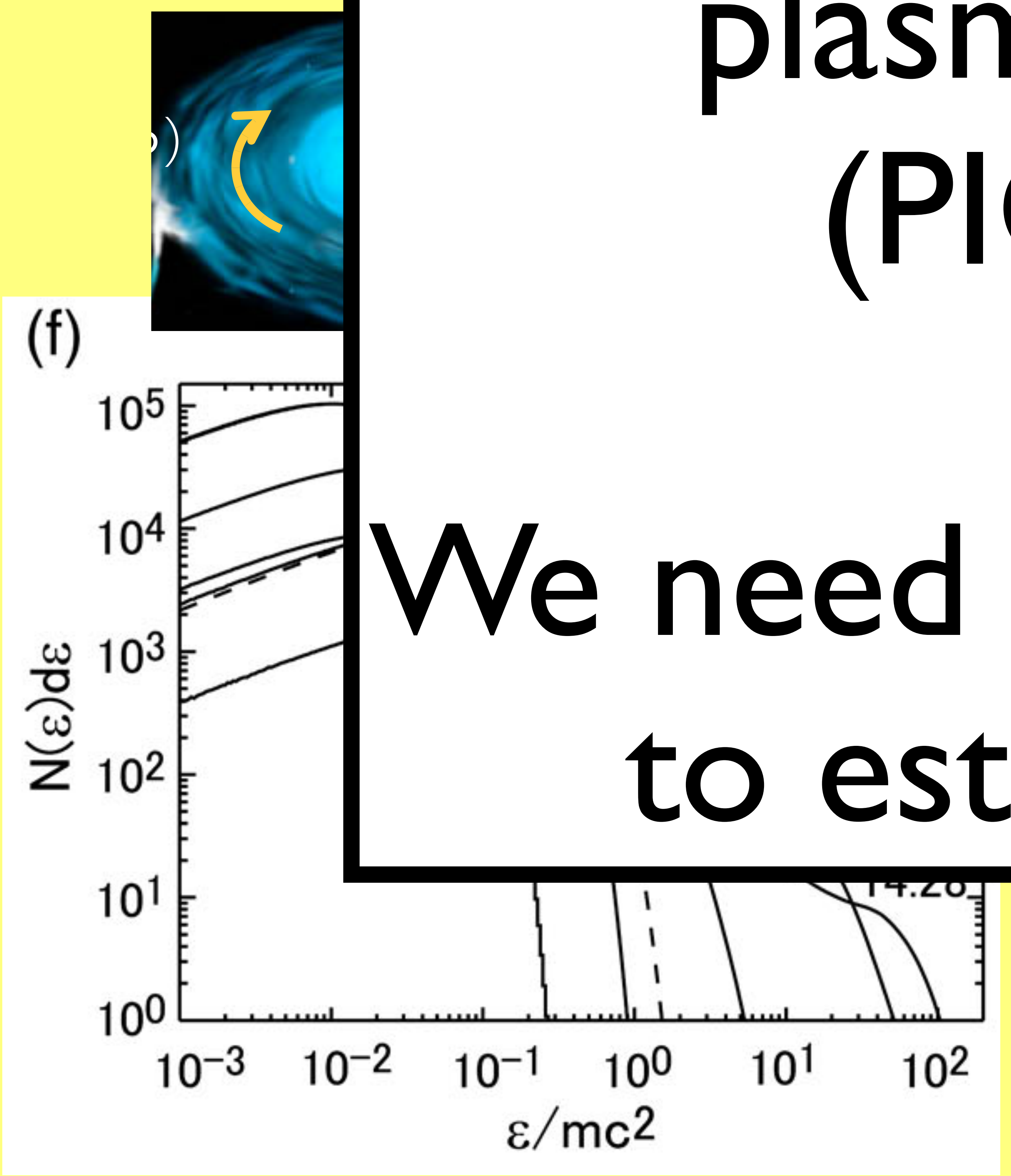

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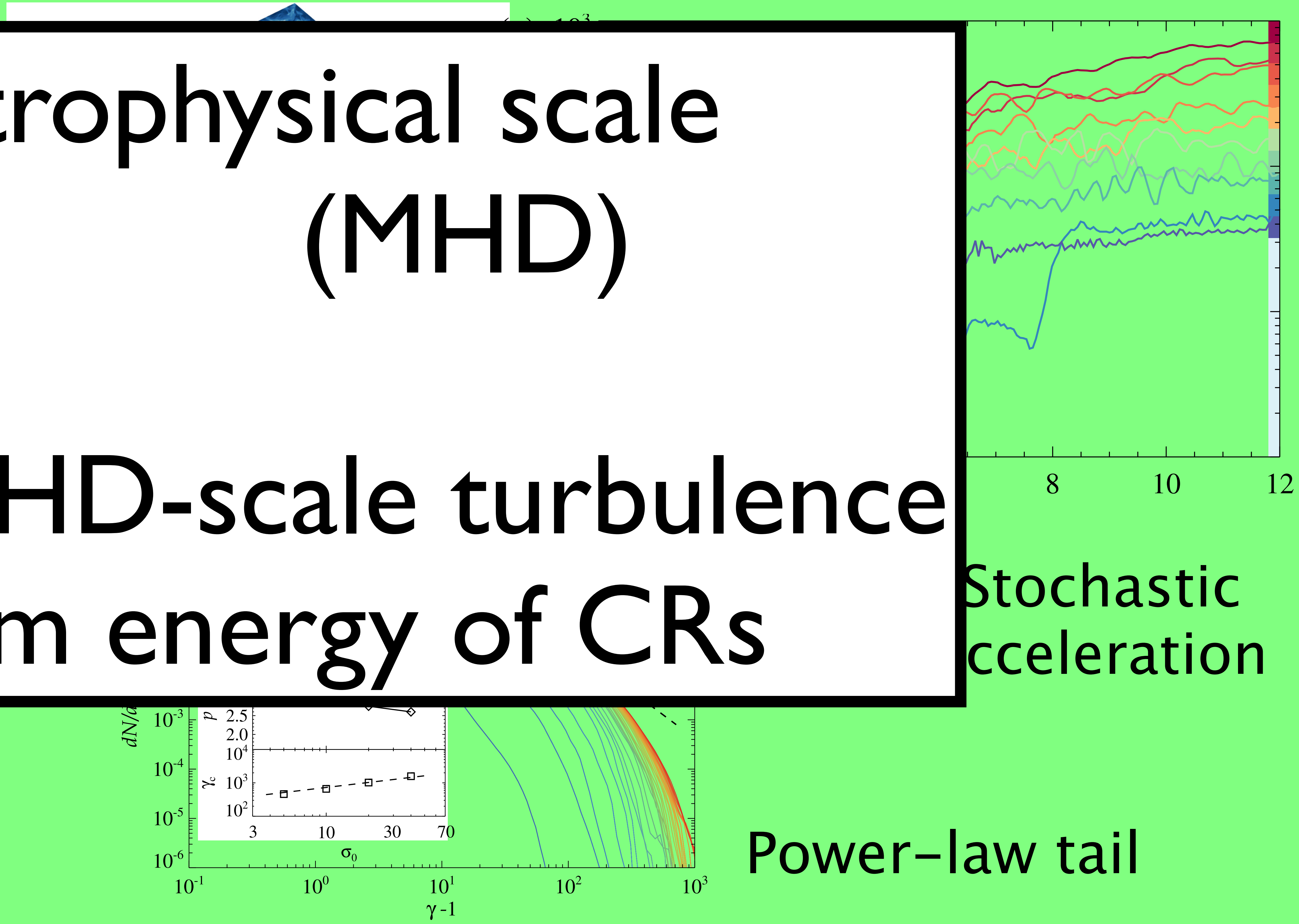


Stochastic
cceleration

Power-law tail

plasma scale << astrophysical scale
(PIC) (MHD)

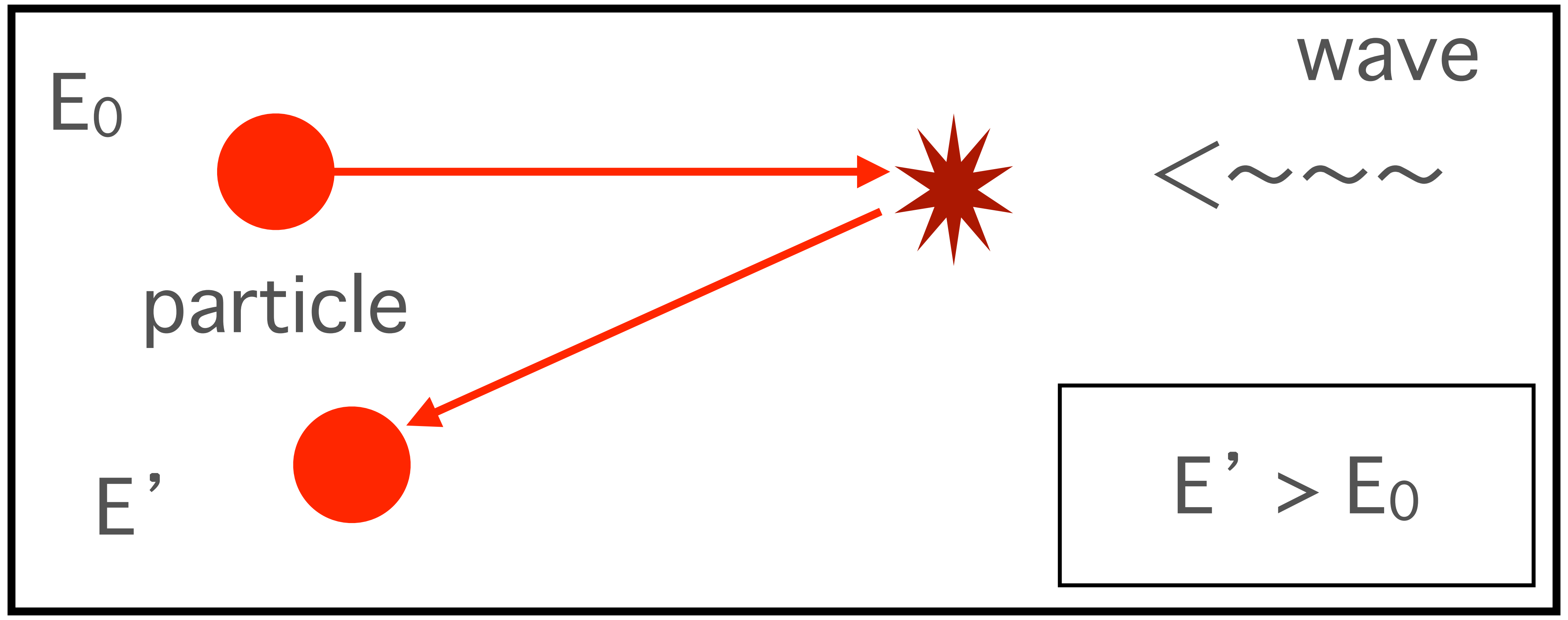
We need to consider MHD-scale turbulence to estimate maximum energy of CRs

