Neutrino Emission from Accretion Flows in Active Galactic Nuclei

Tohoku University

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References:
Murase, SSK, Meszaros, 2020, PRL, 125, 011101
Kheirandish, Murase, SSK, 2021, ApJ, 922, 45
SSK, Murase, Meszaros, 2021, Nat. Comm., 12, 5615

ICRC satellite workshop@Chiba Univ.
Aug. 7, 2023

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- Introduction
- Neutrino emission models in Seyfert galaxies
- Neutrino emission from AGN coronae
- Sub-GeV gamma rays from Seyfert galaxies
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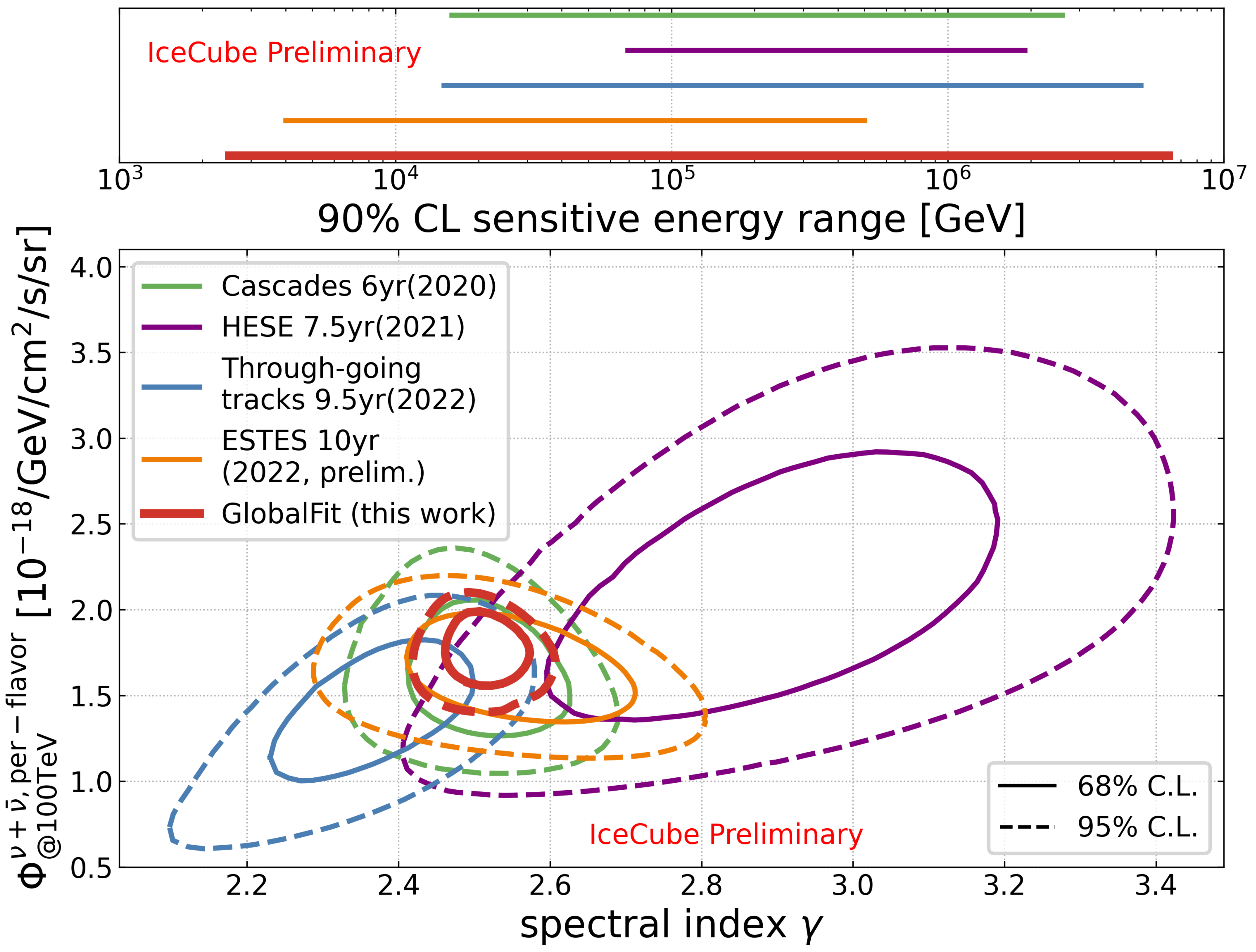
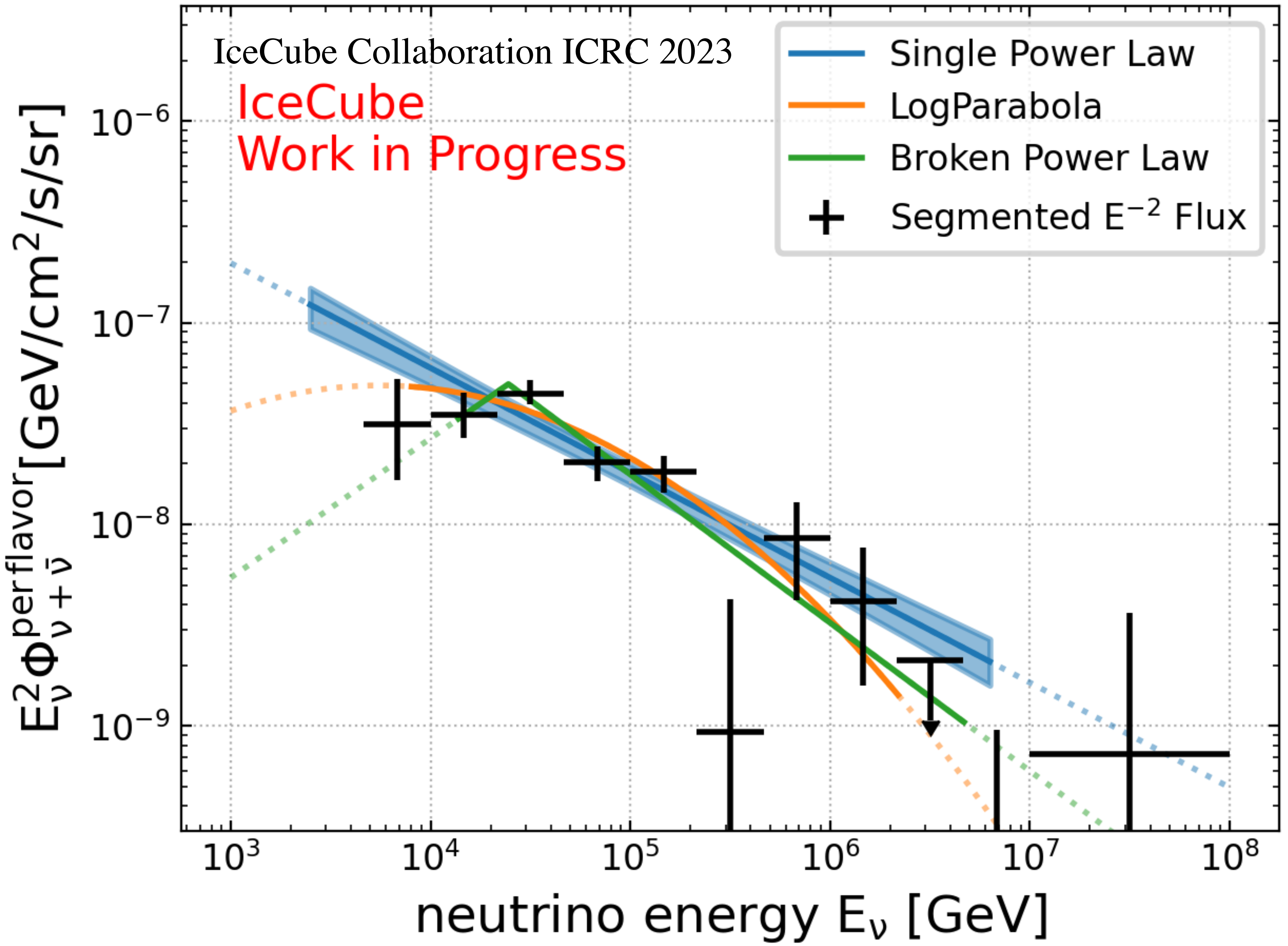
Cosmic Neutrino Background Spectrum

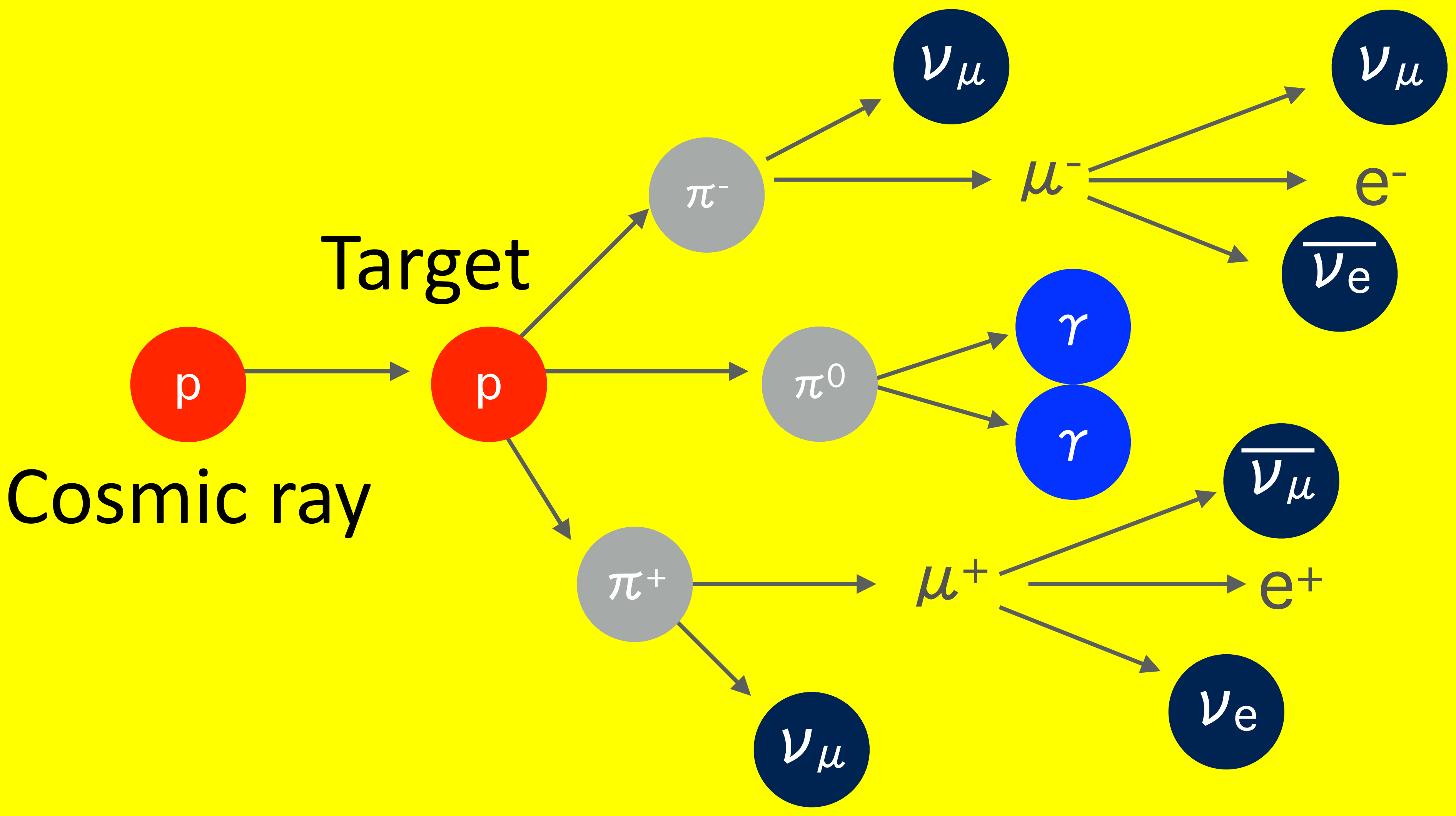




- Soft cosmic neutrino spectra
  → **Medium energy excess (High intensity @~10 TeV)**
- **Origins of cosmic neutrinos are a new big mystery**

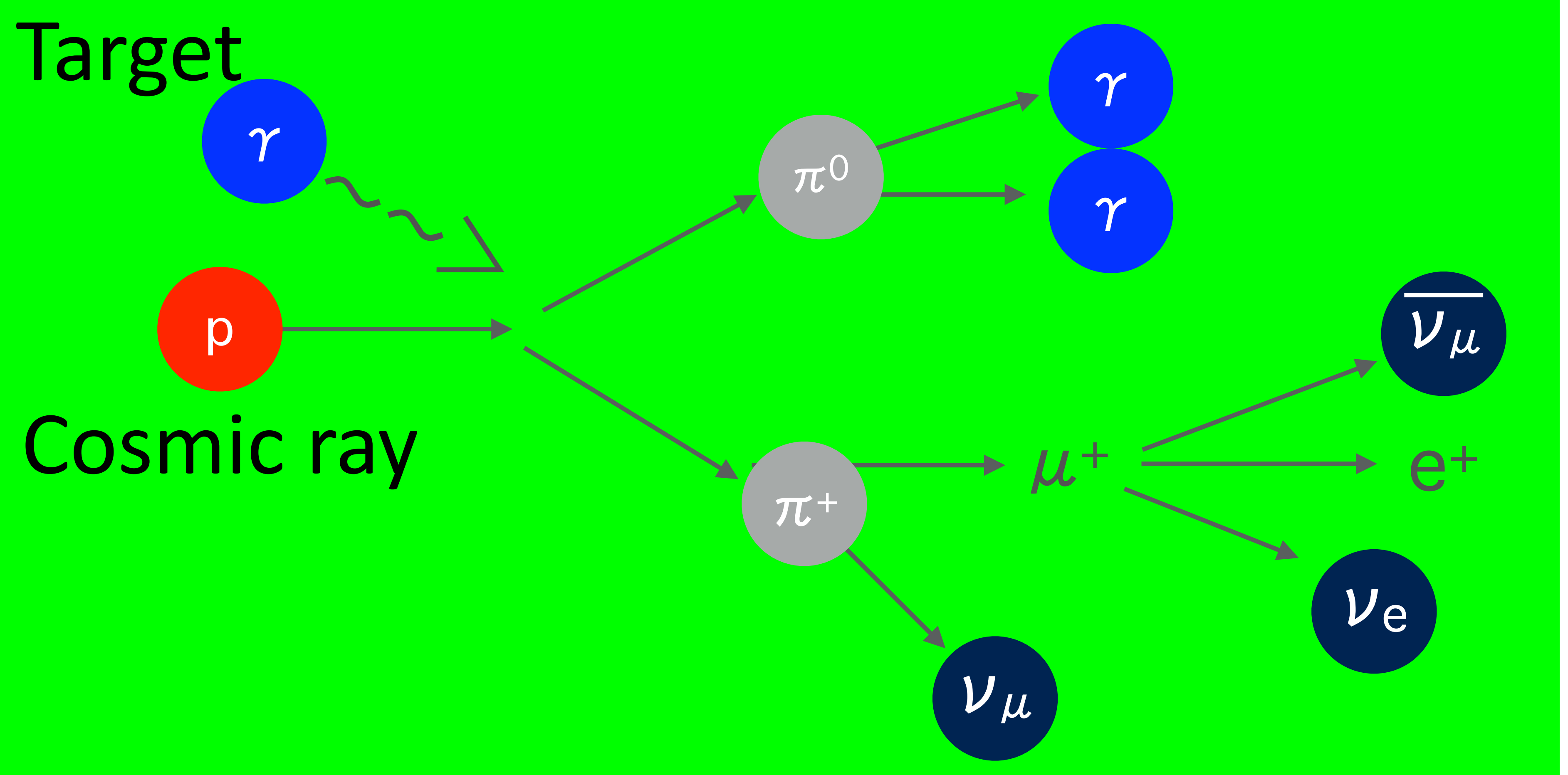
High-energy neutrino production

- pp inelastic collision



- $p+p \to p+p+\pi$
- $\pi^{\pm} \to 3\nu+e$
- $\pi^0 \to 2\gamma$

- Photomeson production ($p\gamma$)



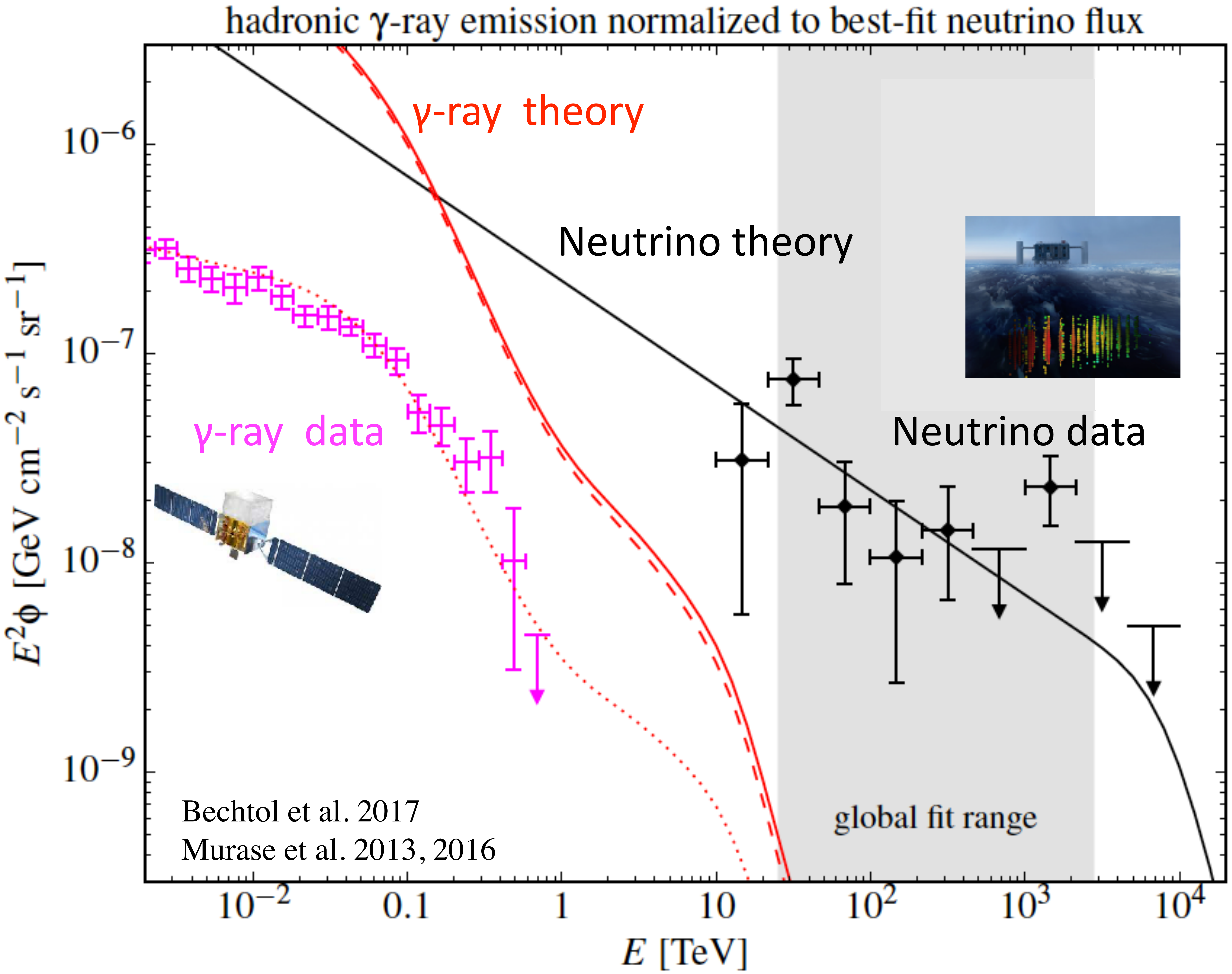
- $p+\gamma \to p+\pi$
- $\pi^{\pm} \to 3\nu+e$
- $\pi^0 \to 2\gamma$

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)**
  $\gamma + \gamma \rightarrow e^+ + e^-$
- X-rays efficiently absorbs GeV γ-rays

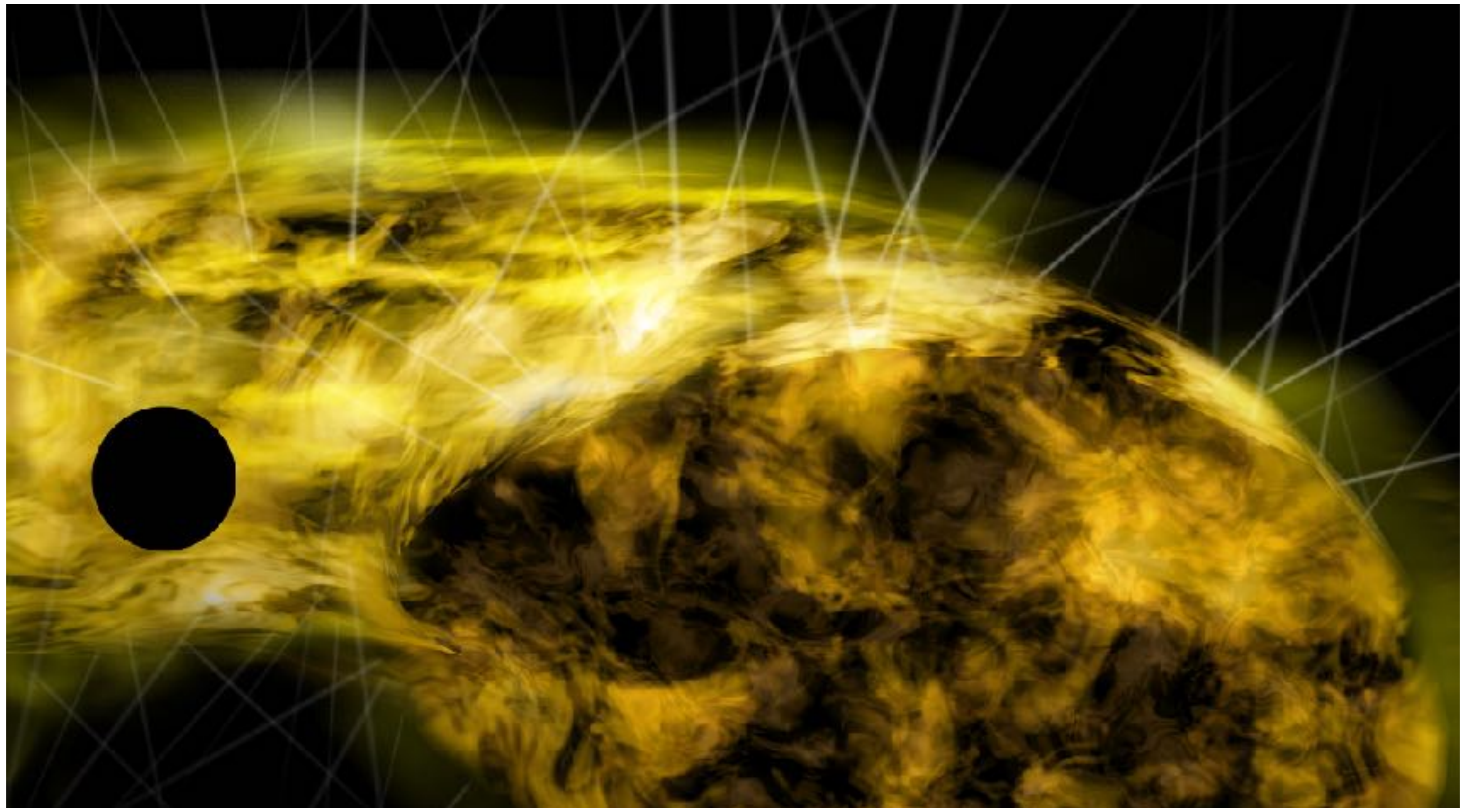


Bechtol et al. 2017
Murase et al. 2013, 2016

Hidden Neutrino Source Candidates

- AGN Core

Kimura et al. 2021

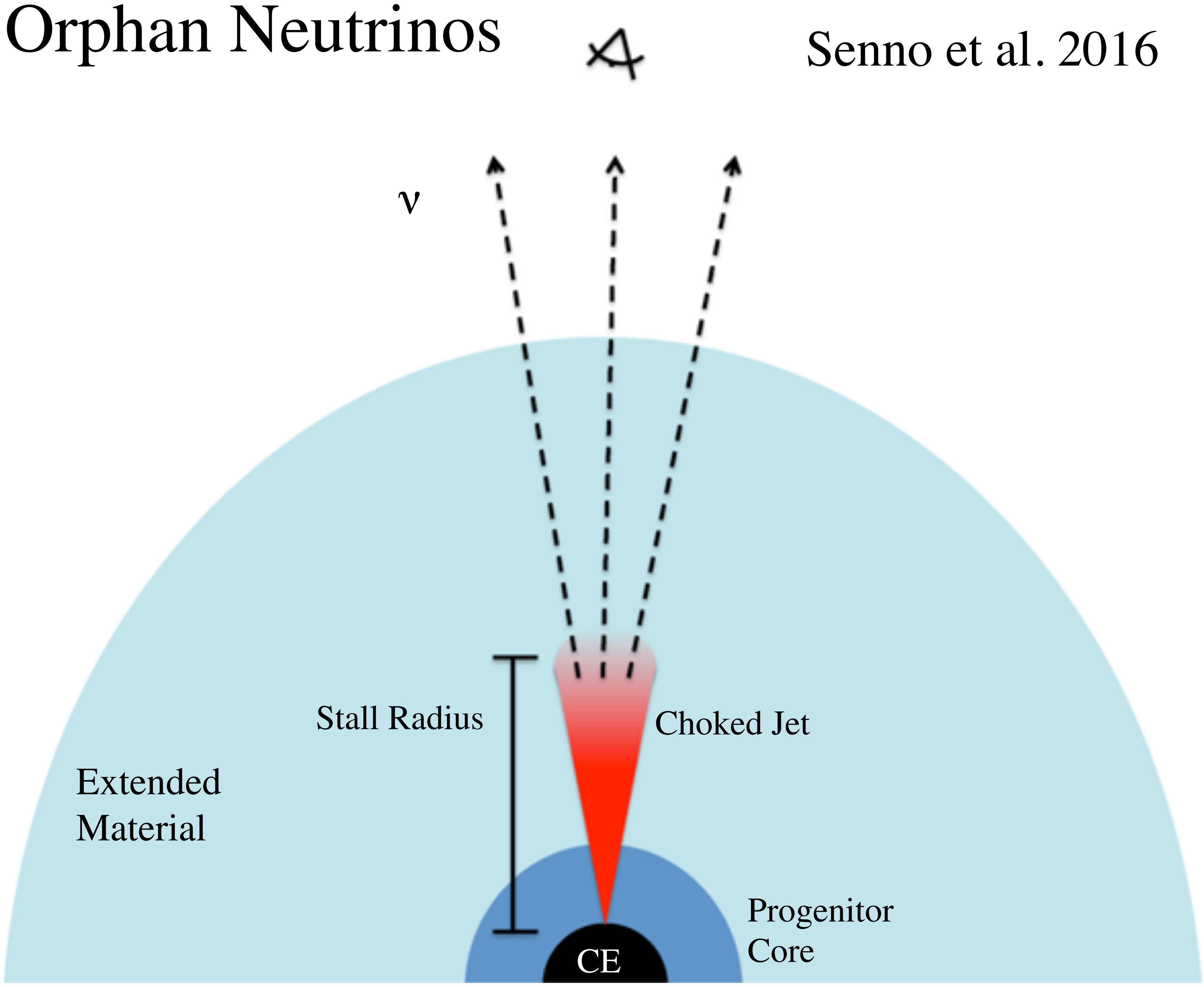


- Most luminous steady source in the Universe
- Source of Cosmic X-ray background
- $\gamma + \gamma \rightarrow e^+ + e^-$

- Choked GRBs

Orphan Neutrinos

Senno et al. 2016

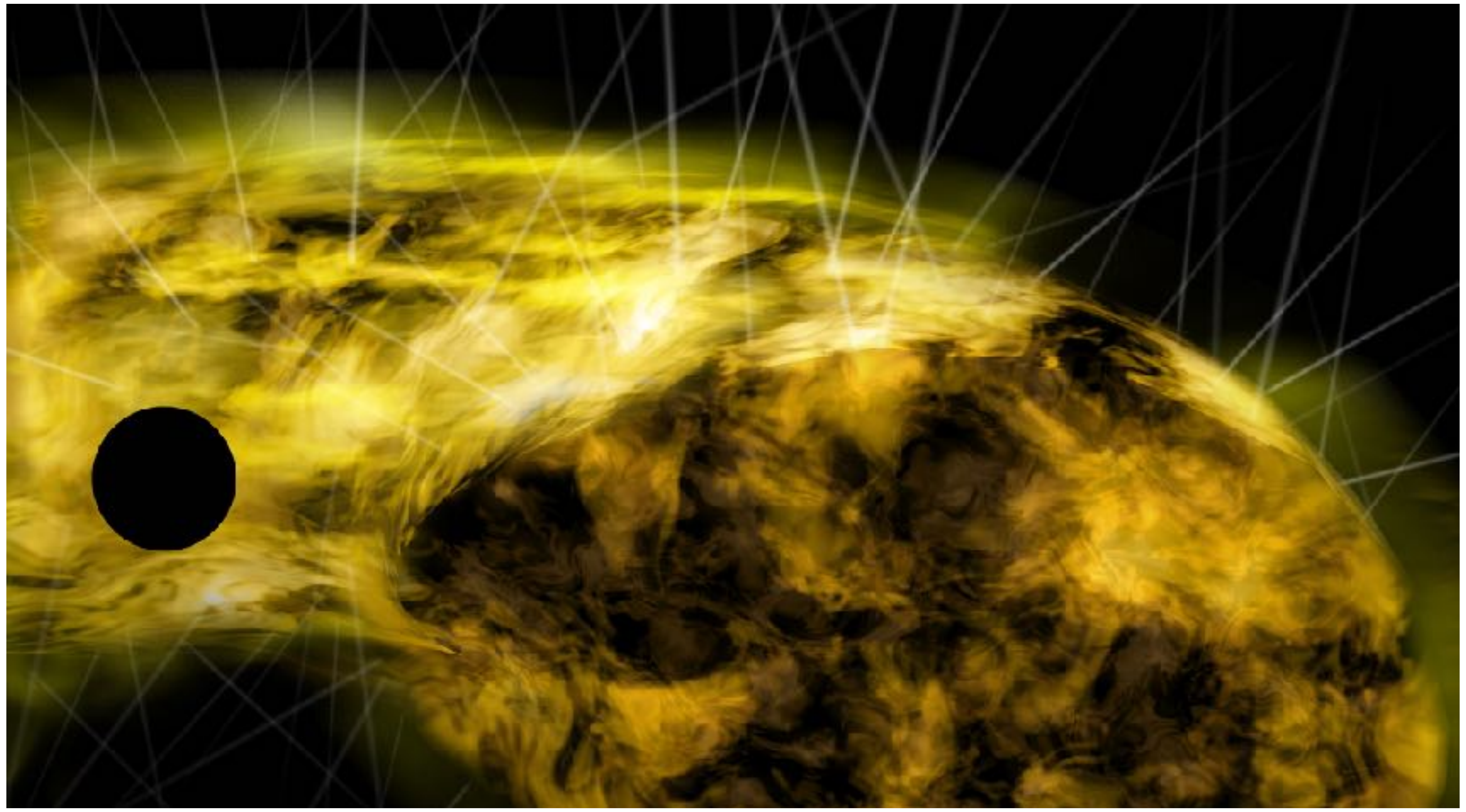


- GRBs failed to penetrate stellar envelope
- Stellar envelope absorbs γ-rays
- $p + \gamma \rightarrow p + e^+ + e^-$