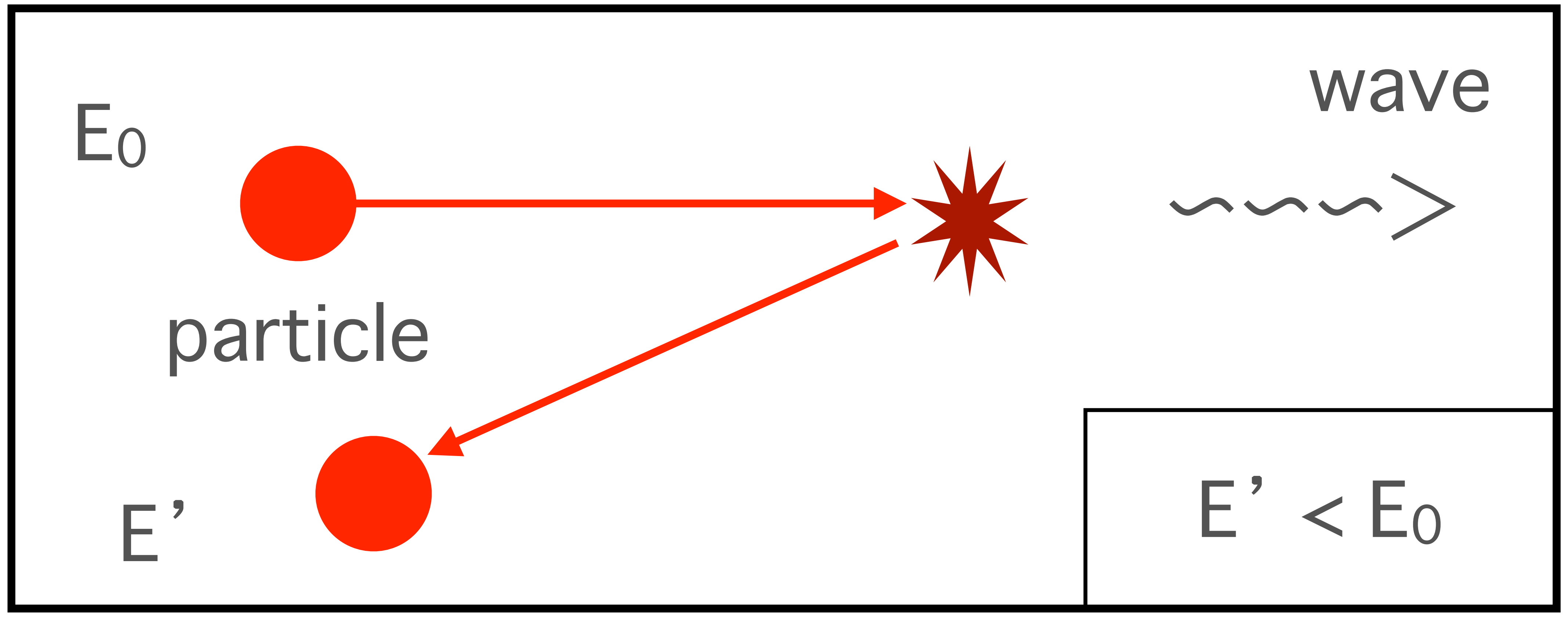
Magnetic reconnection → relativistic particle production
Interaction with Turbulence → further energization

Stochastic Acceleration in MHD Turbulence

CR Acceleration Theory

e.g.) Fermi 1949



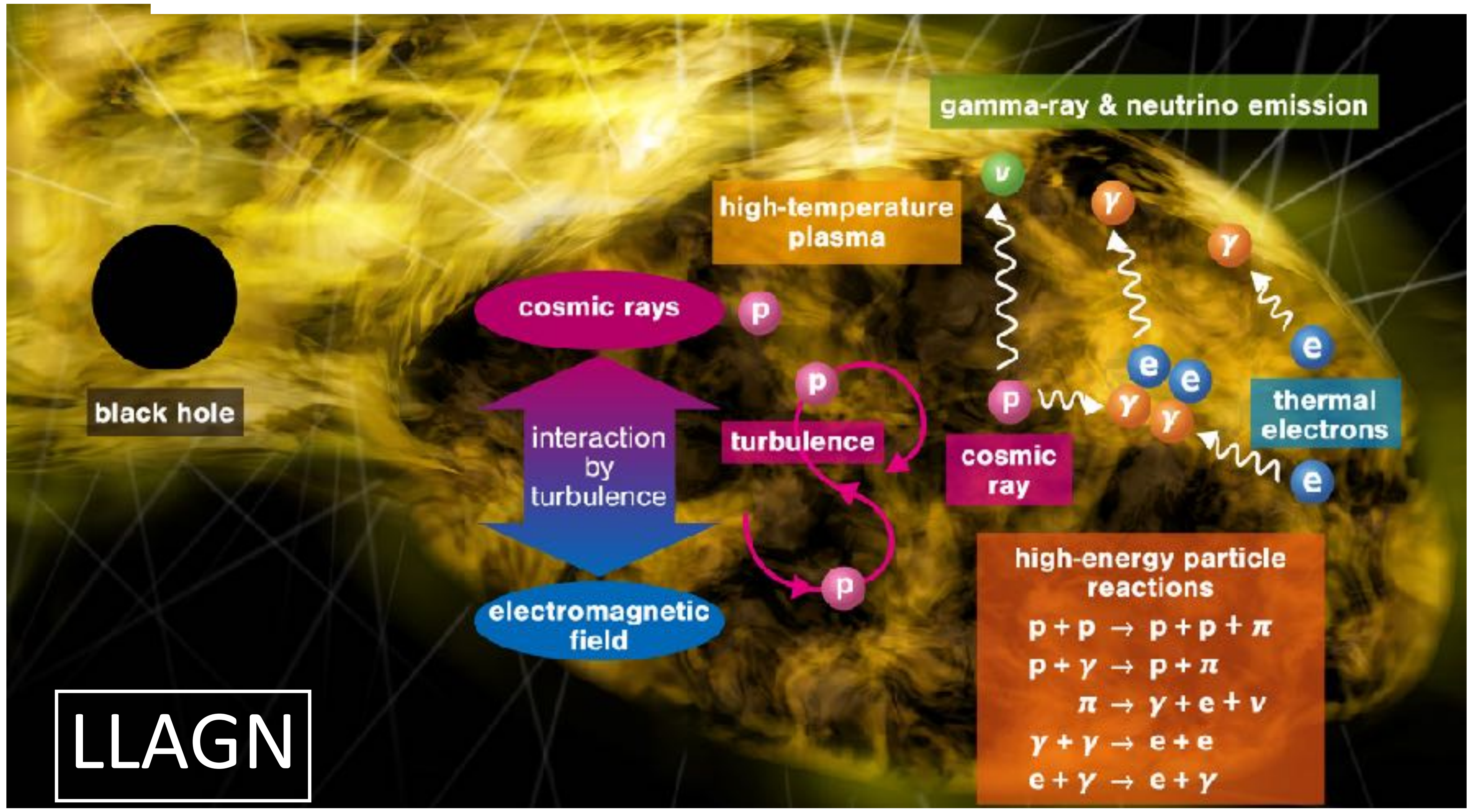


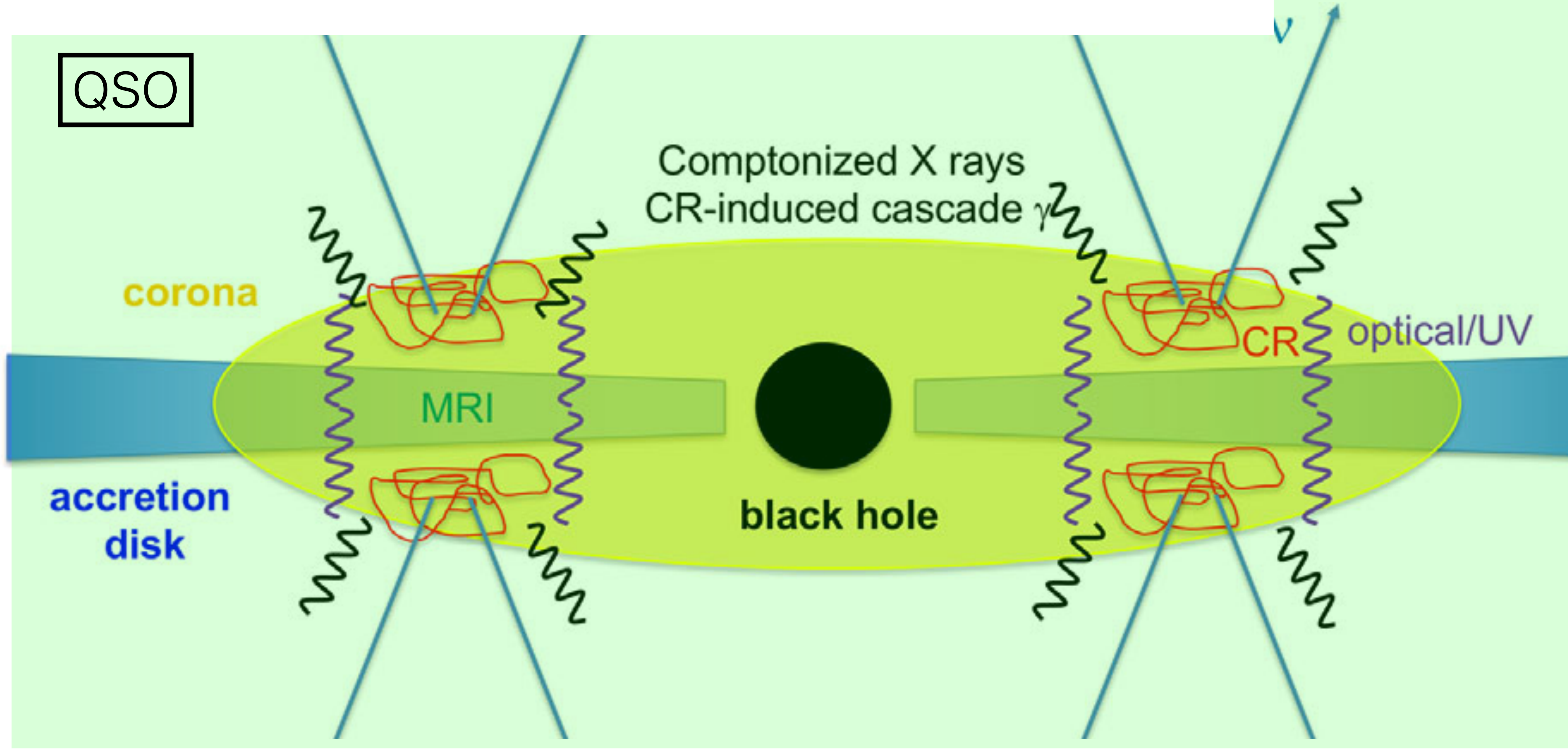
Some gain E, others lose E
→diffusion in E space

$$\frac{\partial F_p}{\partial t} = \frac{1}{E^2}\frac{\partial}{\partial E}\left(E^2 D_E \frac{\partial F_p}{\partial E}\right)$$

AGN Accretion Flow Model

Murase, SSK, Meszaros 2020;
SSK, Murase, Meszaros 2021





- Equations for cosmic-ray protons

$$\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\mathrm{cool}}}F_p\right) - \frac{F_p}{t_{\mathrm{esc}}} + \dot{F}_{p,\mathrm{inj}}$$

$$D_{\varepsilon_p} \approx \frac{\zeta c}{H}\left(\frac{V_A}{c}\right)^2\left(\frac{r_L}{H}\right)^{q-2}\varepsilon_p^2,$$

- Equations for electromagnetic cascades

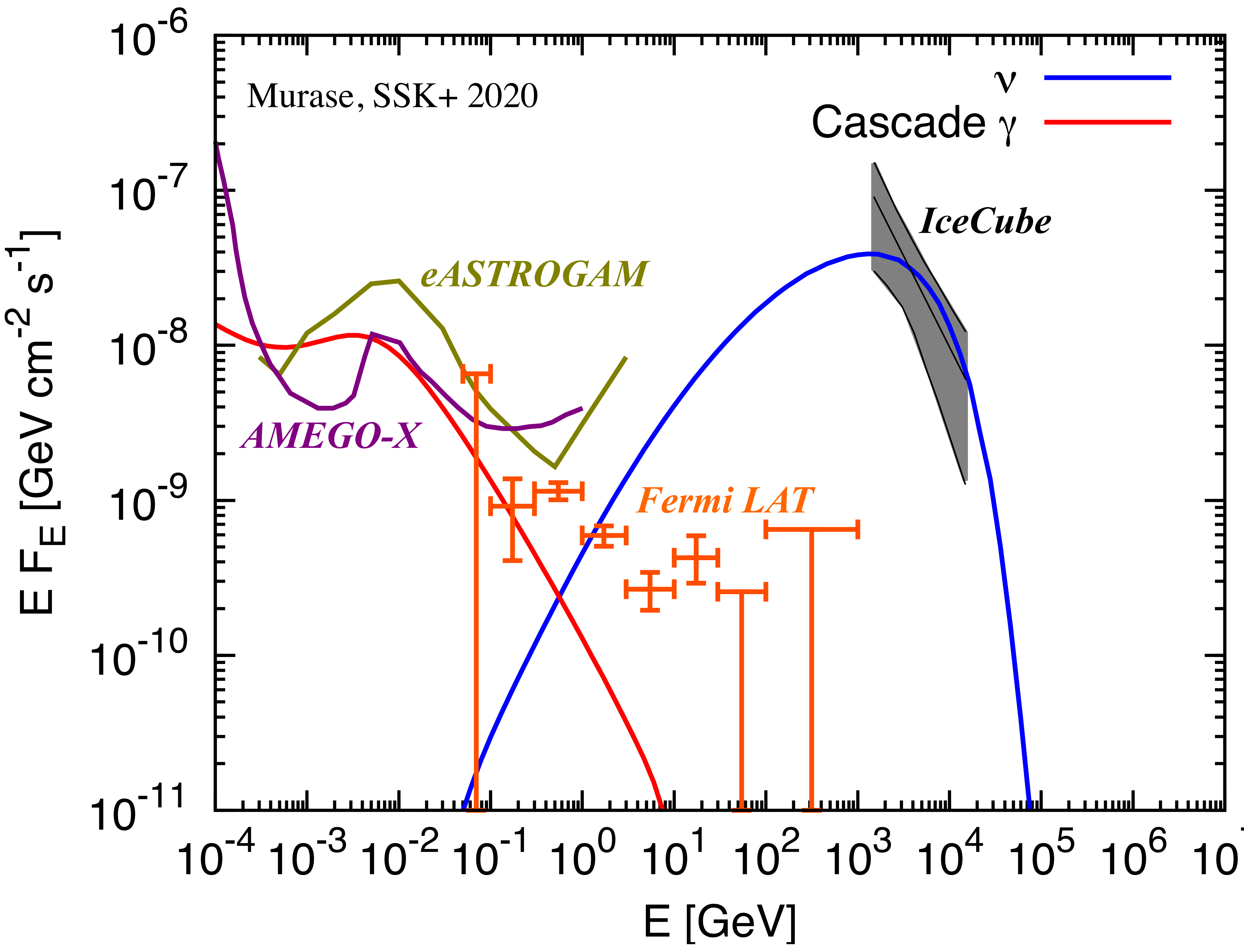
$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\mathrm{esc}}} + \dot{n}^{(\mathrm{IC})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{ff})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{syn})}_{\varepsilon_\gamma} + \dot{n}^{\mathrm{inj}}_{\varepsilon_\gamma},$$

$$\frac{\partial n^e_{\varepsilon_e}}{\partial t} + \frac{\partial}{\partial \varepsilon_e}\left[(P_{\mathrm{IC}} + P_{\mathrm{syn}} + P_{\mathrm{ff}} + P_{\mathrm{Cou}})n^e_{\varepsilon_e}\right] = \dot{n}^{(\gamma\gamma)}_{\varepsilon_e} - \frac{n^e_{\varepsilon_e}}{t_{\mathrm{esc}}} + \dot{n}^{\mathrm{inj}}_{\varepsilon_e},$$

See also SSK+ 2019; Kheirandish, Murase, SSK 2021

Multi-messenger Spectra from NGC 1068

- Possible to explain IceCube data without overshooting γ-ray data
- CR acceleration is suppressed by BH process (p+γ—> p+e±) with UV
- Both pp & pγ (with X-rays) contribute to resulting neutrino flux
- **Cascade emission at 10 MeV —>Testable by MeV γ ray satellites**

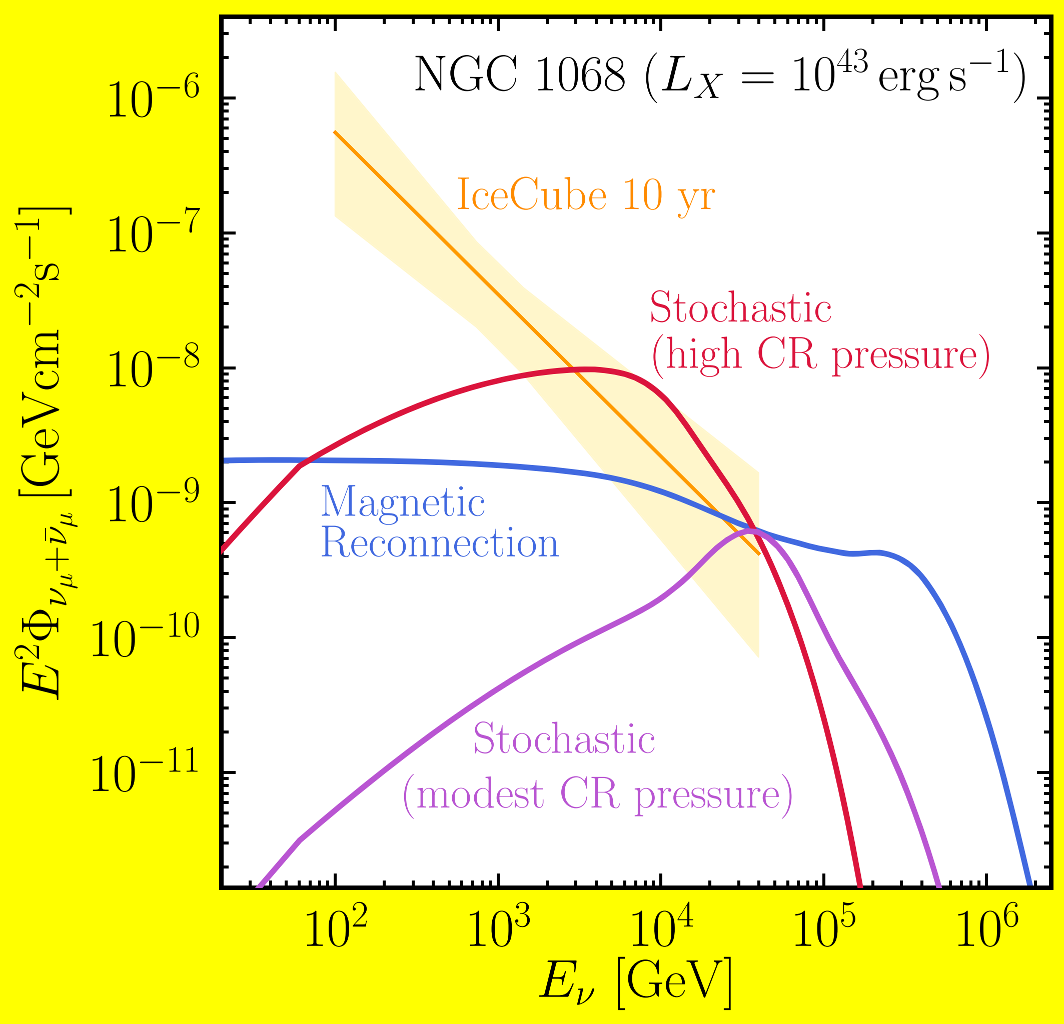


Nearby Seyfert galaxies

Kheirandish, Murase, SSK 2021

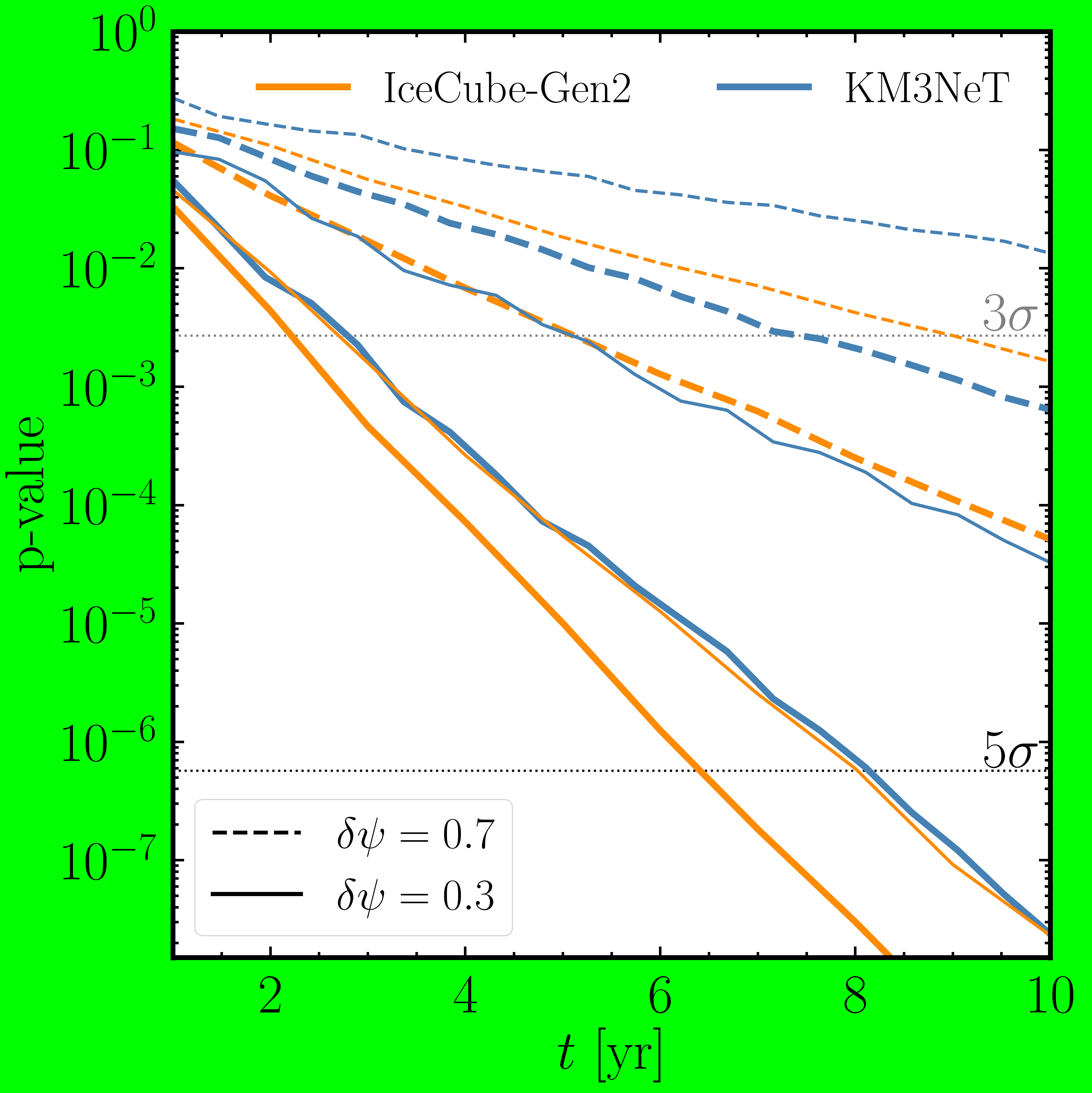
- Our model predicts $L_\nu \propto L_X$
  —> list up bright ν-source candidates

Source
Cen A
Circinus Galaxy
ESO 138-1
NGC 7582
NGC 1068
NGC 4945
NGC 424
UGC 11910
CGCG 164-019
NGC 1275



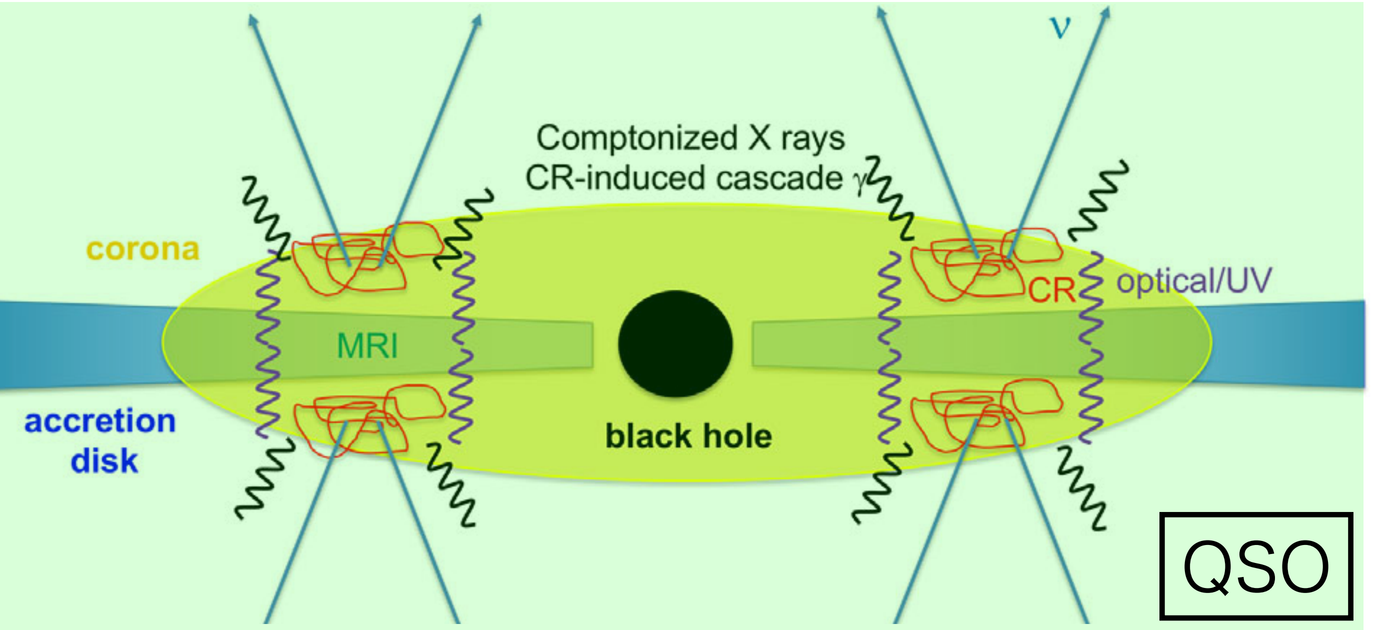
- **Our model predicts that NGC 1068 should be detected first**
- This list is based on BASS catalog we need to examine X-ray data quality