Hidden Neutrino Source Candidates

- AGN Core

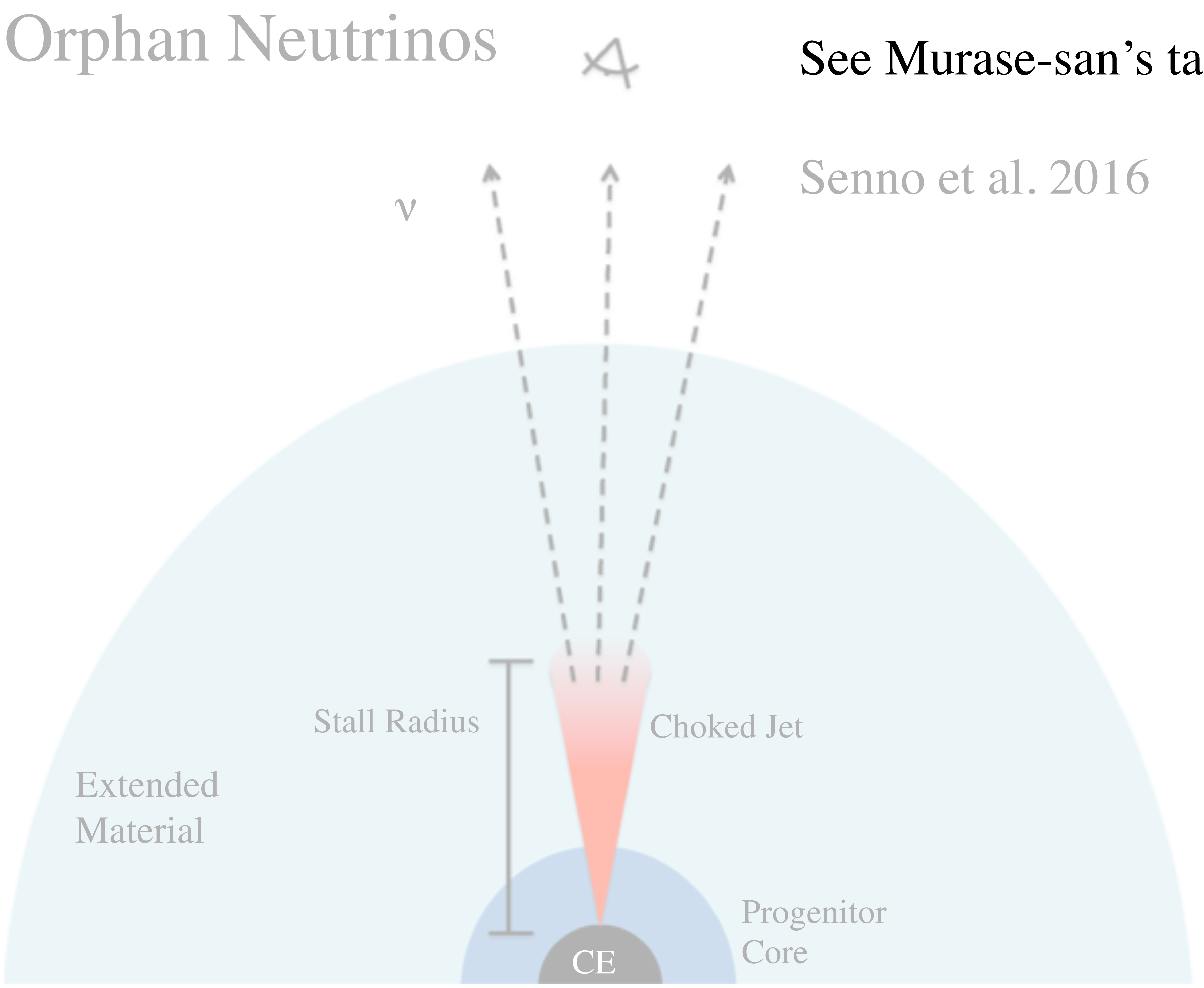
Kimura et al. 2021



- Most luminous steady source in the Universe
- Source of Cosmic X-ray background
- $\gamma + \gamma \rightarrow e^{+} + e^{-}$

- Choked GRBs

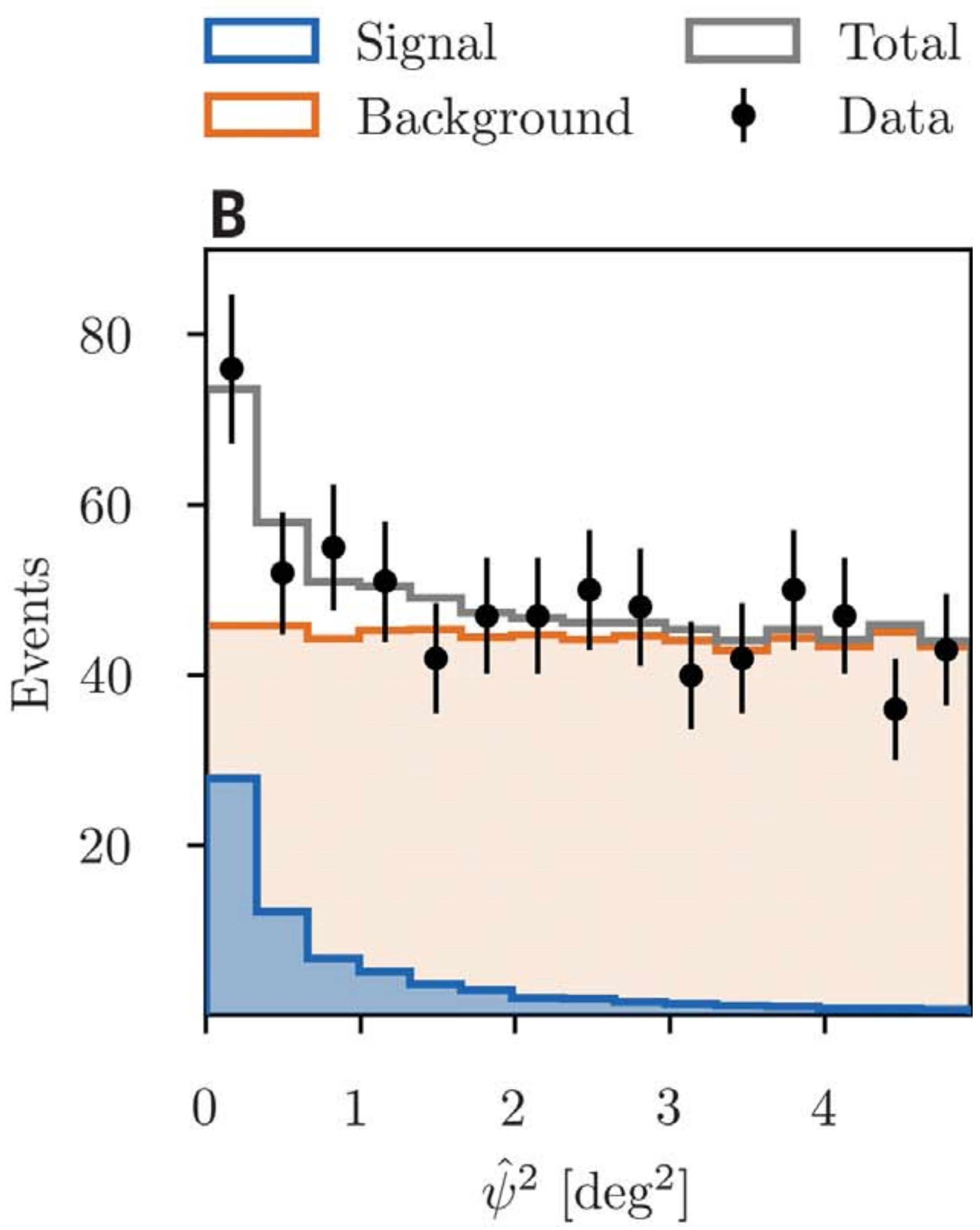
See Murase-san's talk

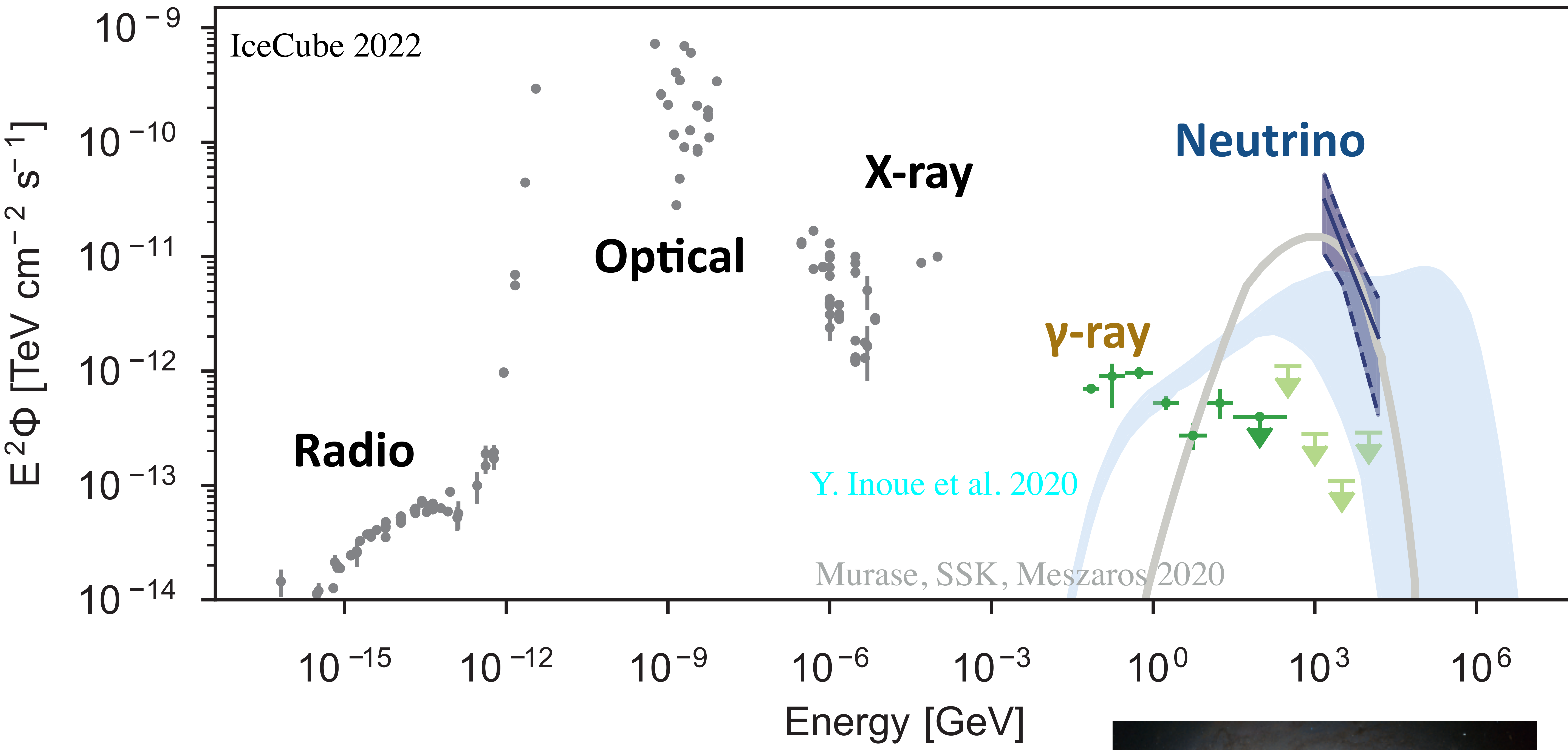


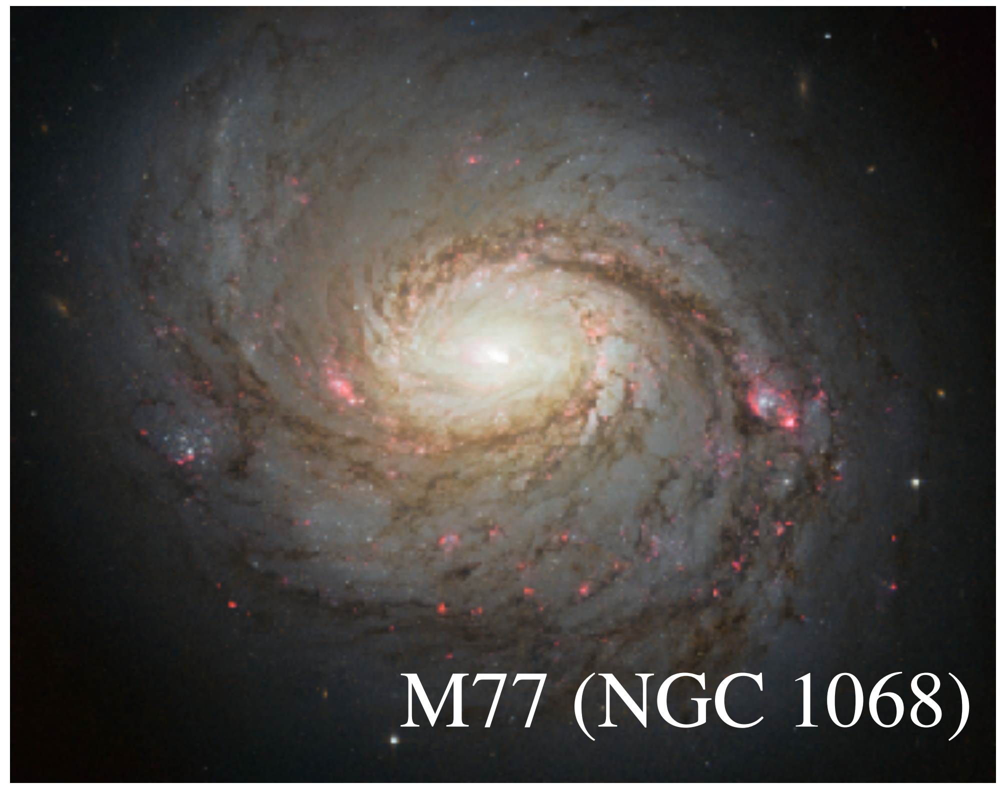
Senno et al. 2016

- GRBs failed to penetrate stellar envelope
- Stellar envelope absorbs γ-rays
- $p + \gamma \rightarrow p + e^{+} + e^{-}$

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.**

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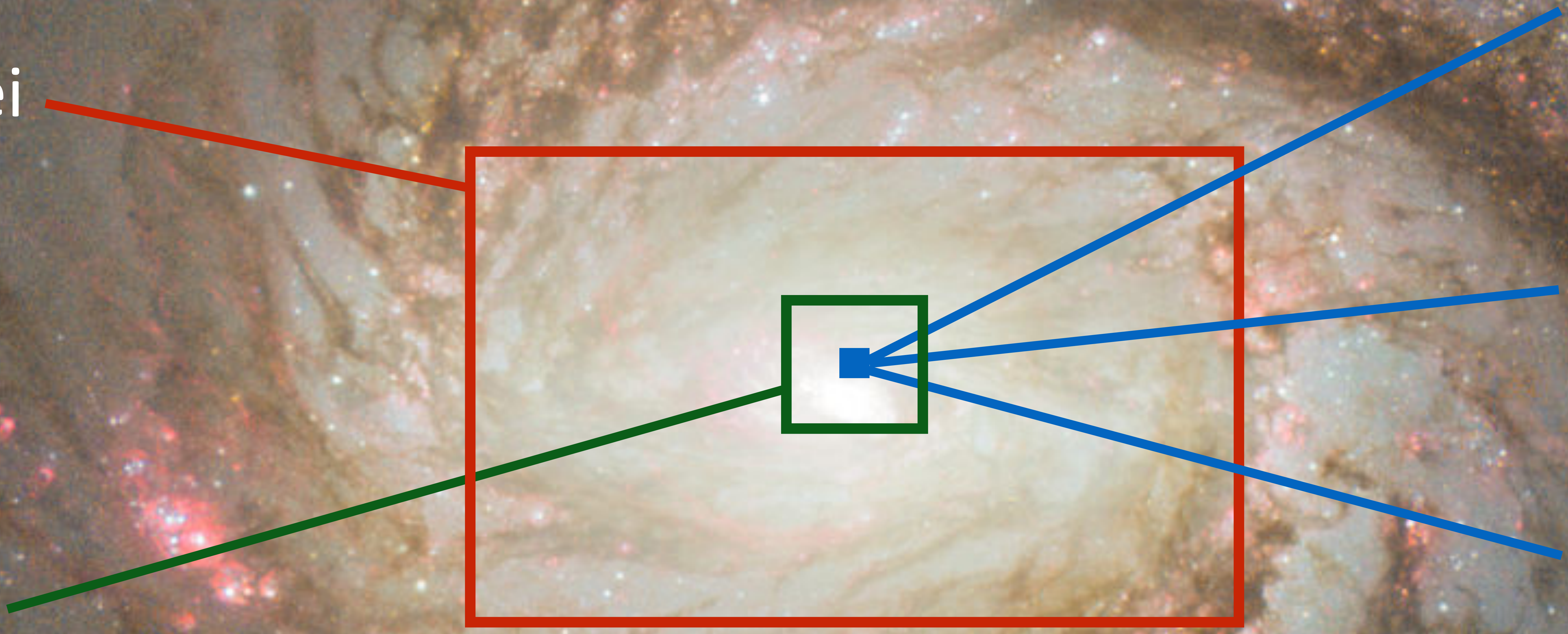
Neutrino & gamma-ray production sites