- Stacking nearby Seyferts

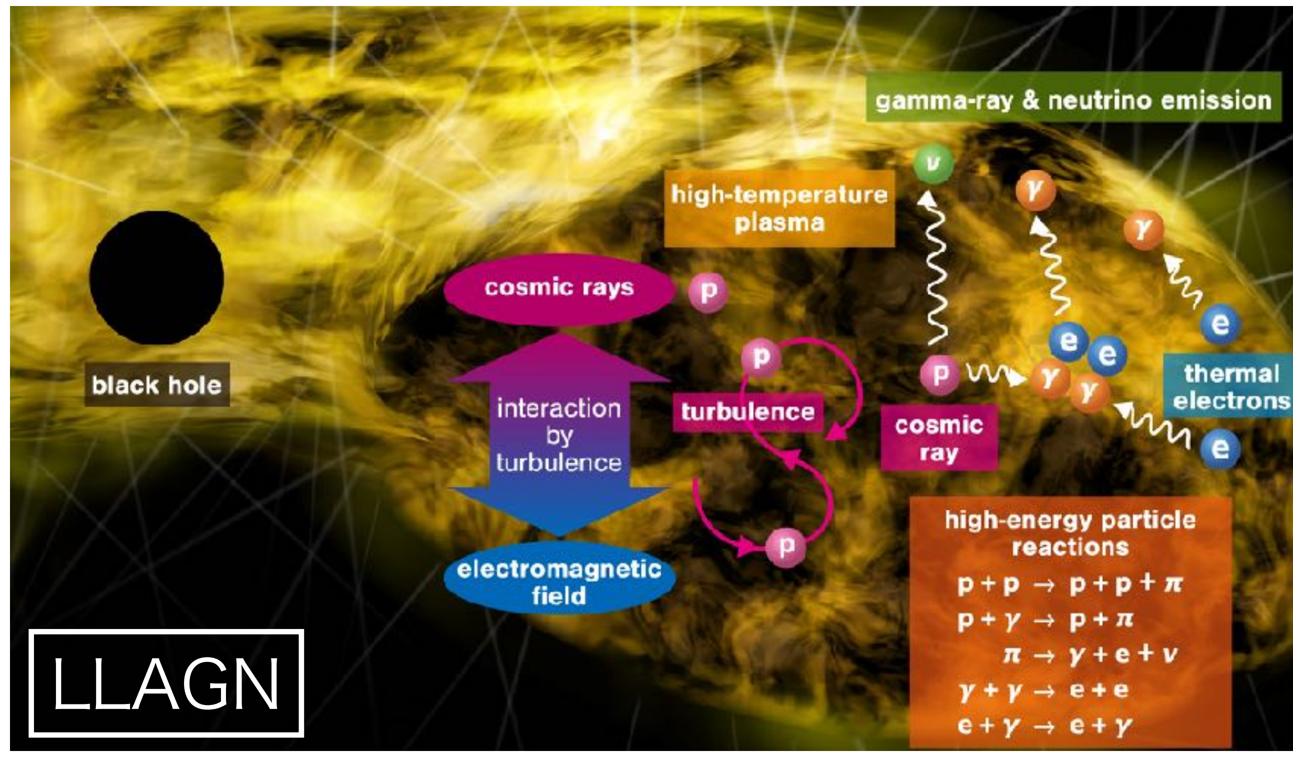


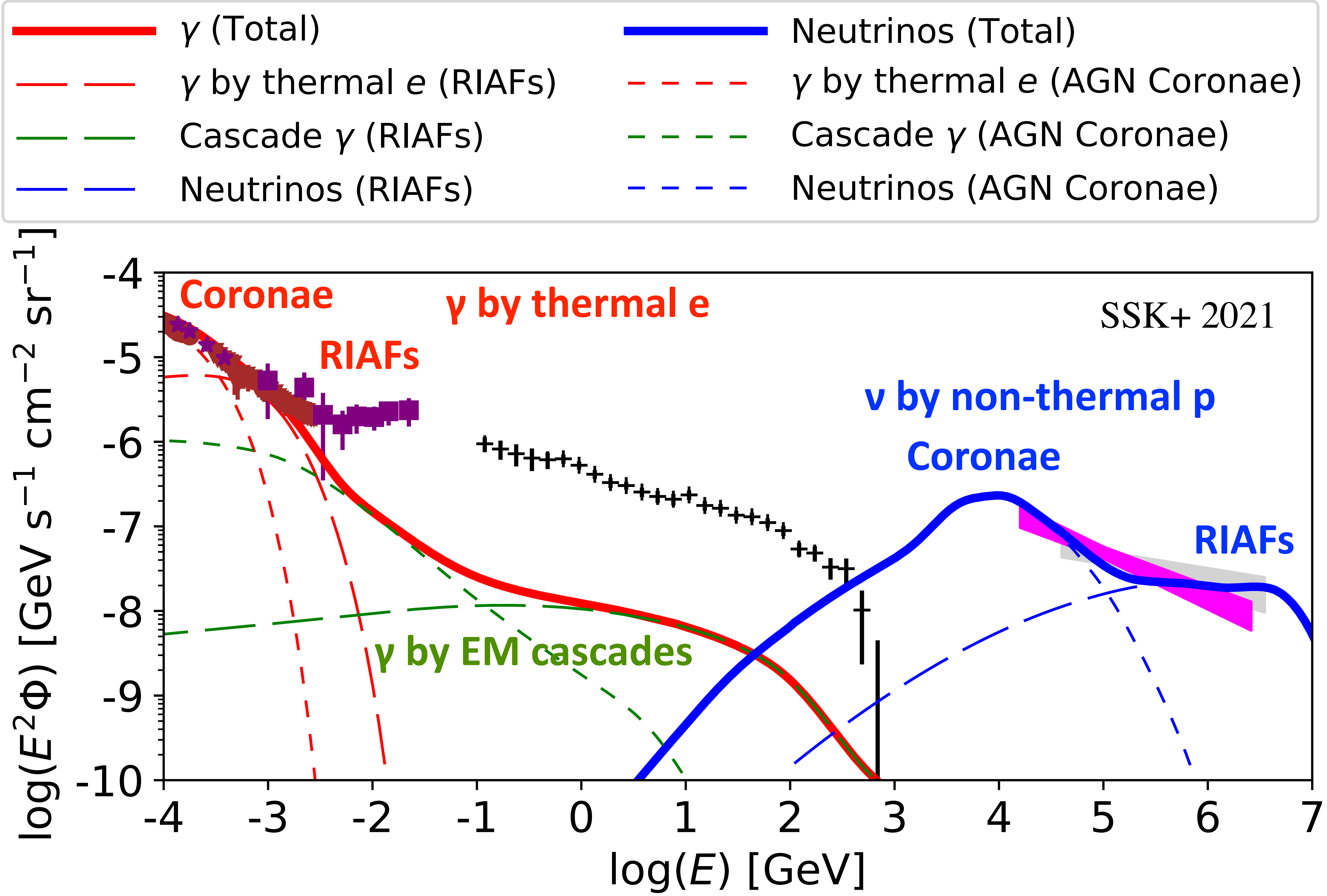
- Future detectors should detect ν from AGN
  —> **testable by future neutrino experiments**

Cosmic High-energy Background from RQ AGNs



$$\Phi_i = \frac{c}{4\pi H_0} \int \frac{dz}{\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}} \int dL_{\rm H\alpha} \rho_{\rm H\alpha} \frac{L_{\varepsilon_i}}{\varepsilon_i} e^{-\tau_{i,\rm IGM}},$$





- QSO: X-ray & 10 TeV neutrinos
- LLAGN: MeV γ & PeV neutrinos
- Copious photons
  → efficient γγ —> e+e-
  → strong GeV γ attenuation
  → GeV flux below the Fermi data
- **AGN cores can account for keV-MeV γ & TeV-PeV ν background**

See also Murase, SSK+ 2020 PRL; SSK+ 2019, PRD; SSK+ 2015

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  - IceCube Neutrinos
  - Classification of Accretion Flows
- Particle Acceleration in Accretion Flows
- Hadronic emission from AGN Accretion Flows
- Summary

Stochastic Acceleration in MHD Turbulence

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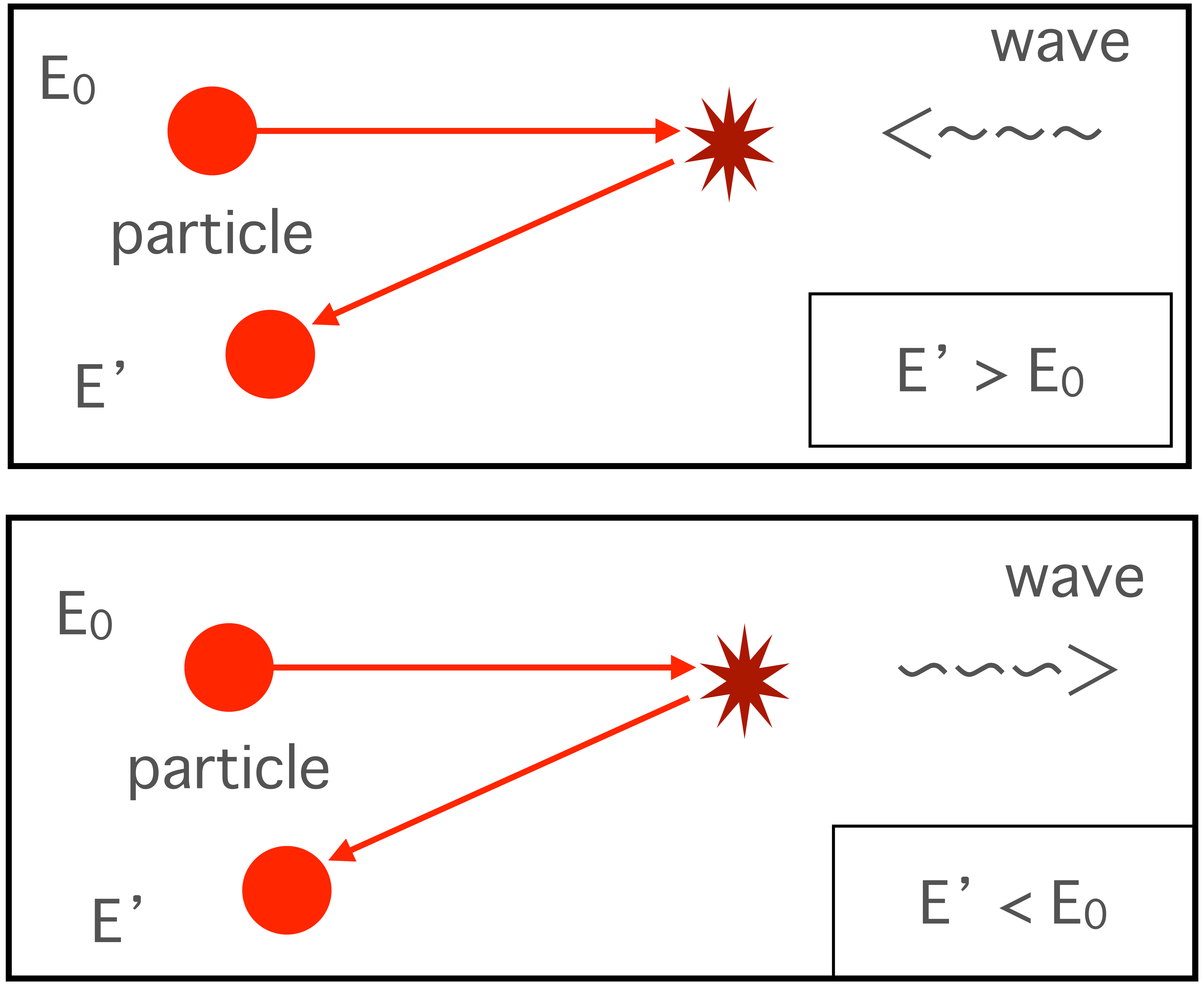
e.g.) Fermi 1949



Some gain E, others lose E

→diffusion in E space

$$\frac{\partial F_p}{\partial t} = \frac{1}{E^2}\frac{\partial}{\partial E}\left(E^2 D_E \frac{\partial F_p}{\partial E}\right)$$

We should confirm this by numerical simulations

MHD simulations + Test Particle Simulations

- We used **Athena++ & ATERUI II** (XC 30, XC50) @ CfCA, NAOJ for MHD sim.