- Large emission regions
  $\gtrsim 10^6 R_G$

- Compact emission regions
  $\lesssim 10^2 R_G$



- Starburst nuclei
  $\sim$ 0.1 - 1 kpc

Loeb & Waxman 2006
Murase et al. 2013

- Mini jets
  $\sim$10 - 100 pc

Michiyama et al. 2022

- AGN winds
  $\sim 10^{-5} - 10^{-3}$pc

Inoue S. et al. 2022

- Accretion shocks
  $\sim 10^{-5} - 10^{-4}$pc

Inoue Y. et al. 2021

- AGN coronae
  $\sim 10^{-5}$pc

Murase, SSK, Meszaros 2020
Kheirandish, Murase, SSK 2021
Eichmann et al. 2022

Large emission regions

- Starburst nuclei Yoast-Hull et al. 2014 Wang et al. 2018
  - Cosmic-ray production@SNR
  - Neutrino production@ISM

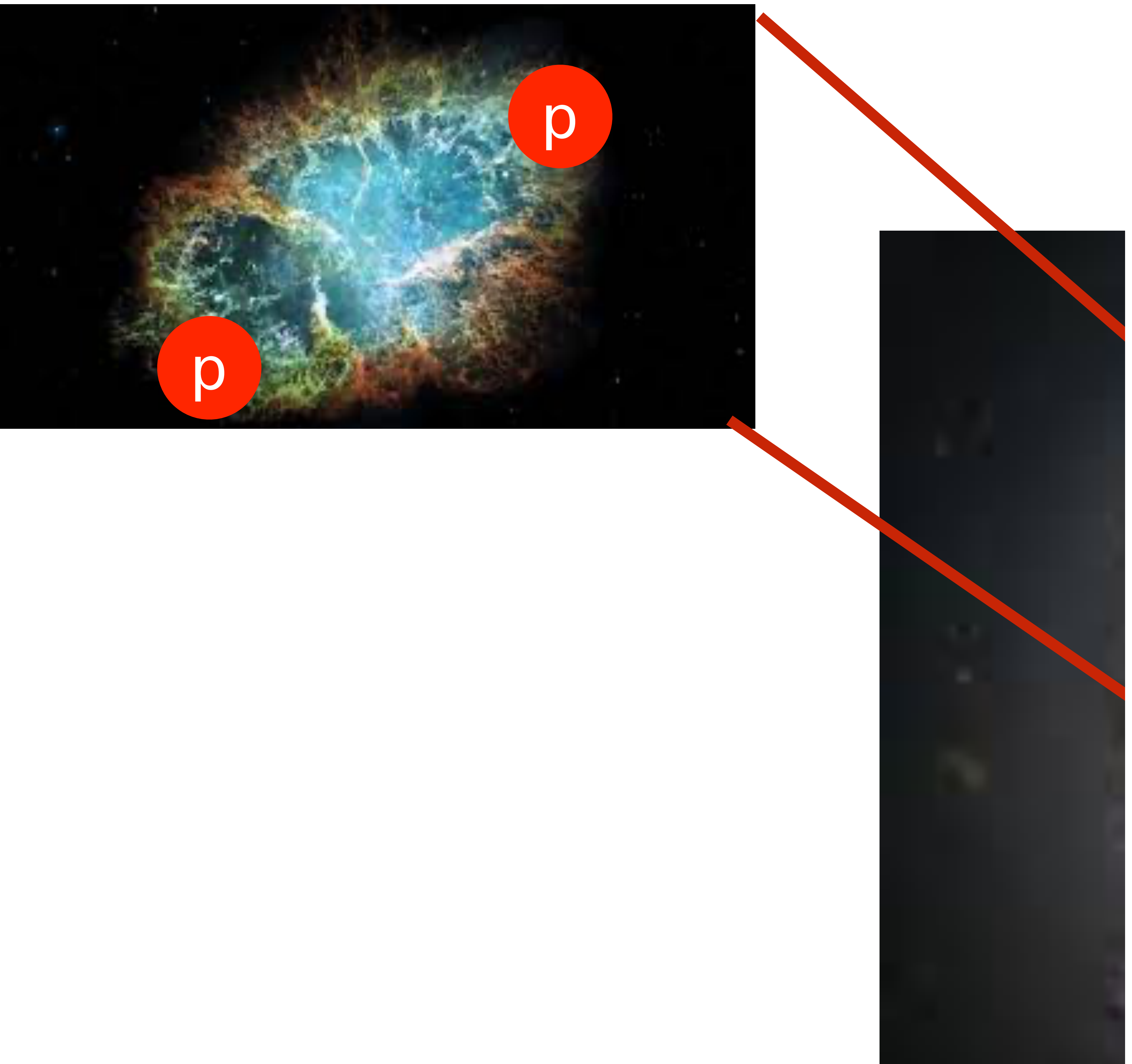
- Mini jets Michiyama et al. 2022
  - Cosmic-ray production@jets
  - Neutrino production@jets or ISM

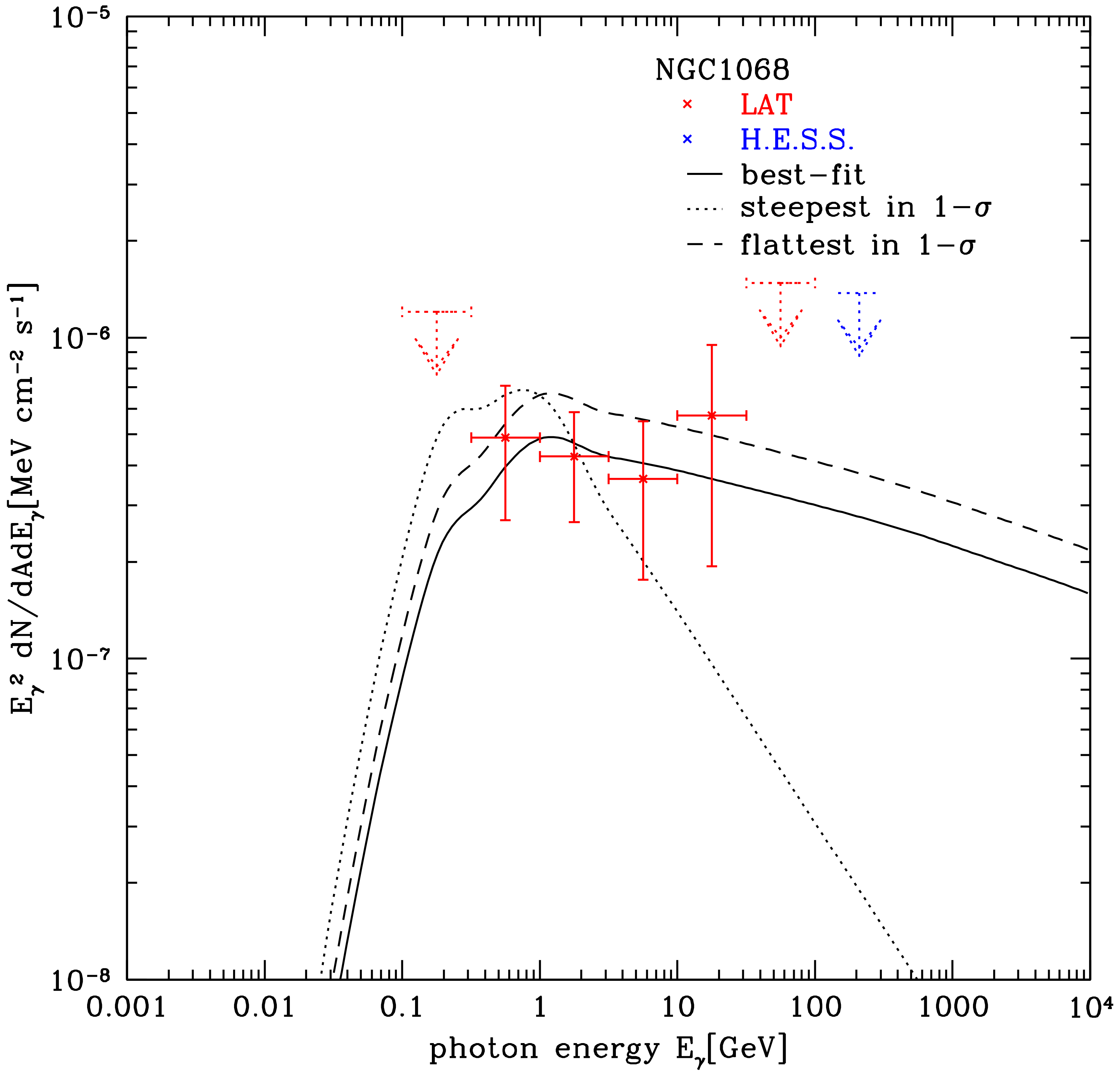
Large emission regions

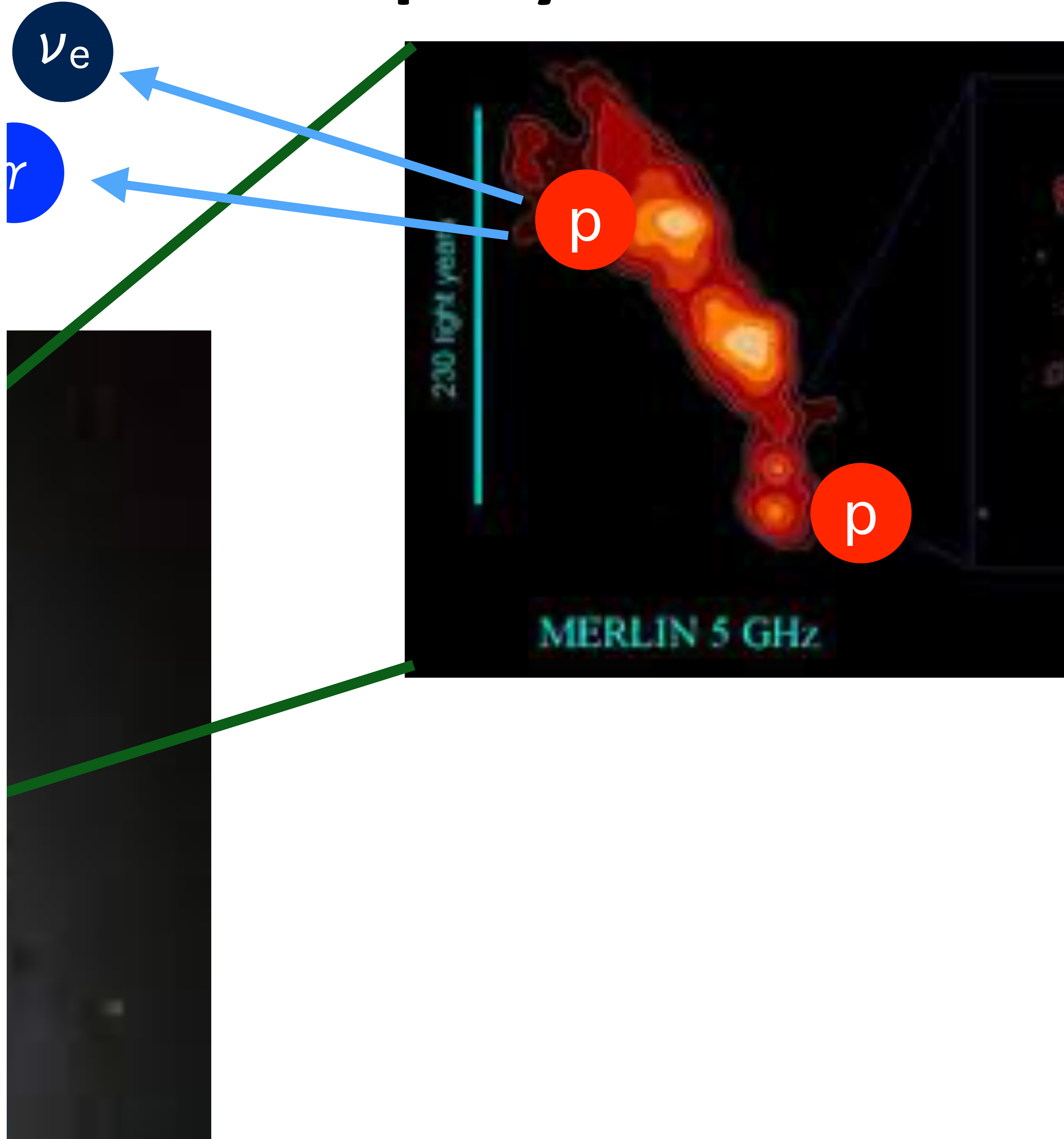
- Starburst nuclei Yoast-Hull et al. 2014 Wang et al. 2018
  - Cosmic-ray production@ SNR
  - Neutrino production@ ISM

- Mini jets Michiyama et al. 2022
  - Cosmic-ray production in jets
  - Neutrino production in jets or ISM

Hadronuclear interaction —> γ-rays consistent with GeV γ-ray data



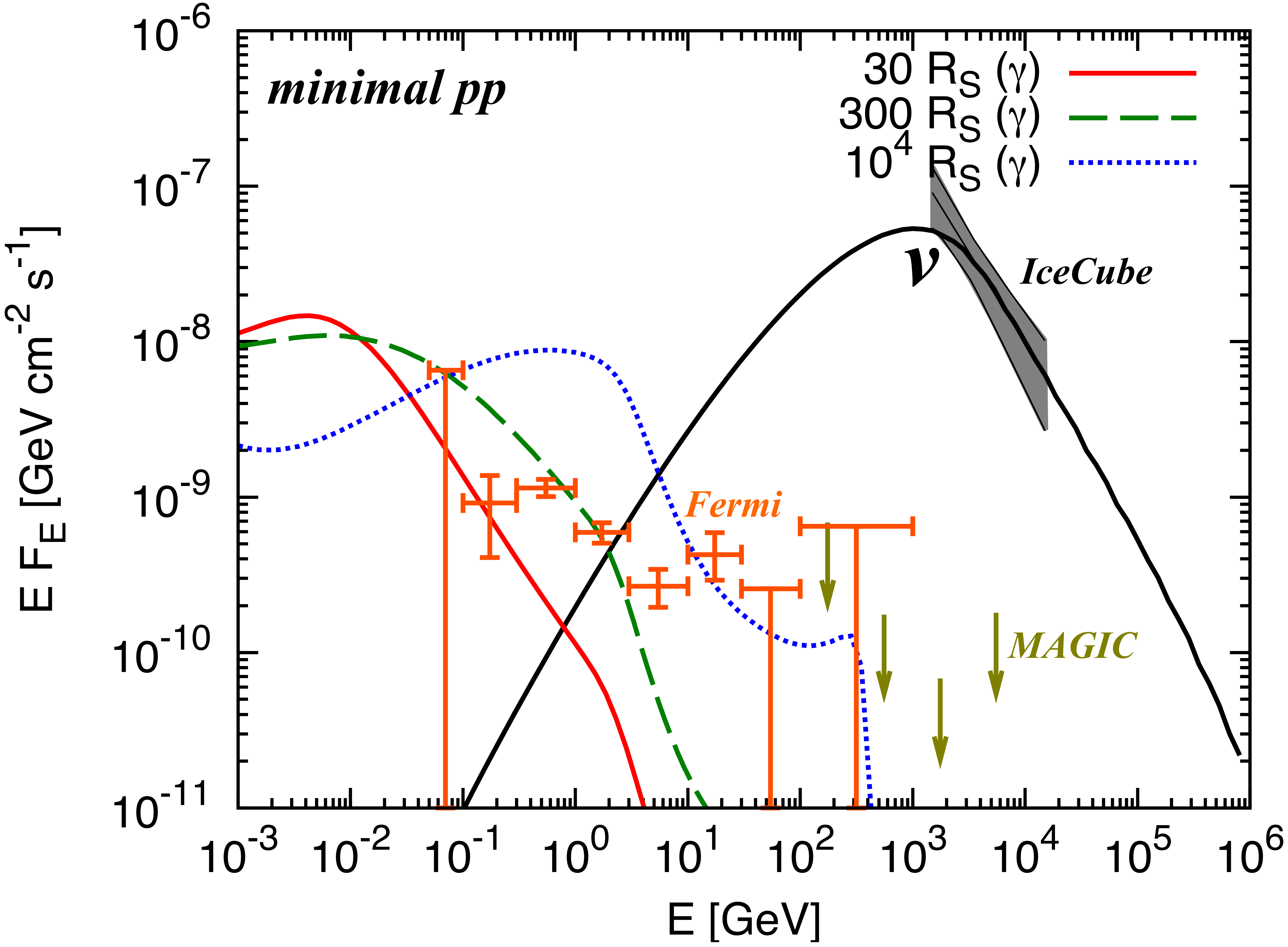




γ-ray constraints

Murase 2022

- NGC 1068 should be hidden sources
  —> demands compact emission sites
- EM cascade modeling with γ-ray data:
  —> Emission region: $R \lesssim 100 R_S$



- **This constraint rules out**
  - starburst nuclei ($R \gtrsim 10^6 R_G$)
  - radio jets ($R \gtrsim 10^5 R_G$)
  as neutrino emission sites

Neutrino & gamma-ray production sites

- Large scale emission regions

- Starburst nuclei
  $\sim$kpc

  Loeb & Waxman 2006
  Murase et al. 2013

- Mini jets
  $\sim$10 - 100 pc

  Michiyama et al. 2022

- Compact emission regions

- AGN winds
  $\sim 10^{-5} - 10^{-3}$pc

  Inoue S. et al. 2022

- Accretion shocks
  $\sim 10^{-5} - 10^{-4}$pc

  Inoue Y. et al. 2021

- AGN coronae
  $\sim 10^{-5}$pc

  Murase, SSK, Meszaros 2020
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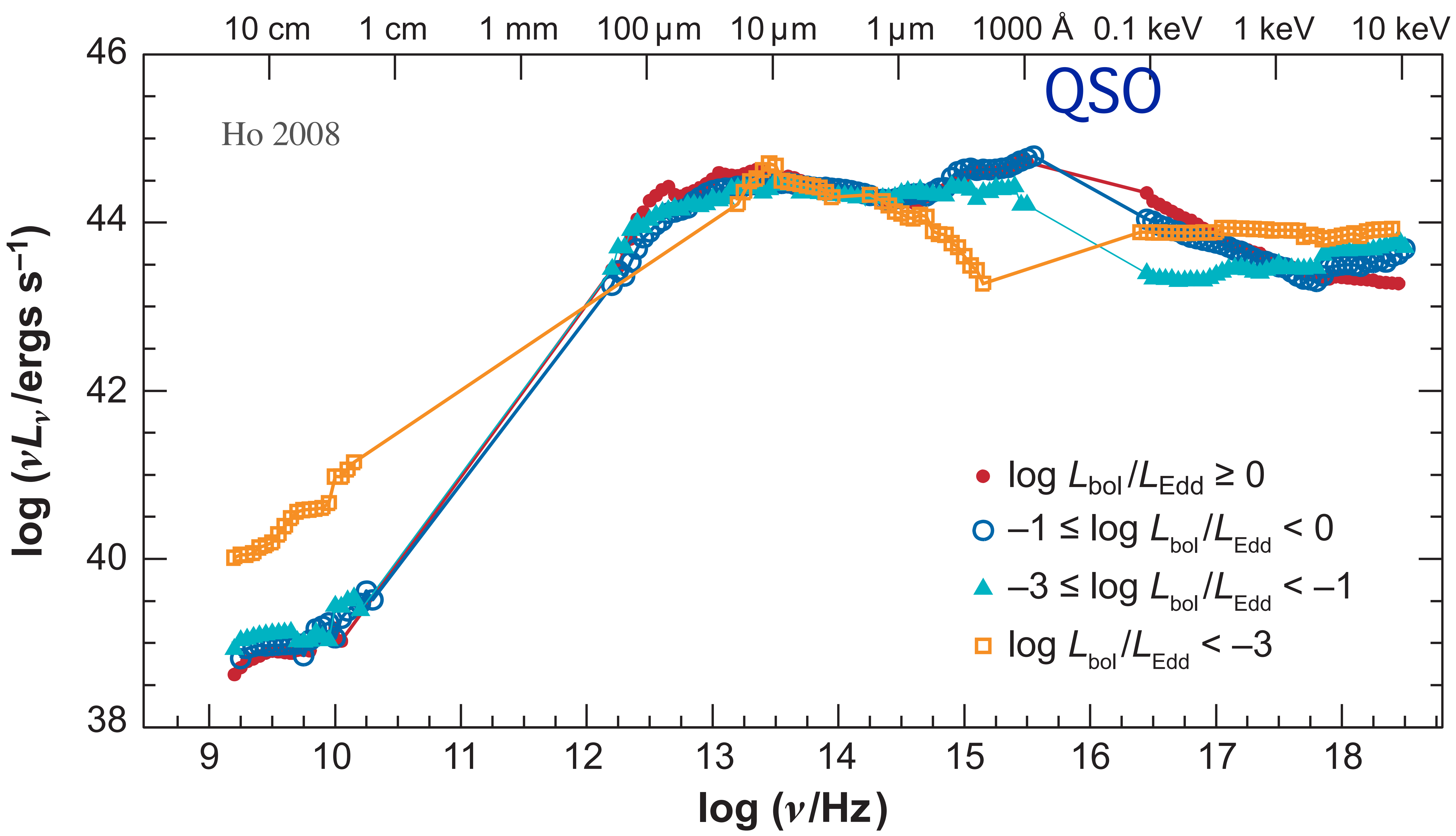
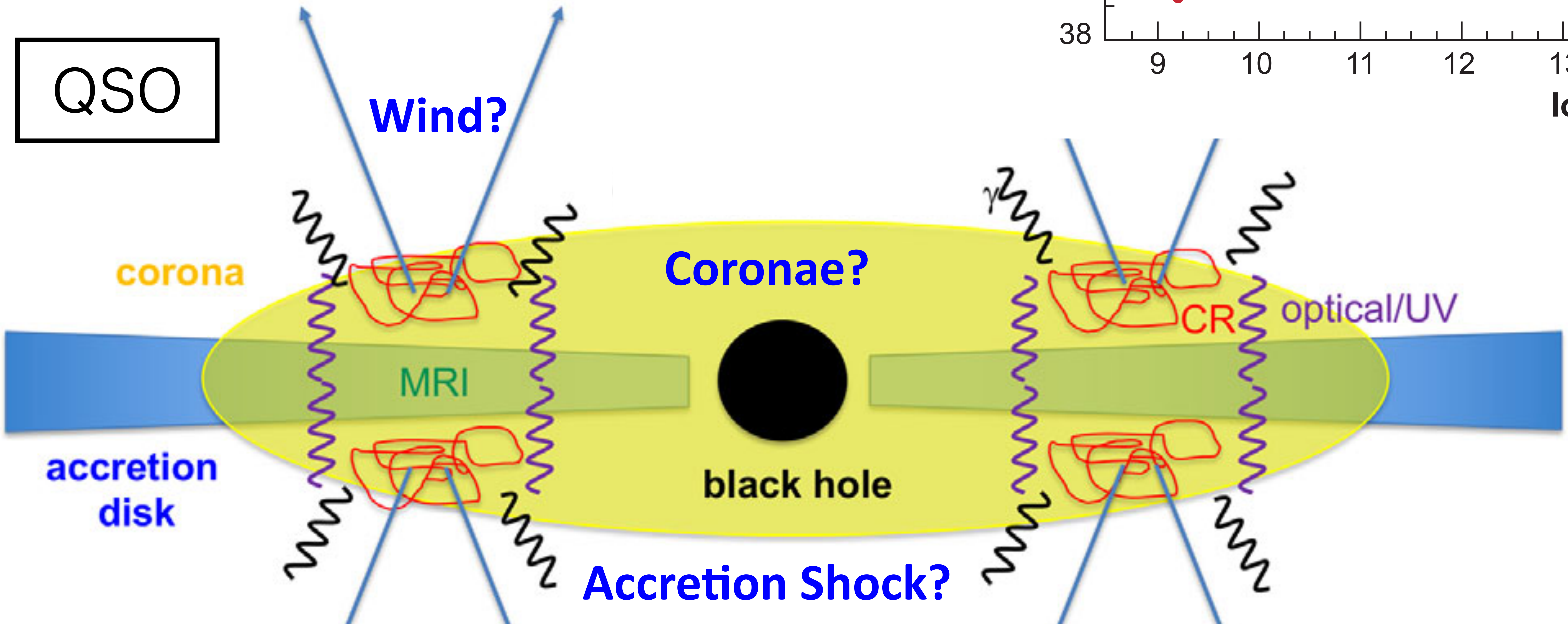
  Eichmann et al. 2022

AGN Accretion Flows

- SED: Blue bump & strong X-rays
  → Optically thick disk + Corona



QSO



AGN wind scenario

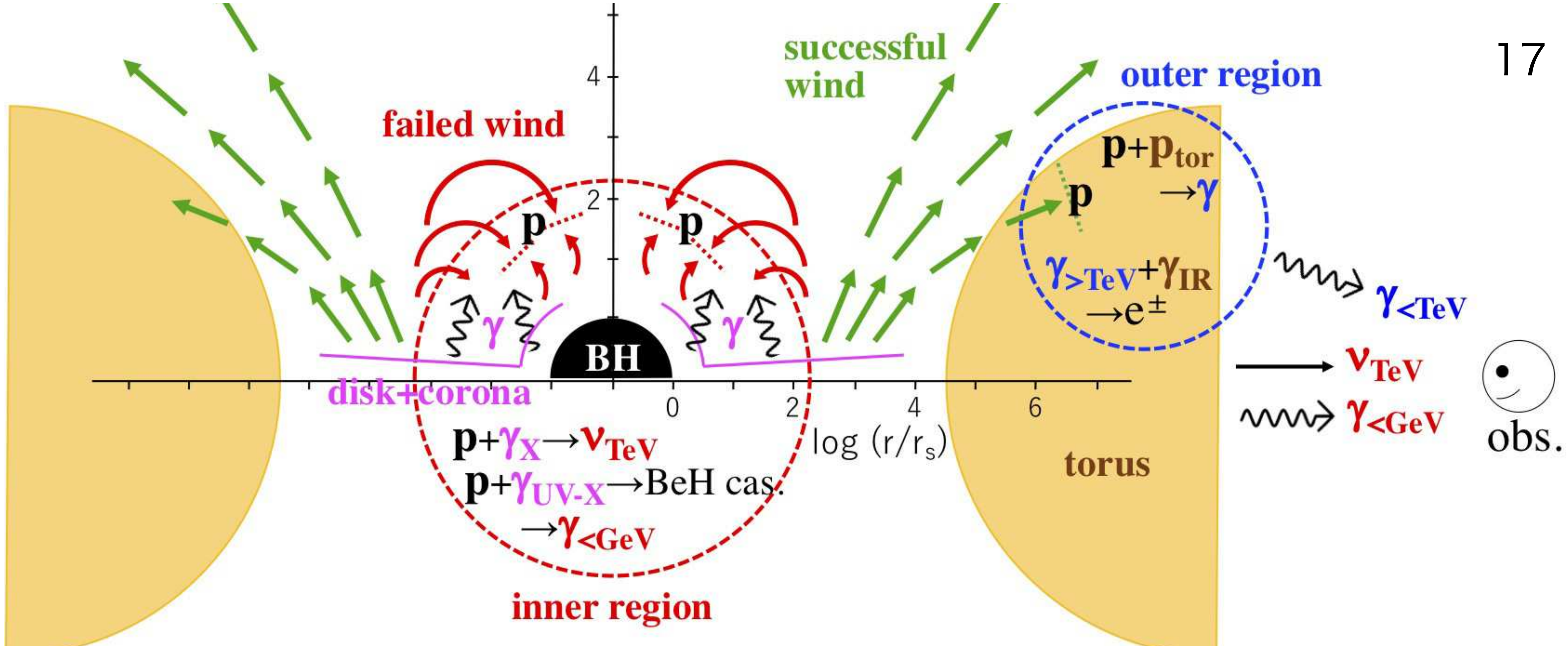
Inoue S. et al. 2022

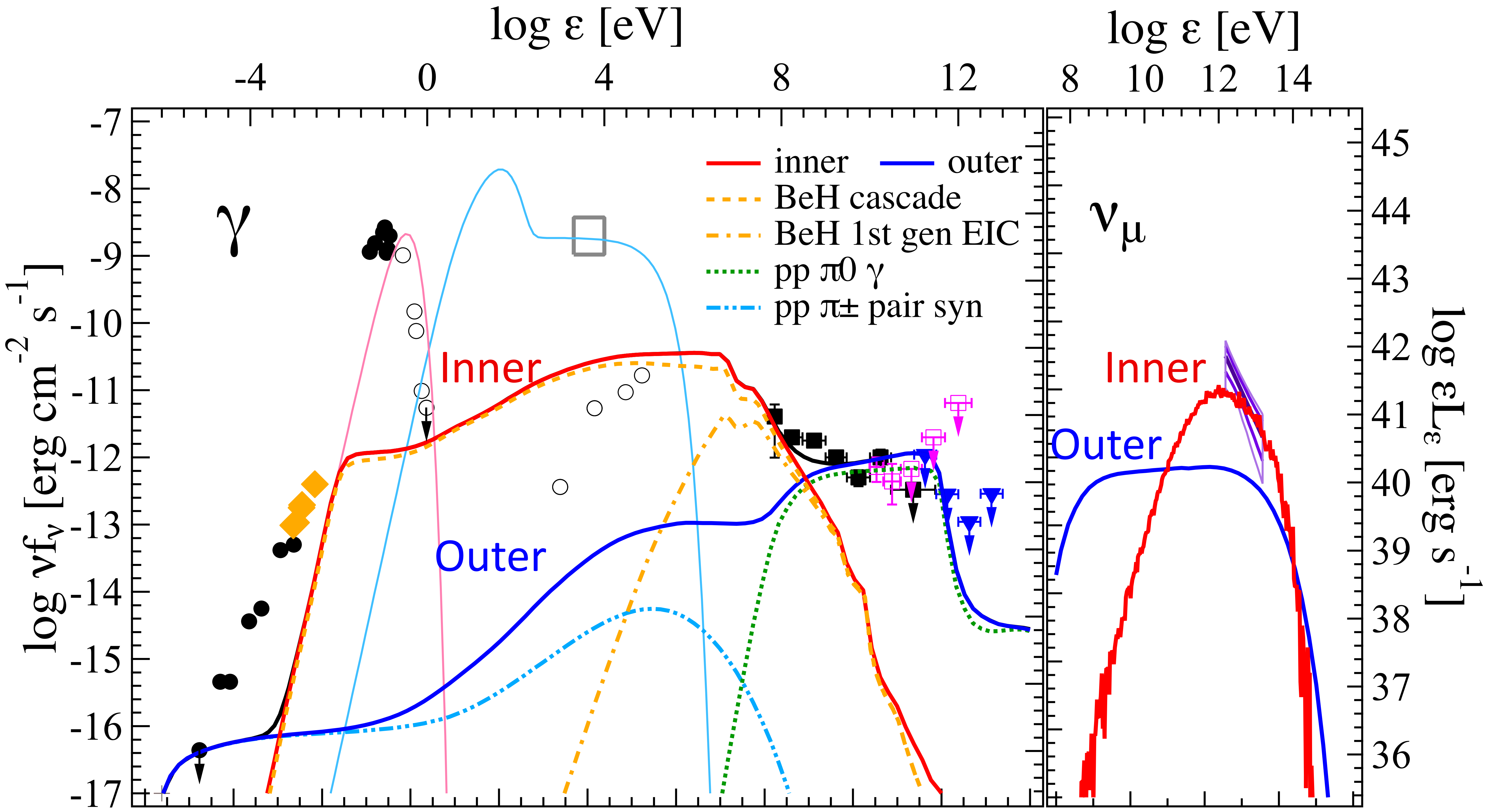
- **Two-zone model**
  - Inner region ($\lesssim 100R_G$)
    → ν production & γ attenuation
  - Outer region ($\gtrsim 0.1\mathrm{pc}$)
    → γ production
- **Merit:**
  - Explain γ & ν by one scenario
  - Outer wind can explain γ-rays with natural parameter sets
- **Demerit:**
  - needed to use unnatural values:

$$v_w \sim 10^8\ \mathrm{cm/s} \ll v_{\rm esc} \sim 10^{10}\ \mathrm{cm/s}$$

- $v_w \sim v_{\rm esc}$ —> slow acceleration

$$\eta_{\rm acc} \gtrsim 10^4: t_{\rm acc} = \eta_{\rm acc}(r_L/c)(c/v_{\rm sh})^2$$