Stone et al. 2020

SSK et al. 2019 MNRAS

Low resolution: $(N_r, N_\theta, N_\phi) = (640, 320, 768)$ with 2nd-order

SSK et al. in prep

Hish resolution: $(N_r, N_\theta, N_\phi) = (840, 560, 1120)$ with 3rd-order

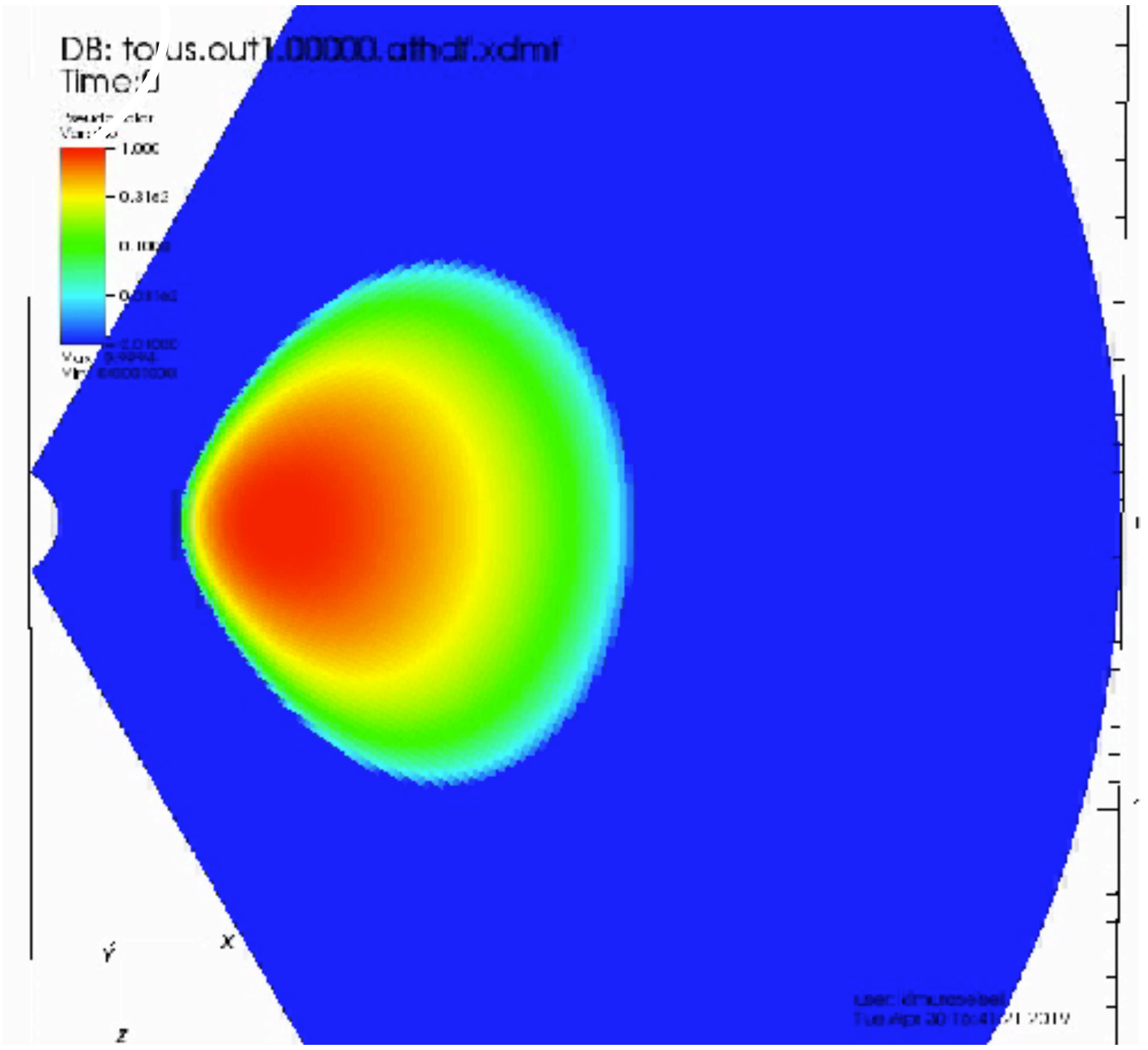
$$\frac{\partial \rho}{\partial T} + \nabla \cdot (\rho \boldsymbol{V}) = 0,$$

$$\frac{\partial (\rho \boldsymbol{V})}{\partial T} + \nabla \cdot \left(\rho \boldsymbol{V} \boldsymbol{V} - \frac{\boldsymbol{B} \boldsymbol{B}}{4\pi} + P^{*} \square \right) = -\rho \nabla \Phi,$$

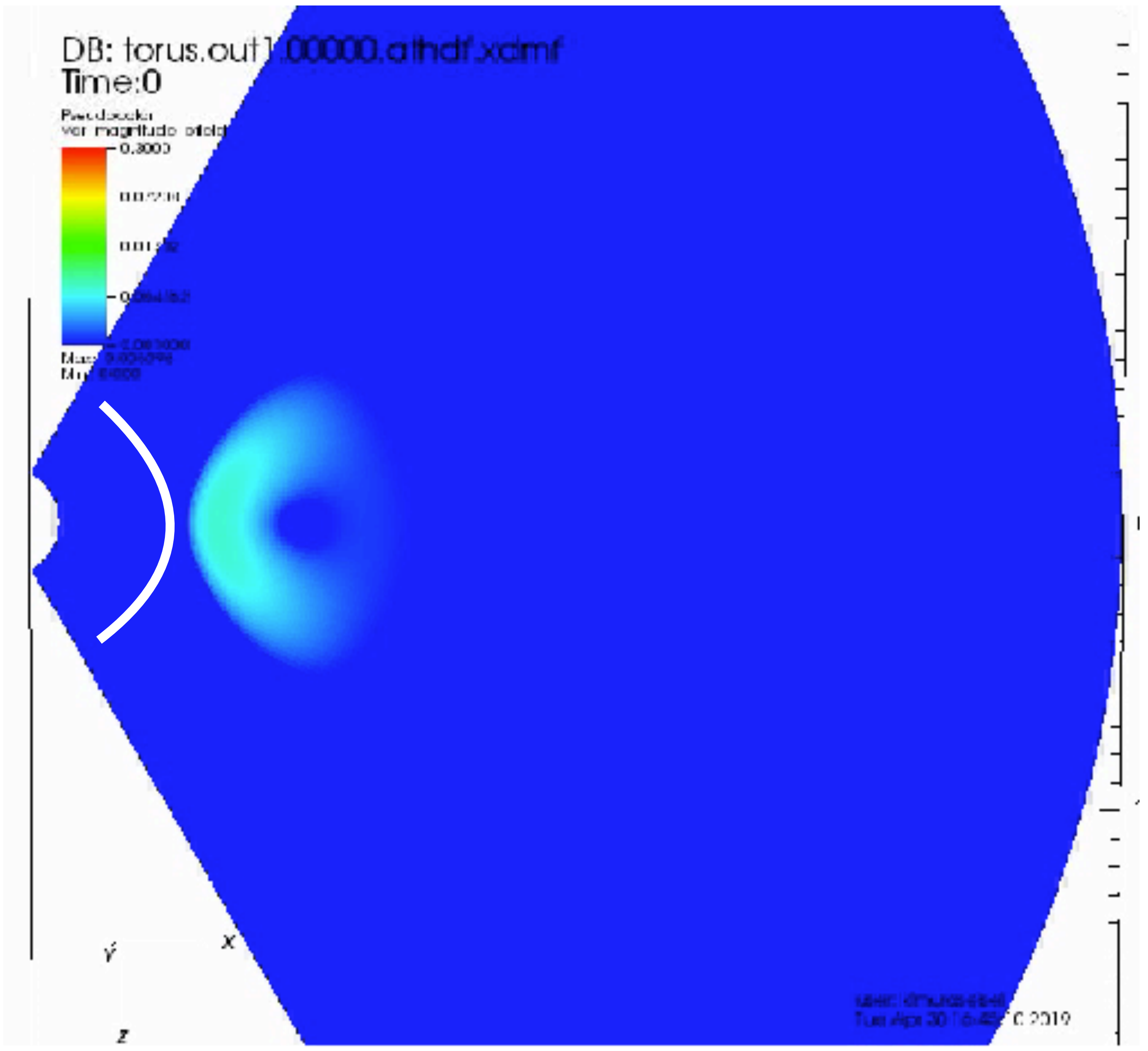
$$\frac{\partial E_{\rm tot}}{\partial T} + \nabla \cdot \left[\left(E_{\rm tot} + P^{*} \right) \boldsymbol{V} - \frac{\boldsymbol{B} \cdot \boldsymbol{V}}{4\pi} \boldsymbol{B} \right] = -\rho \boldsymbol{V} \cdot \nabla \Phi,$$

$$\frac{\partial \boldsymbol{B}}{\partial T} - \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) = 0,$$

Density



Magnetic field



- Calculate orbits of ~ 10^4 particles by solving their equations of motion
- We focus on very high energy particles of E > PeV

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = \mathrm{e} \left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c} \right),$$

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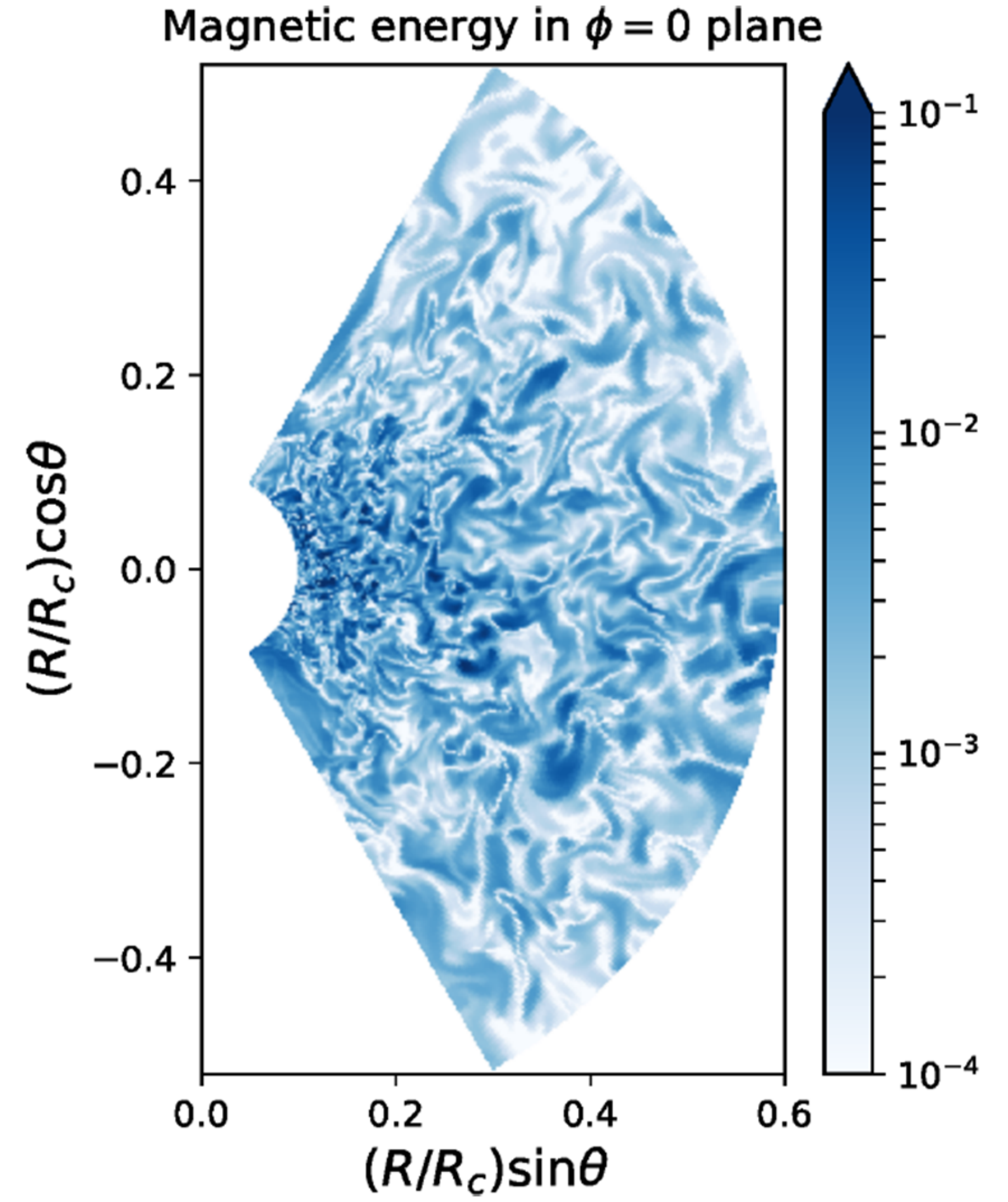