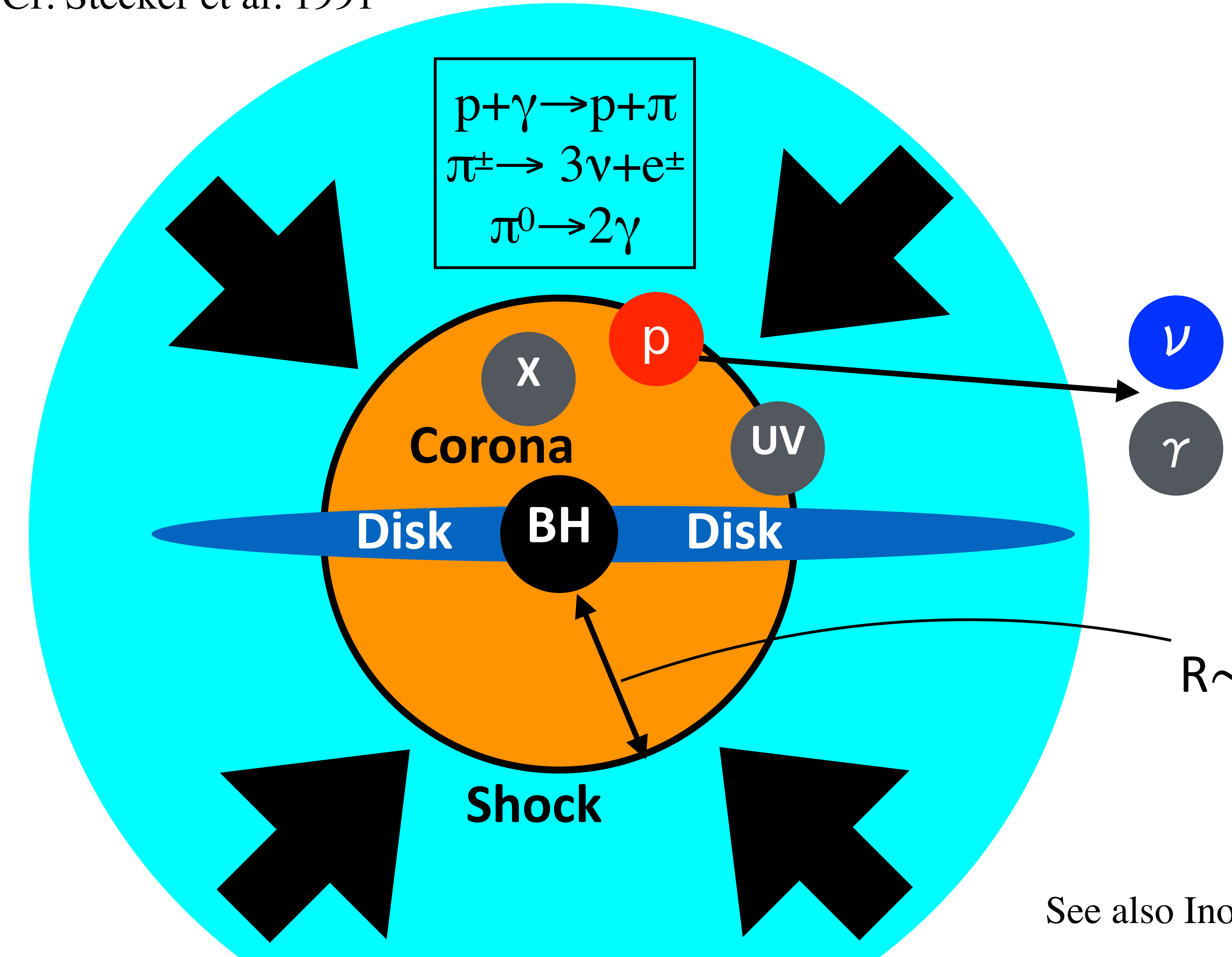


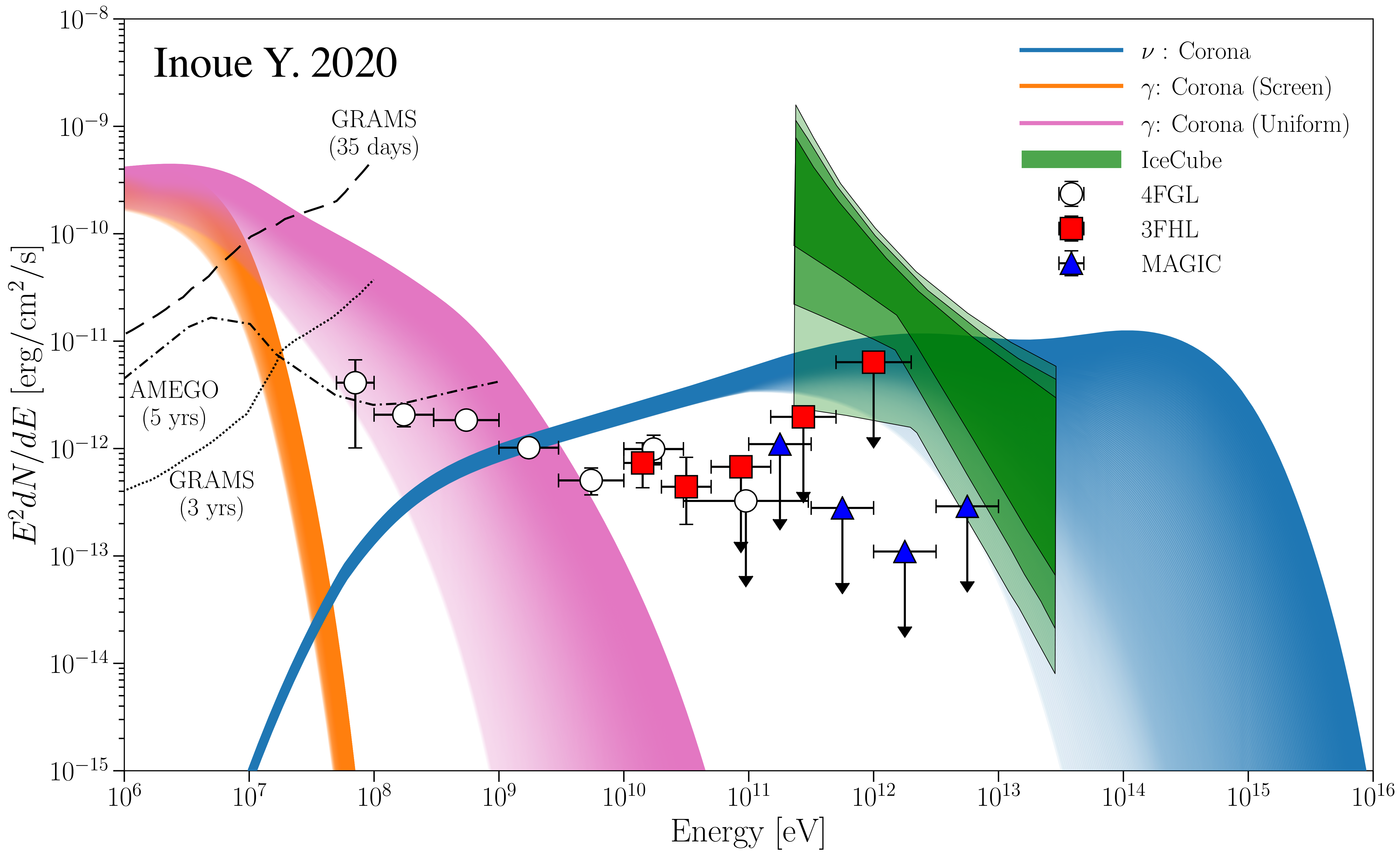


Accretion Shock Scenario

- CR production @ accretion shock
- Neutrino production using AGN photons
- **Consider weak B-field** (B∼10-100 G)

Cf. Stecker et al. 1991



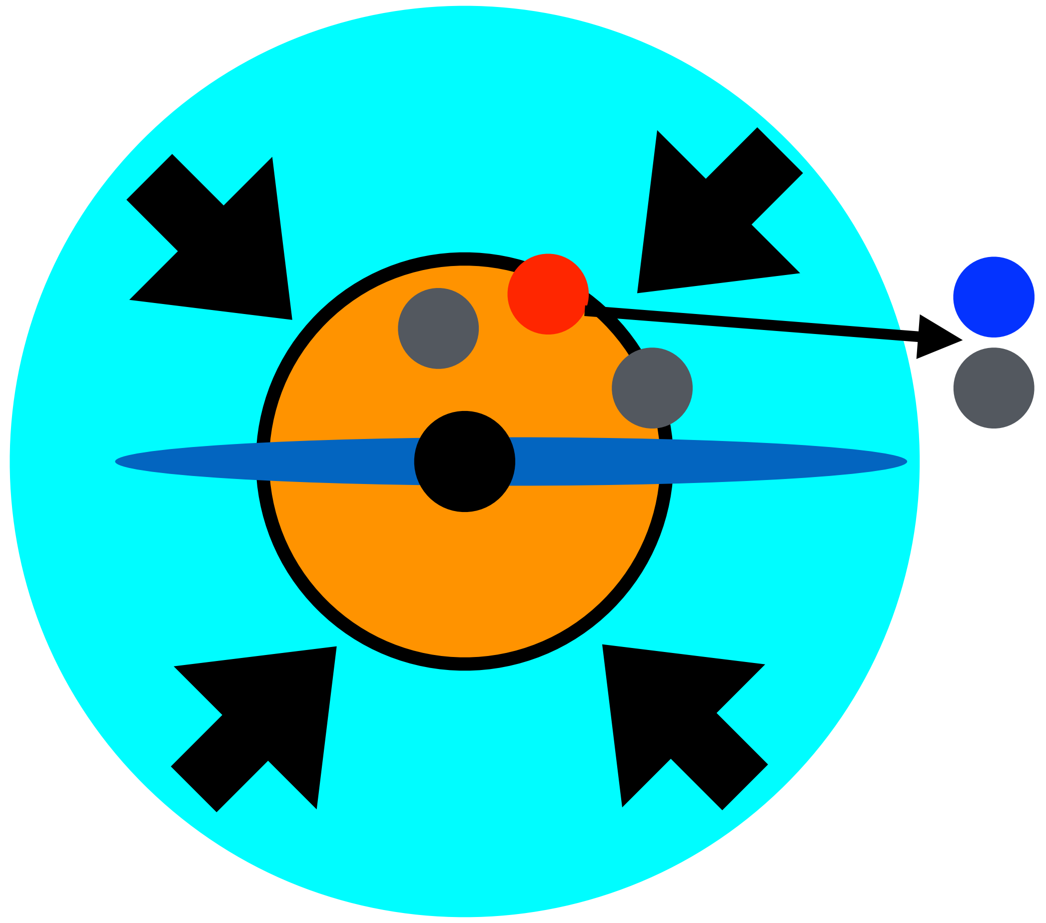


- Possible to reproduce ν data without overshooting γ data
- γ-rays come from different region e.g., starburst or jets

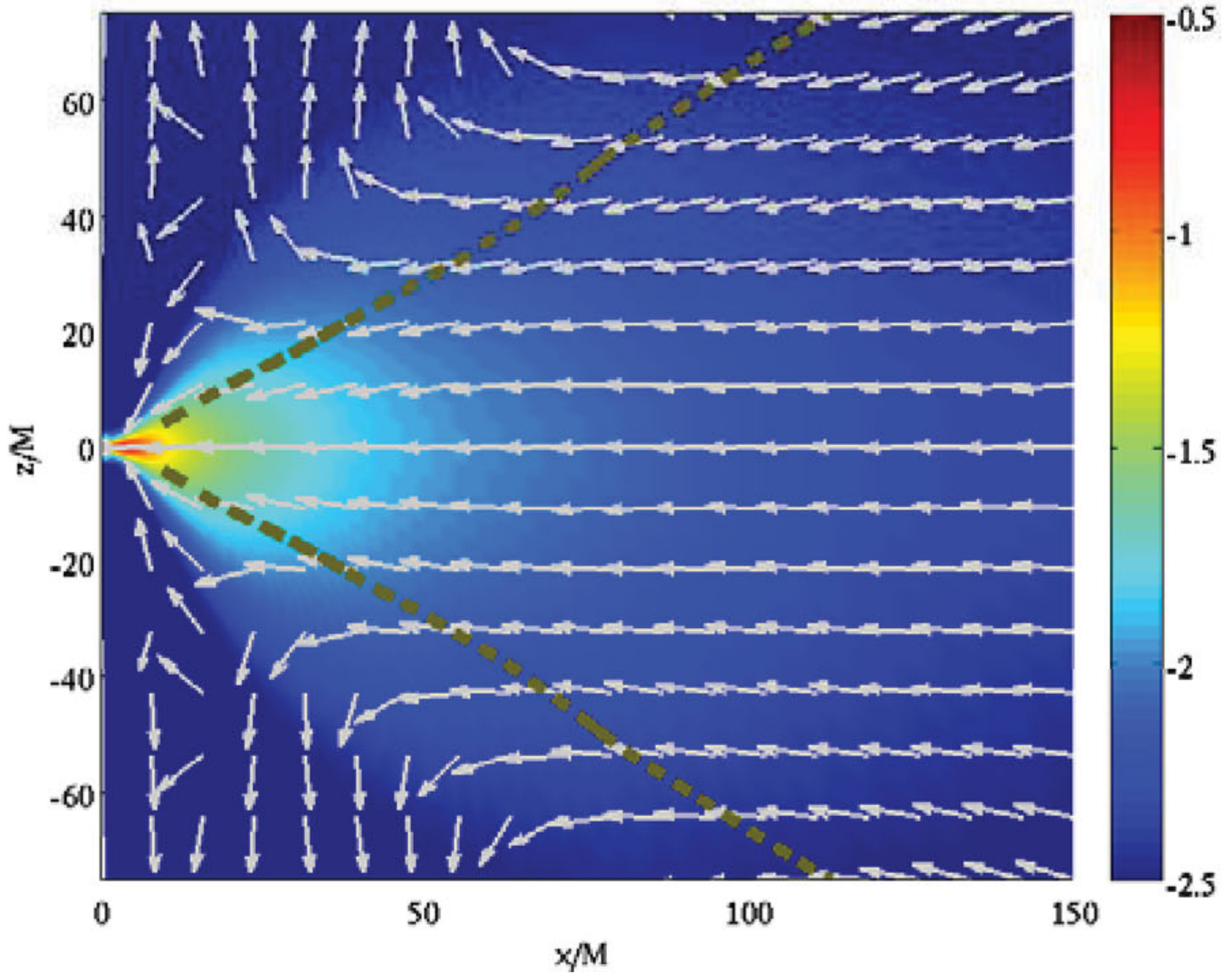
See also Inoue Y. et al. 2019

Demerit of Accretion Shock Scenario

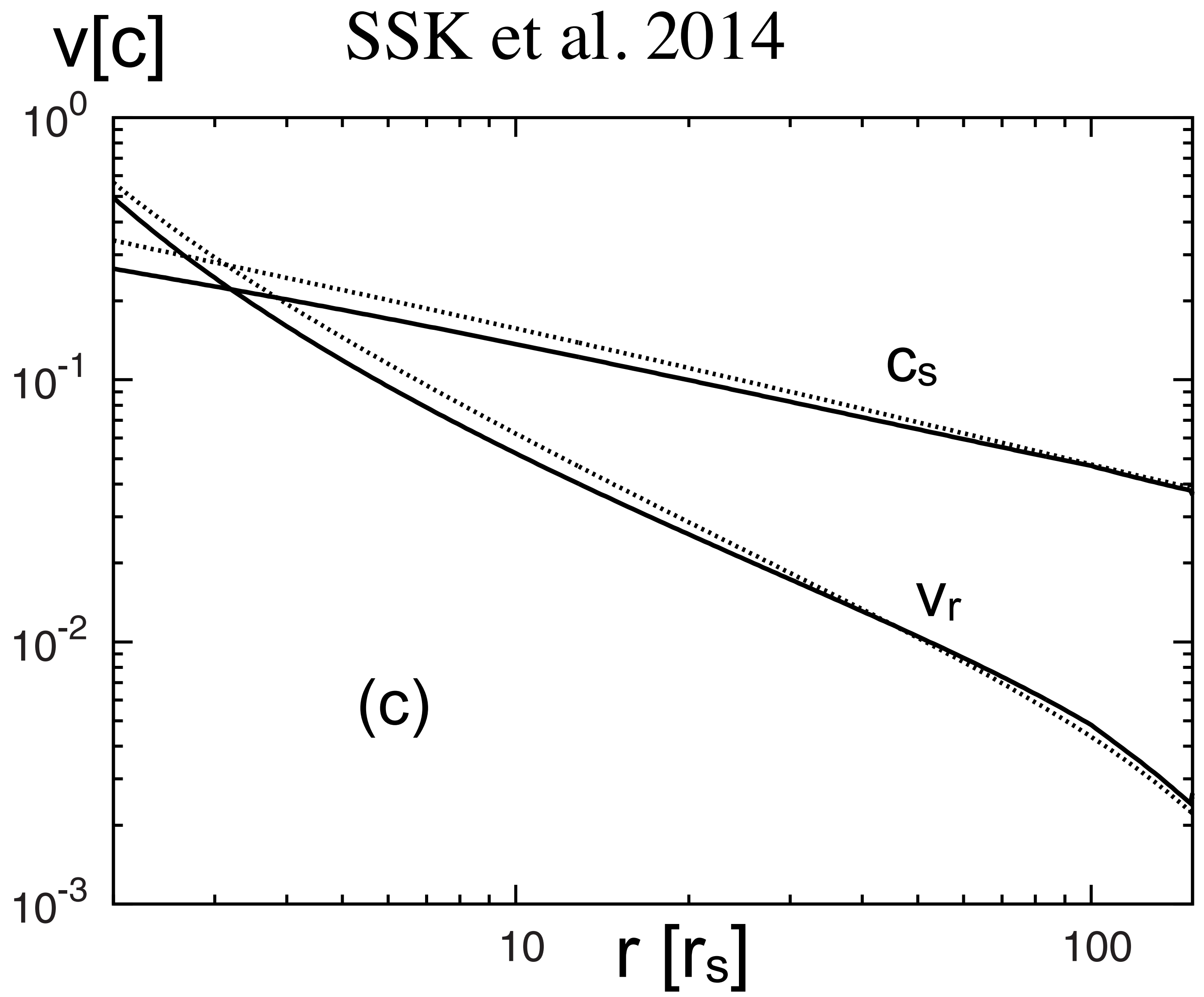
- Existence of shock is unclear
  (Magneto-)hydrodynamic simulations
  do not find any shock structure



Narayan et al. 2012



SSK et al. 2014

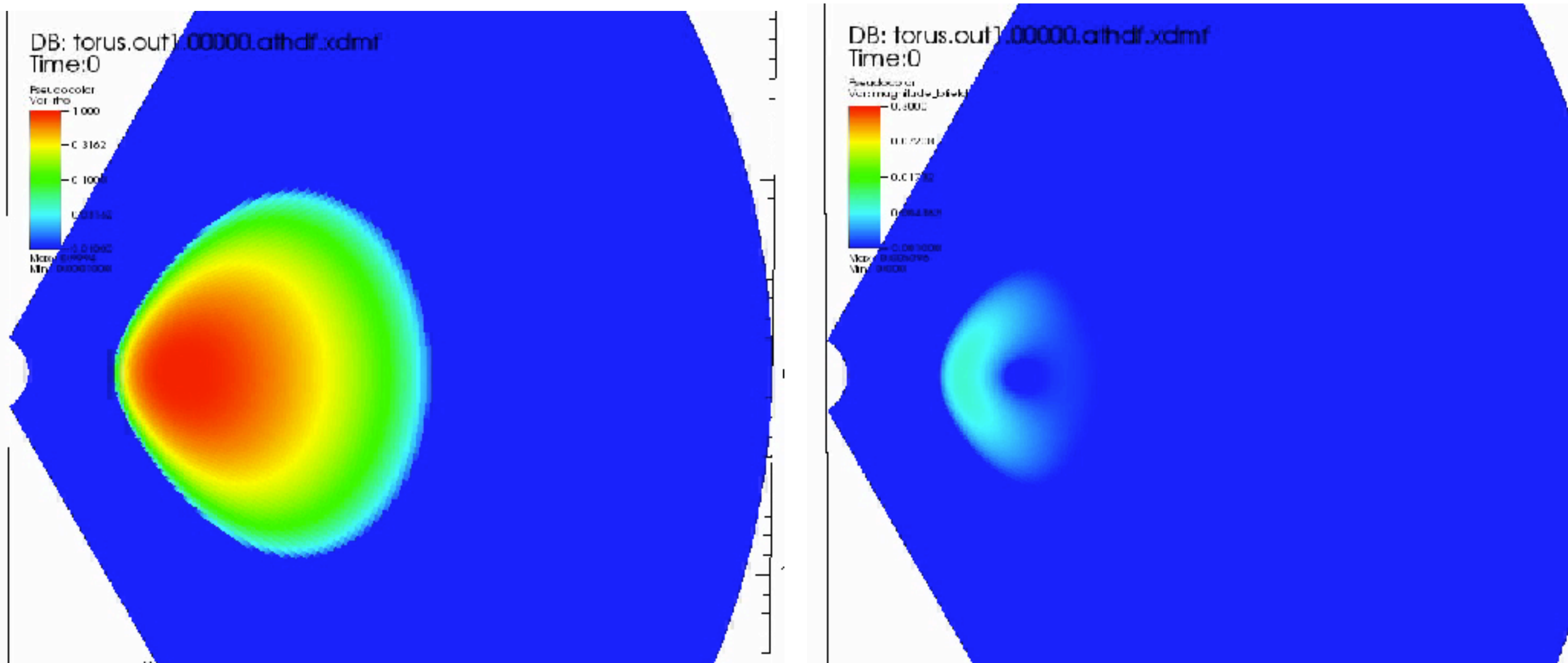


- Weak B fields in accretion shock scenario
  - accretion phenomena driven by B fields
  - MHD instabilities amplify B fields

$$B \sim 10^3 - 10^4 \text{ G}$$

Balbus & Hawley 1991, 1998

SSK et al. 2019



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  - ~~Starburst nuclei~~
    ~~$\sim$kpc~~
    ~~Loeb & Waxman 2006~~
    ~~Murase et al. 2013~~
  - ~~Mini jets~~
    ~~$\sim$10 - 100 pc~~
    Michiyama et al. 2022
- Compact emission regions
  - AGN winds
    $\sim 10^{-5} - 10^{-3}$pc
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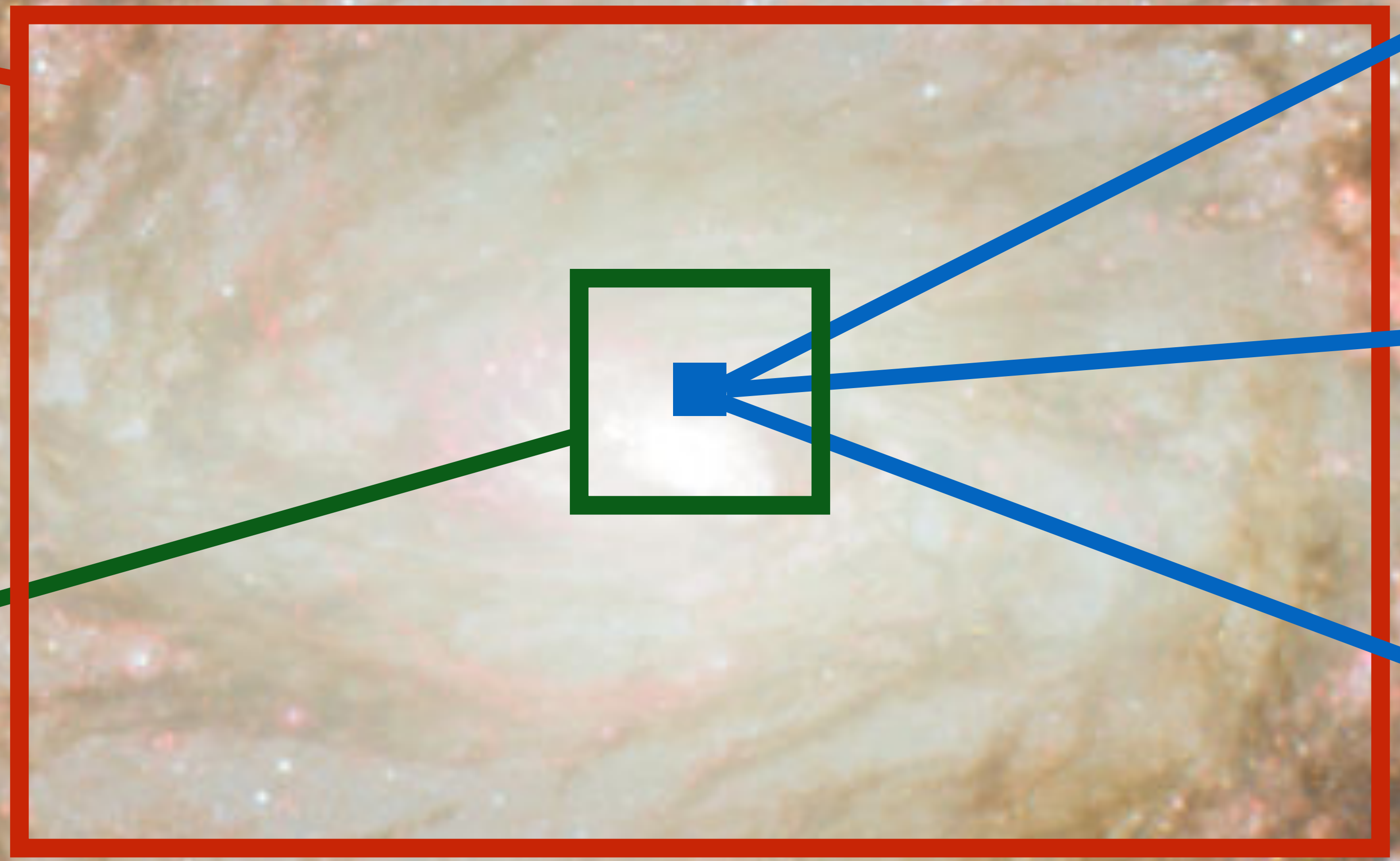

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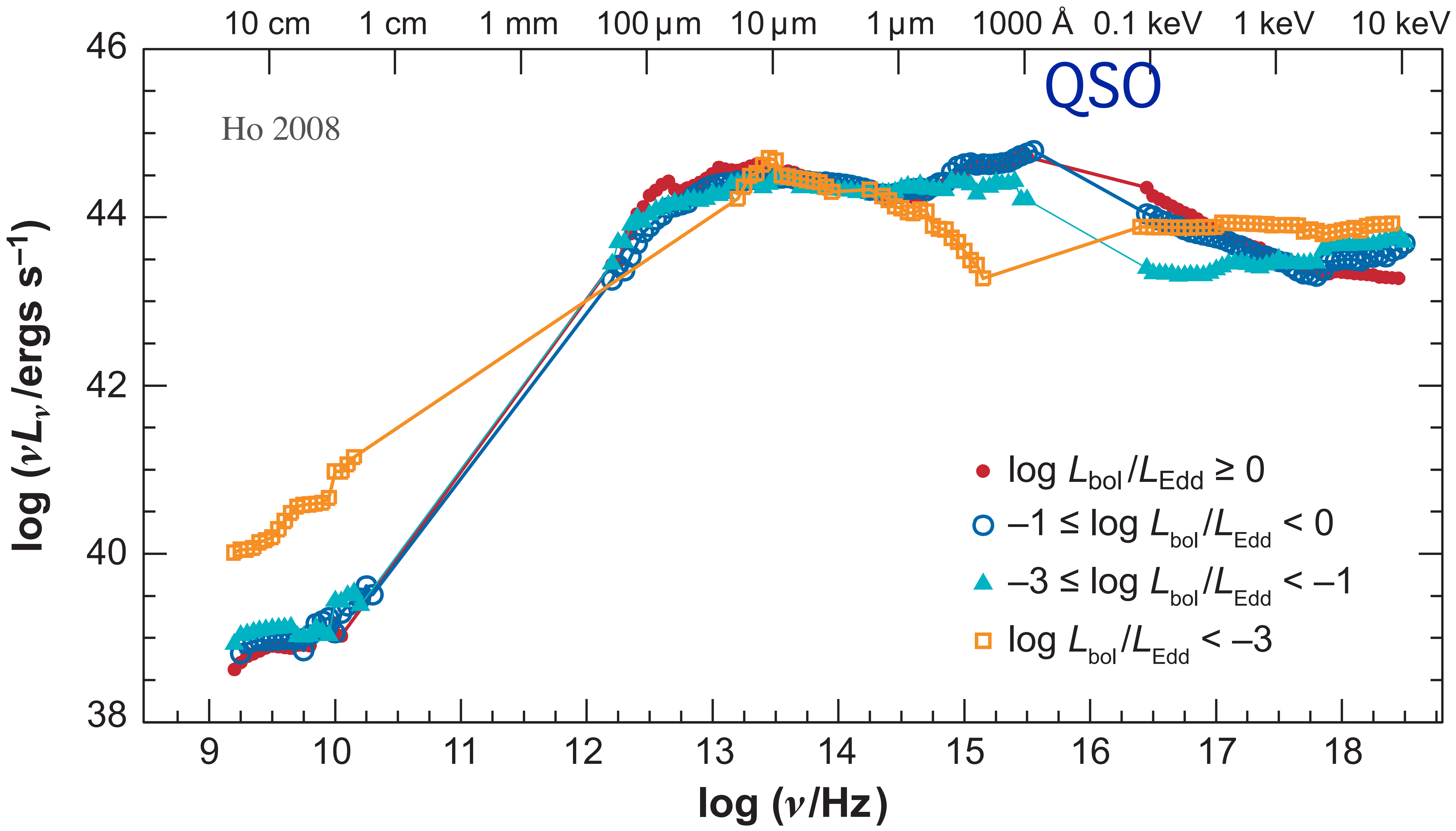