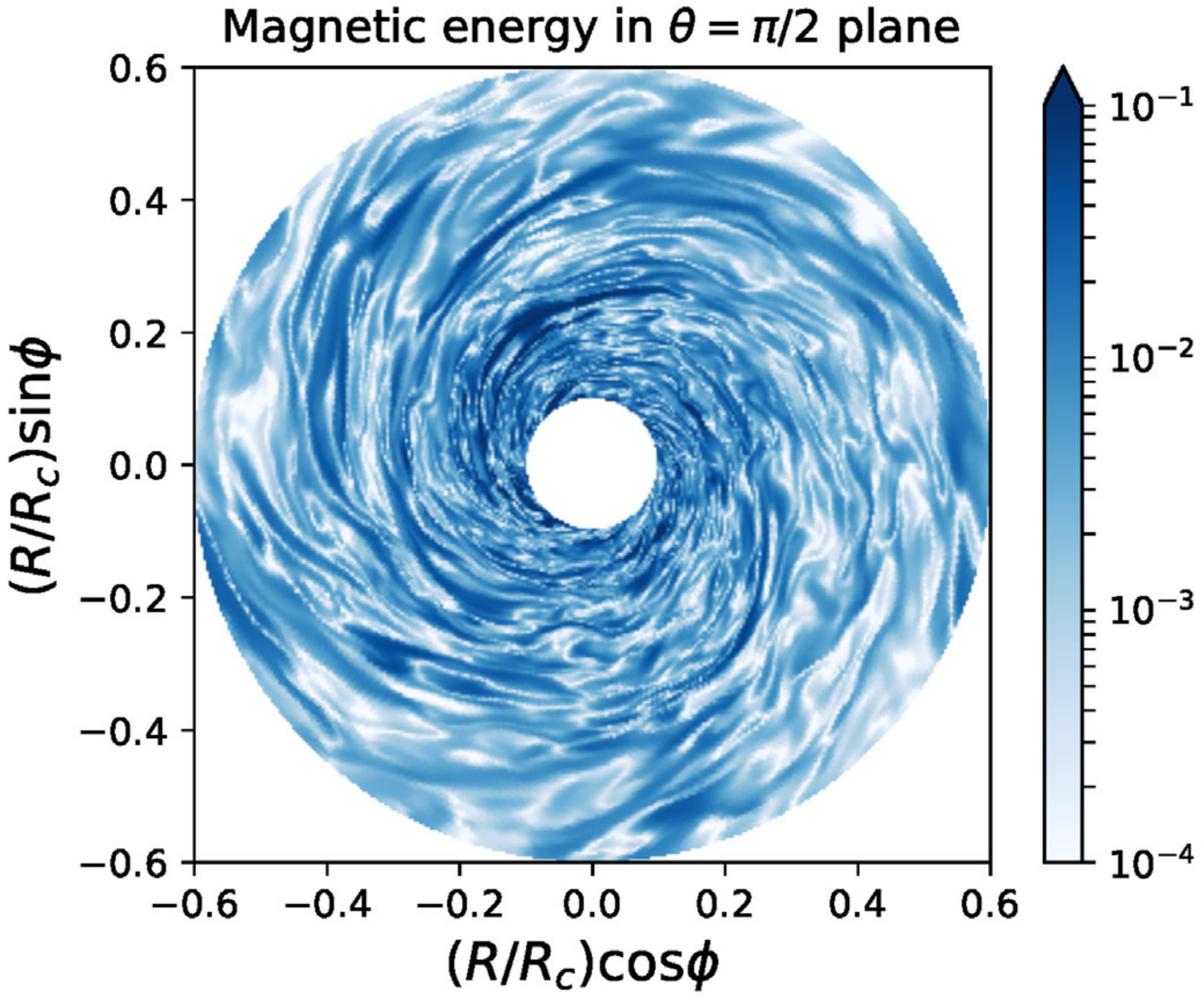

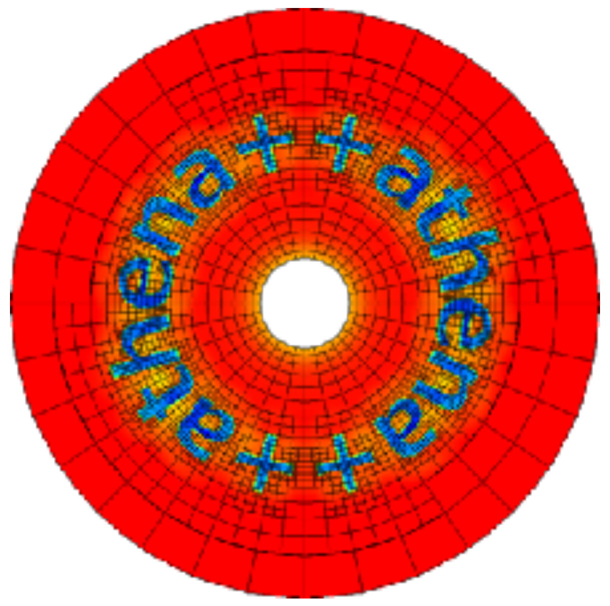

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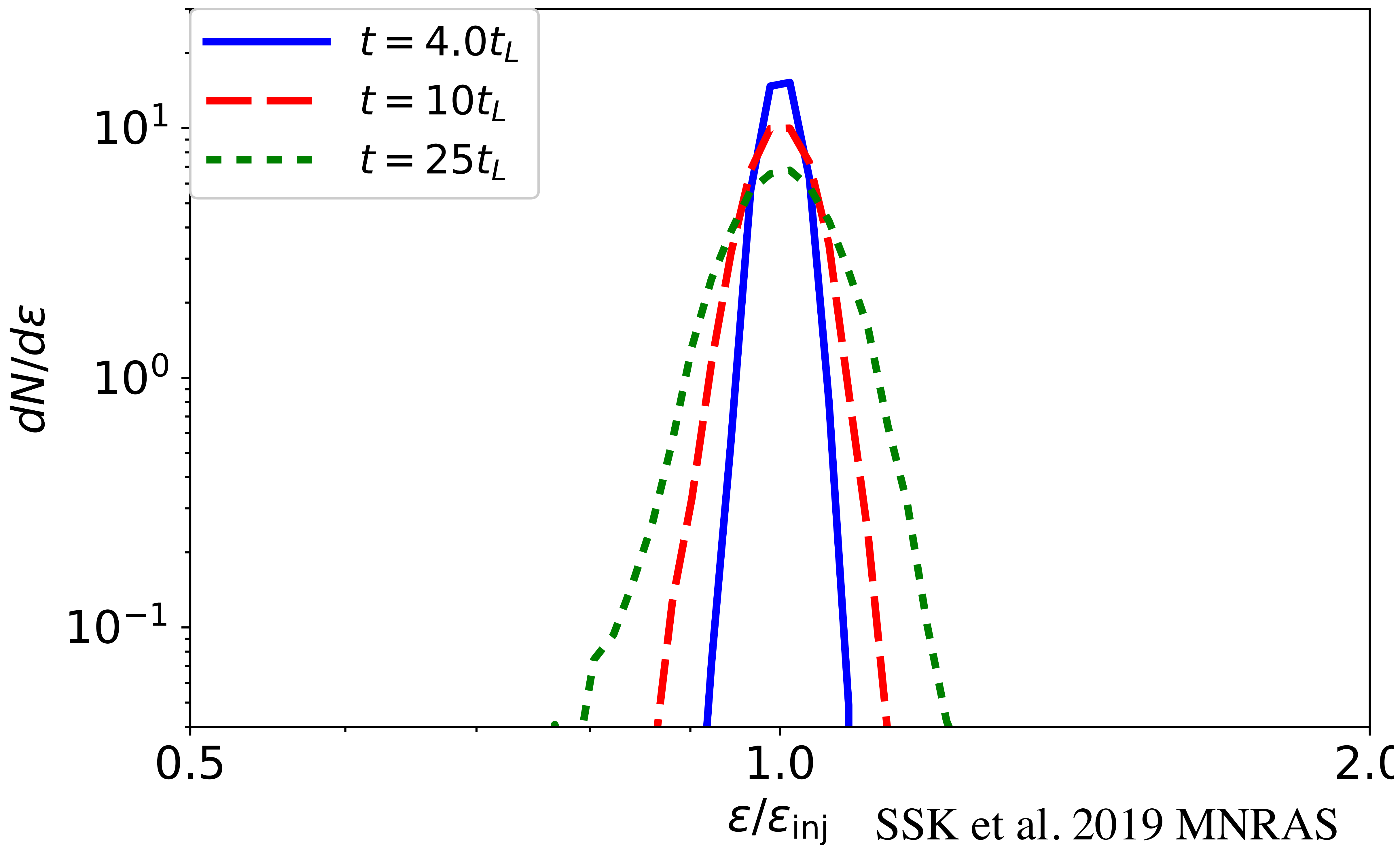
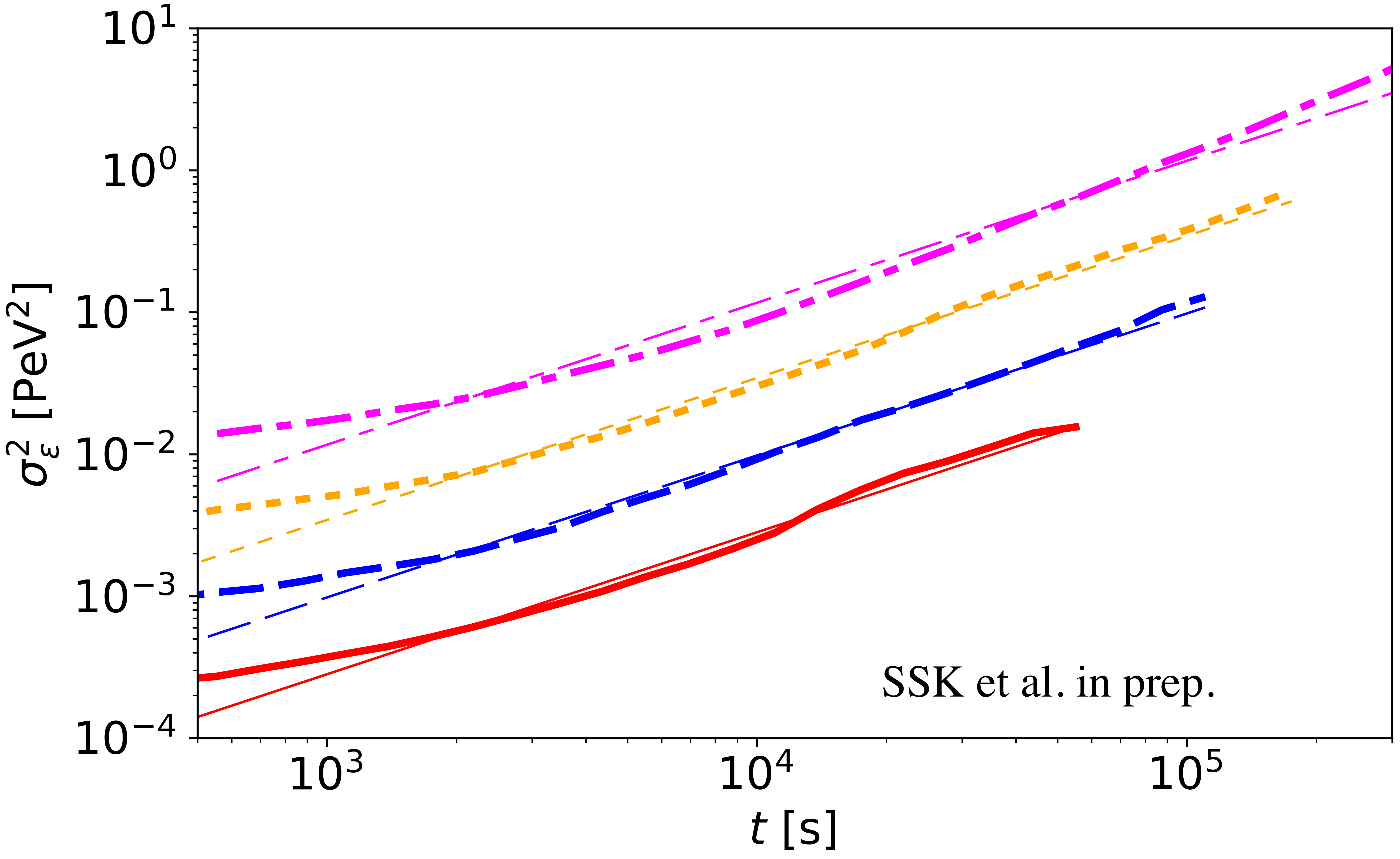
Diffusion in Energy Space

- Low-resolution runs



SSK et al. 2019 MNRAS

- High-resolution runs



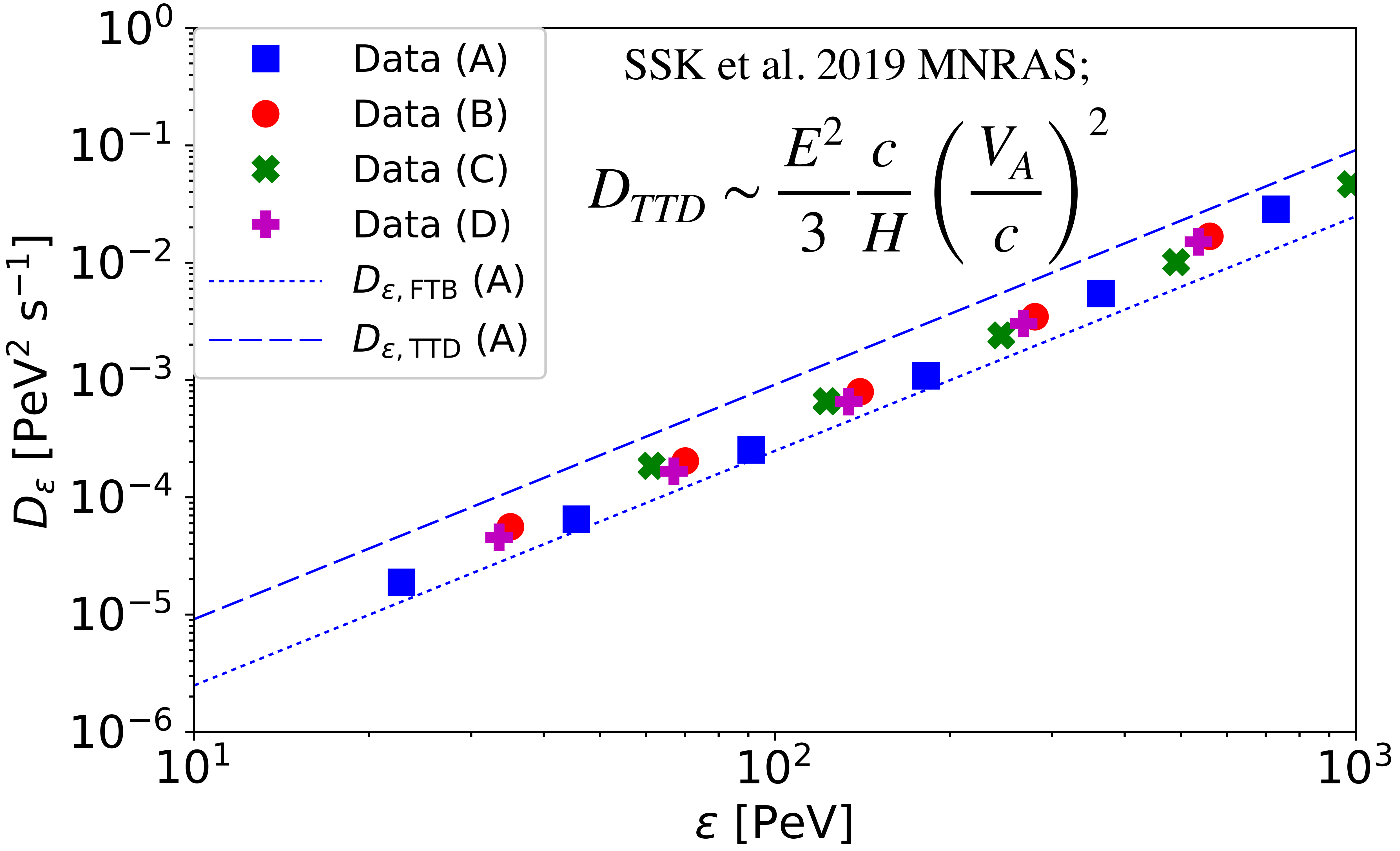
- Evaluate particle energies in fluid rest frame
- Evolution of Energy distribution function: dispersion (σ_E^2) increases with time

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p}\right)$$

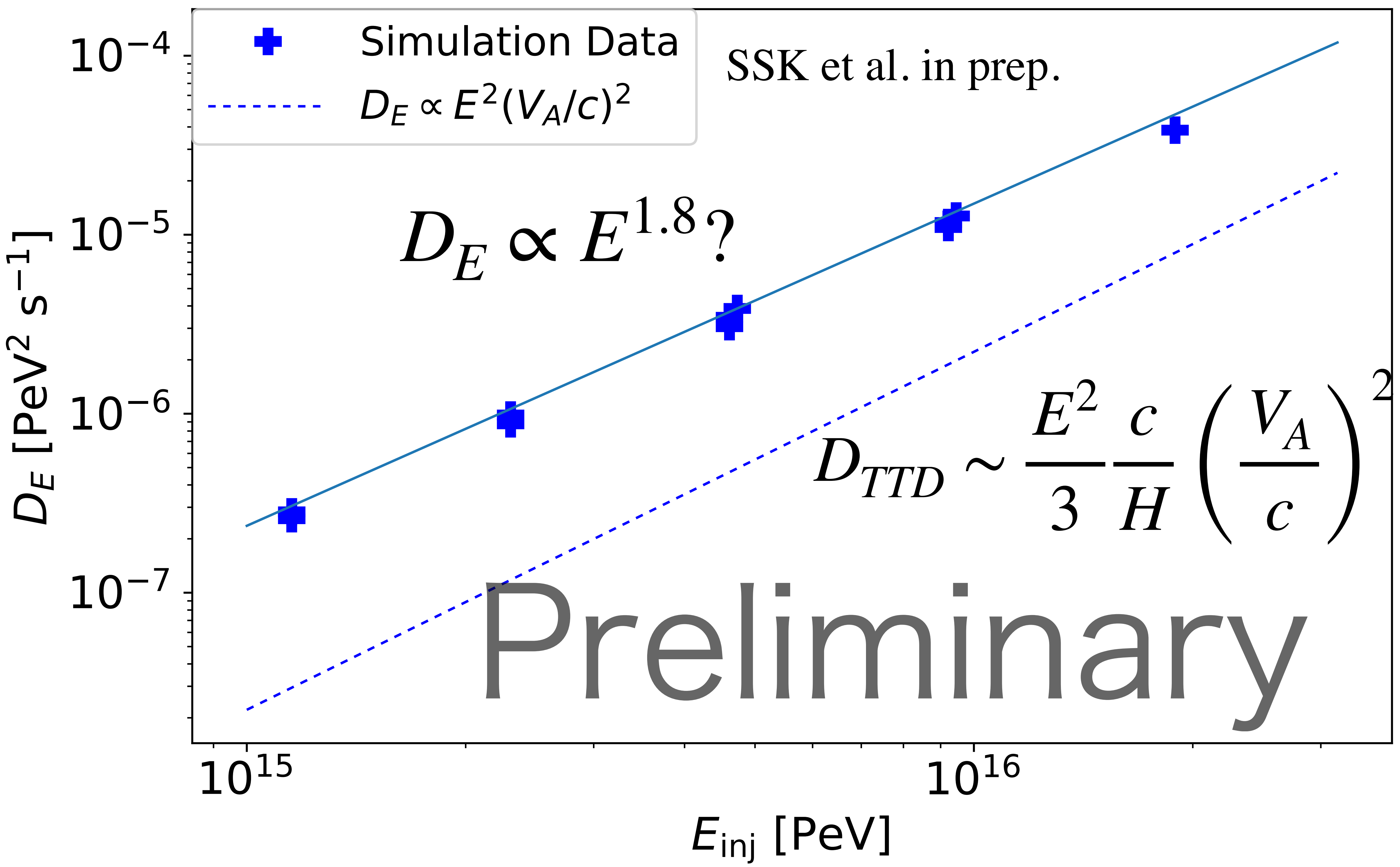
—> $$\sigma_\epsilon^2 \approx 2D_{\epsilon_{\rm ini}} t.$$

Diffusion Coefficients in E space

- Low-resolution runs



- High-resolution runs



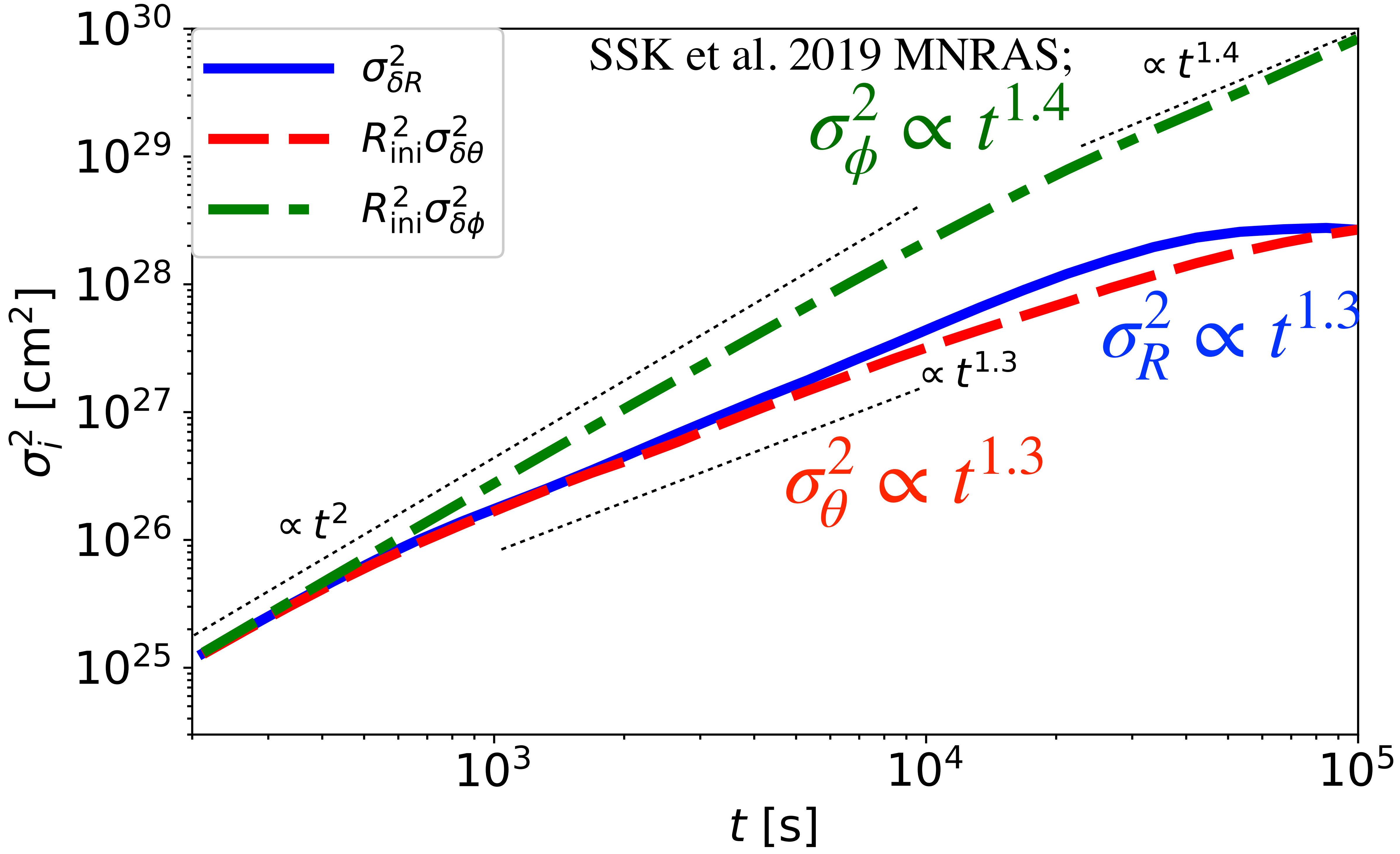
- All the particles interact with the largest eddies
- Roughly consistent with analytic estimates

- $D_E > D_{TTD}$
- Physical interpretation is still unclear

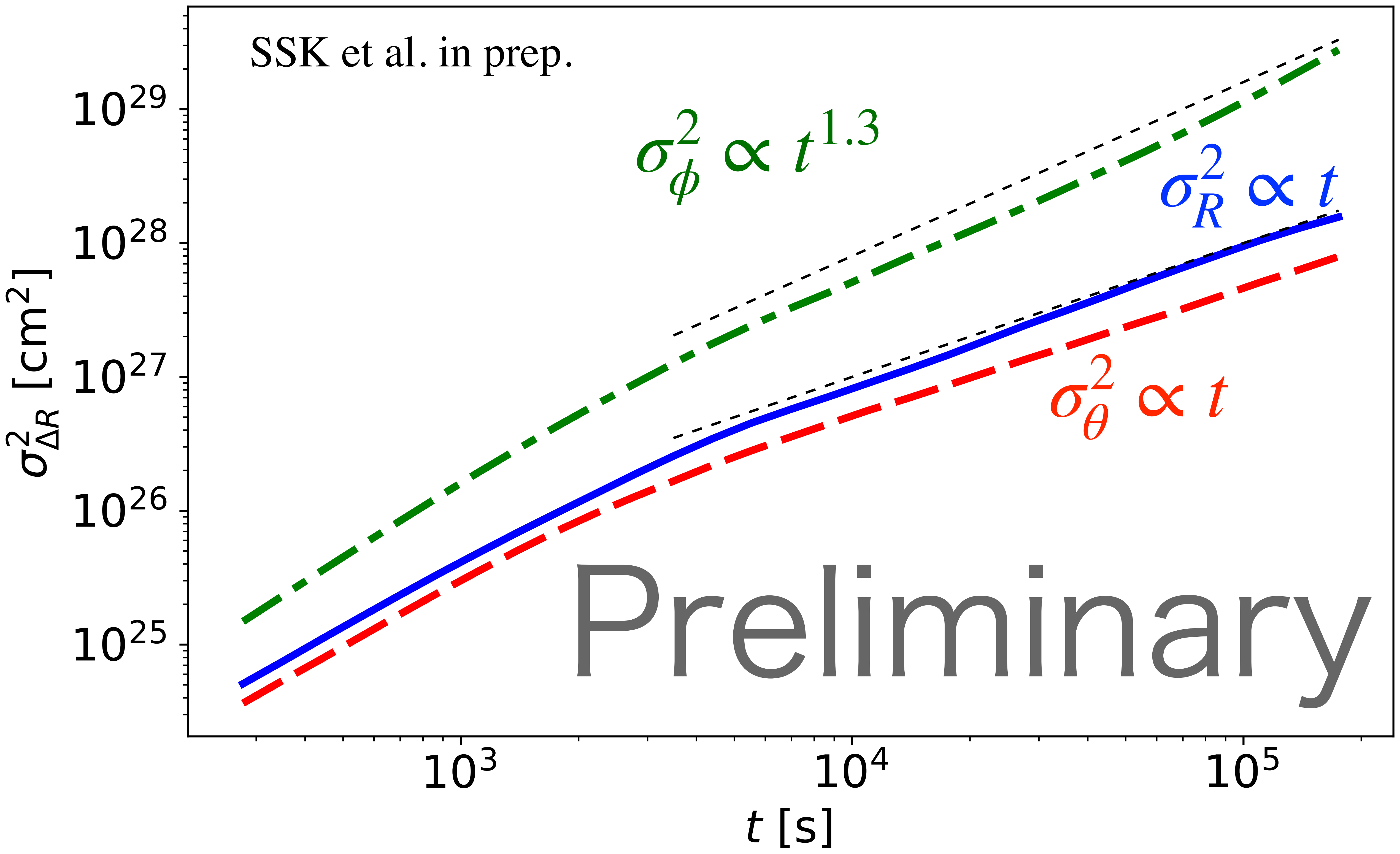
D_E depends on resolution

Diffusion in R space

- Low-resolution runs



- High-resolution runs

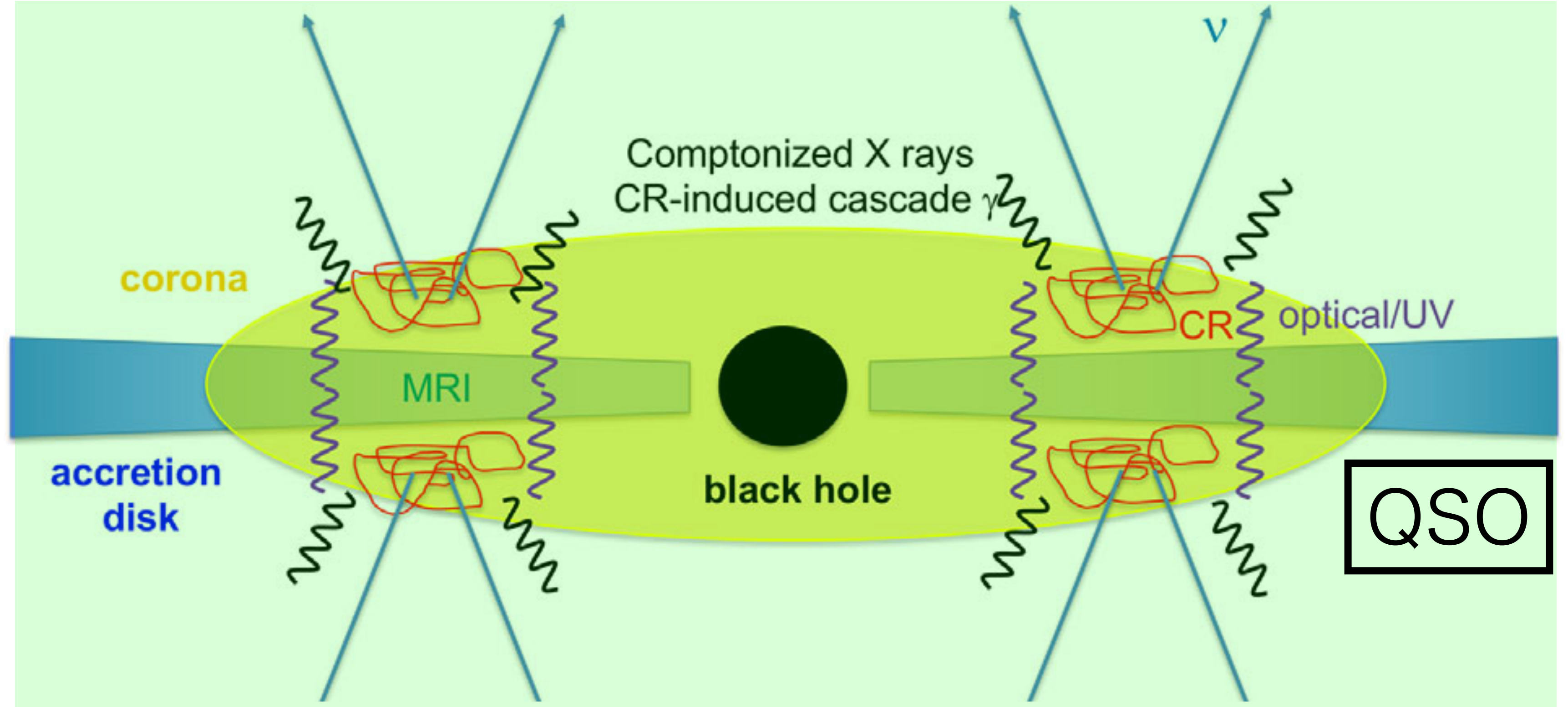


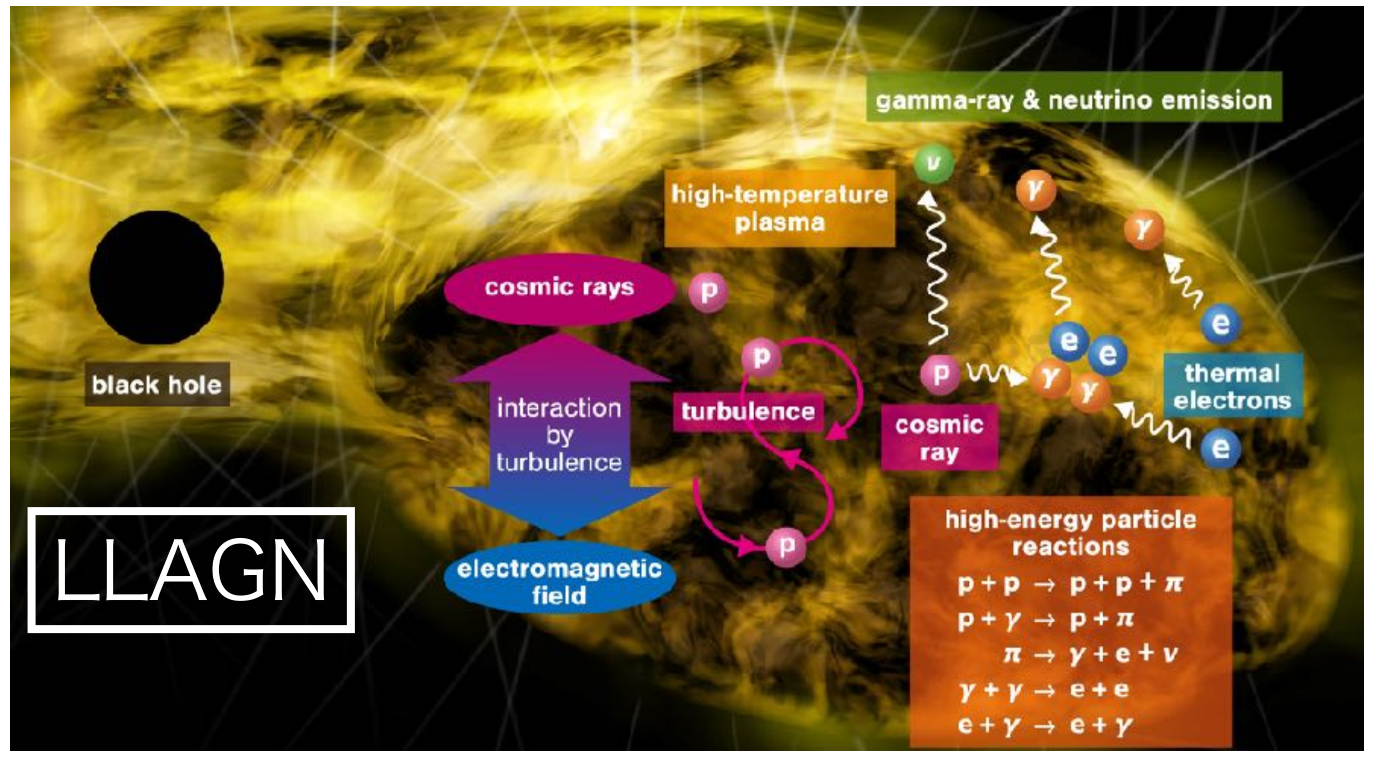
- Super-diffusion in all the directions

- Diffusion in R and θ directions
- Super-diffusion in ϕ direction

$\sigma^2_{\Delta R}$ depends on resolution

Summary





- IceCube discovered evidence of neutrino signal from Seyfert galaxy
- We constructed neutrino emission models from coronae and RIAFs
- Our models can explain IceCube data without contradicting γ-ray data
- MHD + test-particle simulations confirmed that CR particles in accretion flows can be described by diffusion equation in energy space