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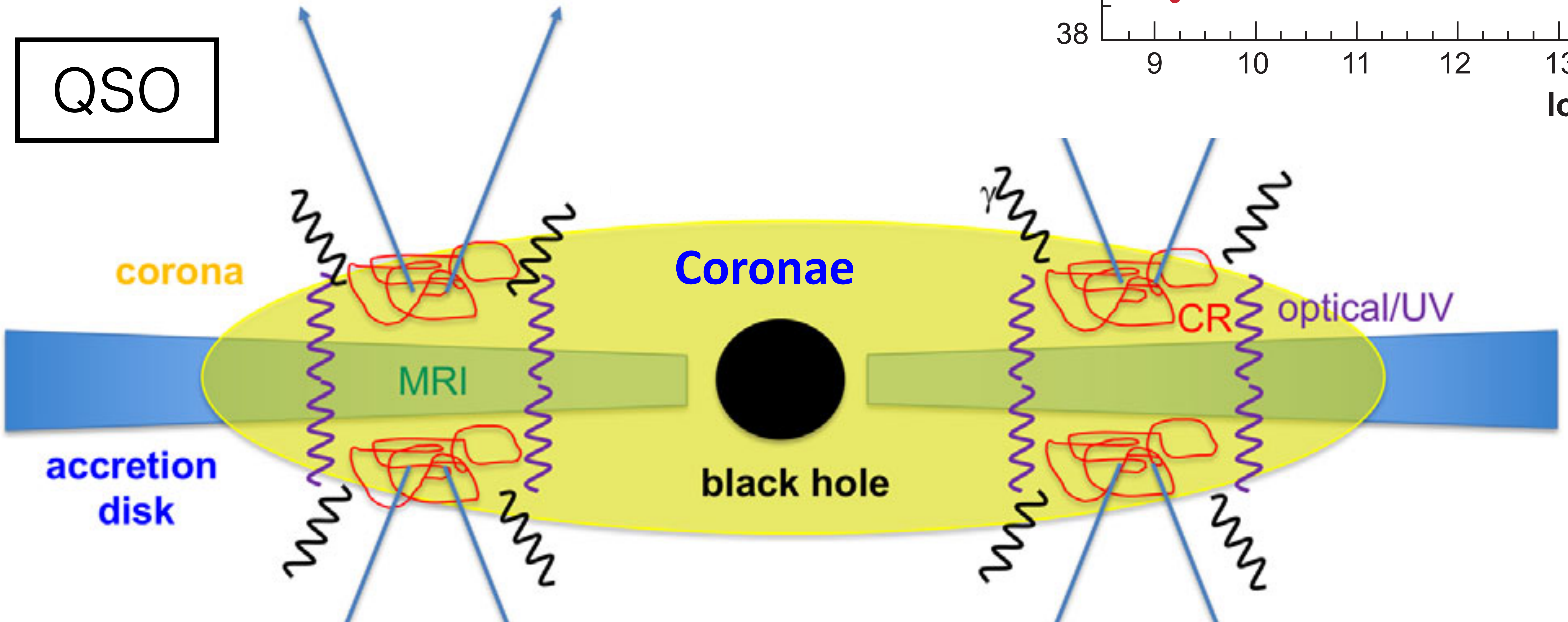
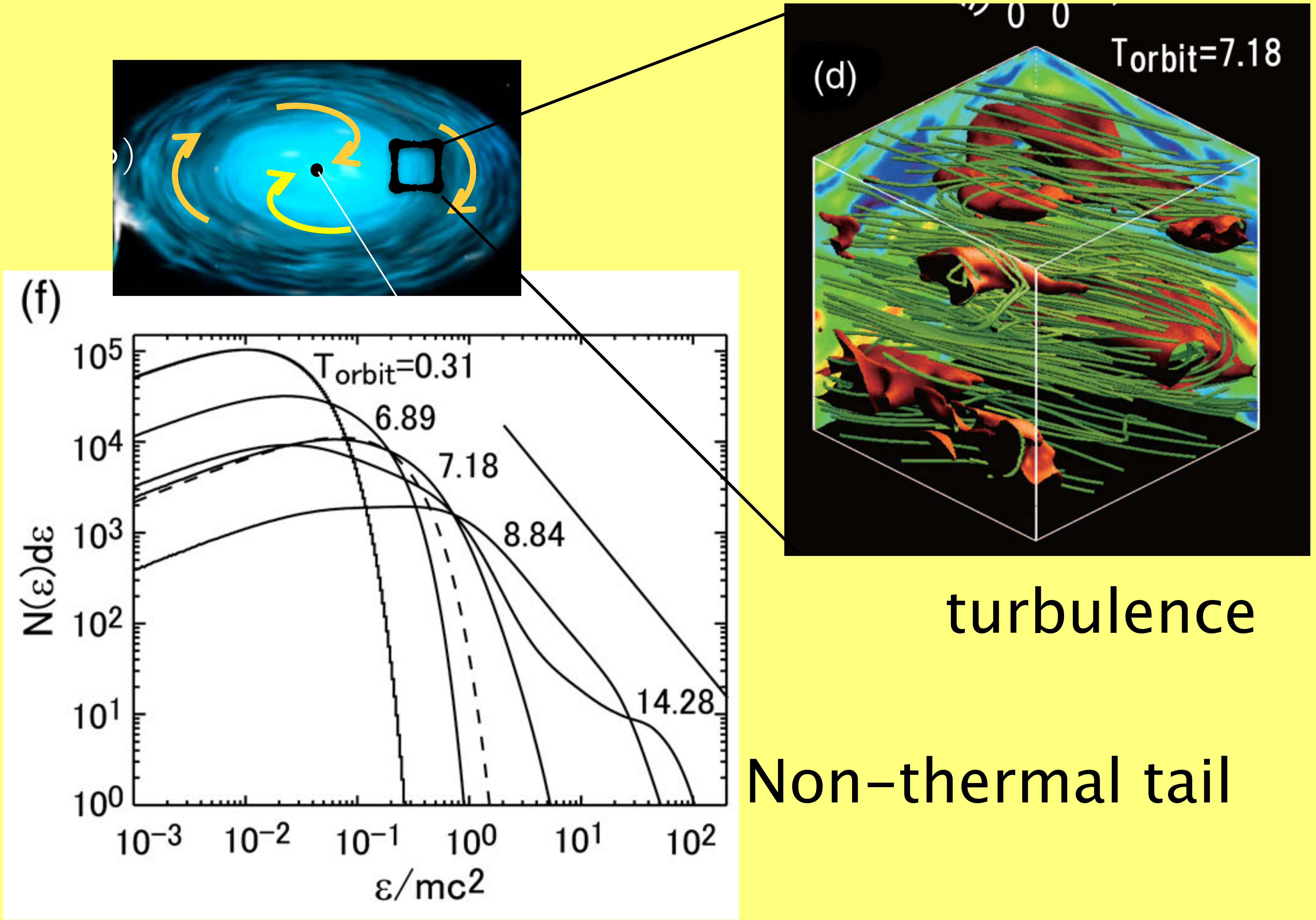


Particle Acceleration in Turbulence

Particle-In-Cell Simulations in shearing box

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

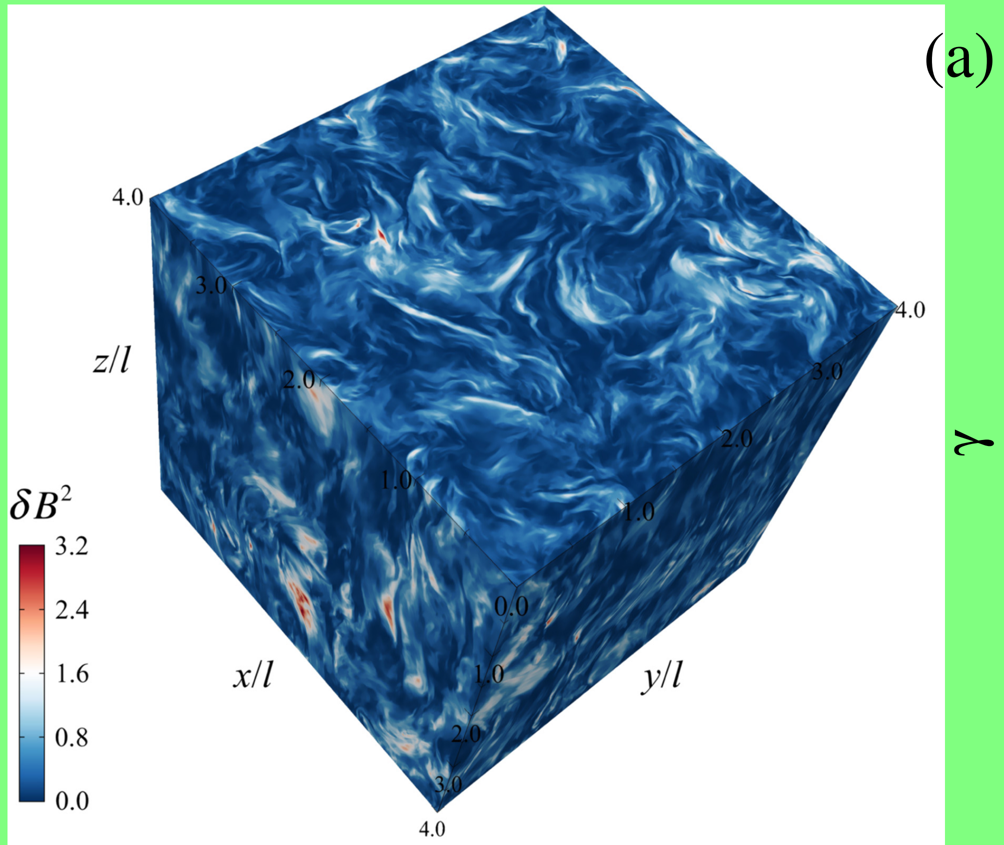


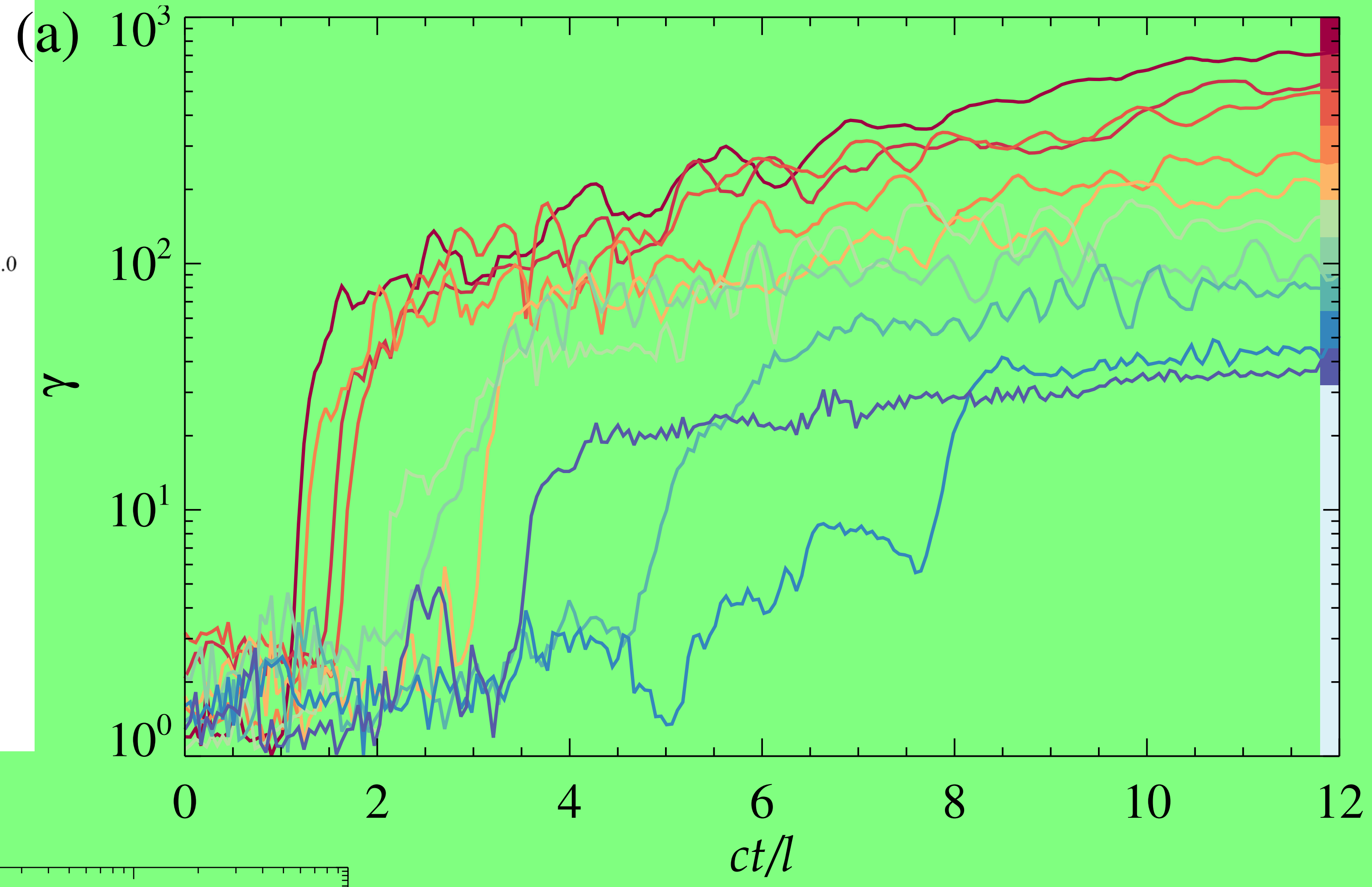
turbulence

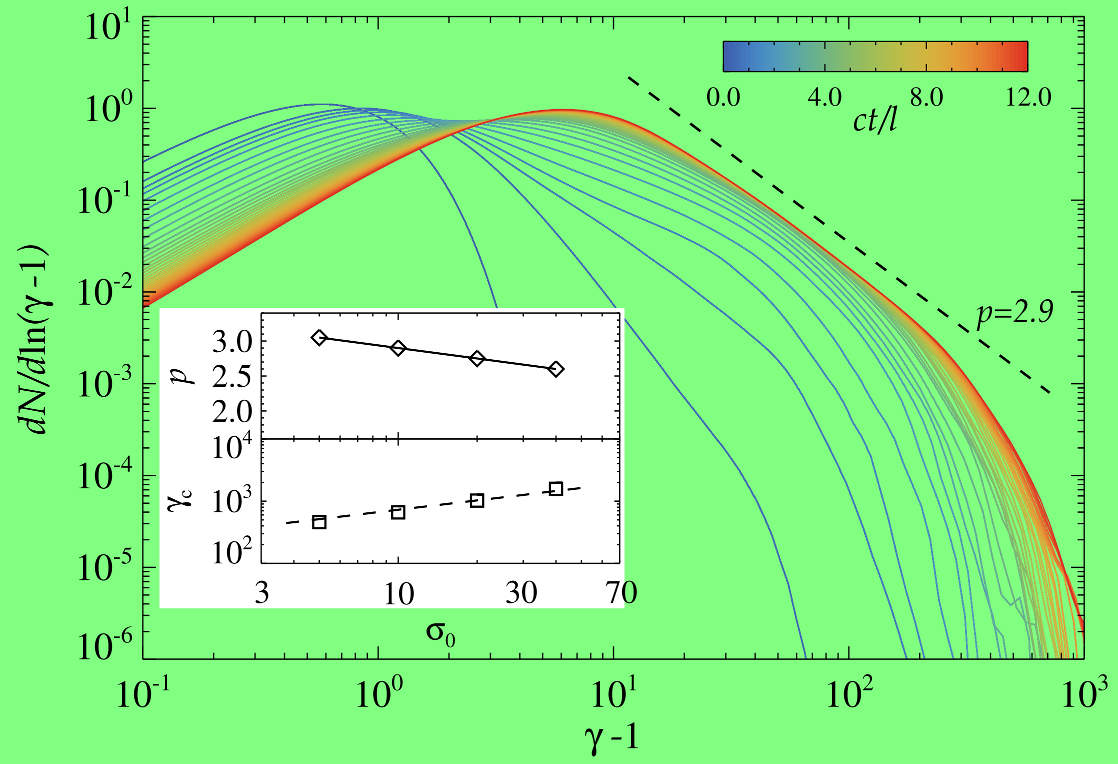
Non-thermal tail

Particle-In-Cell Simulations with turbulence

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







Stochastic acceleration

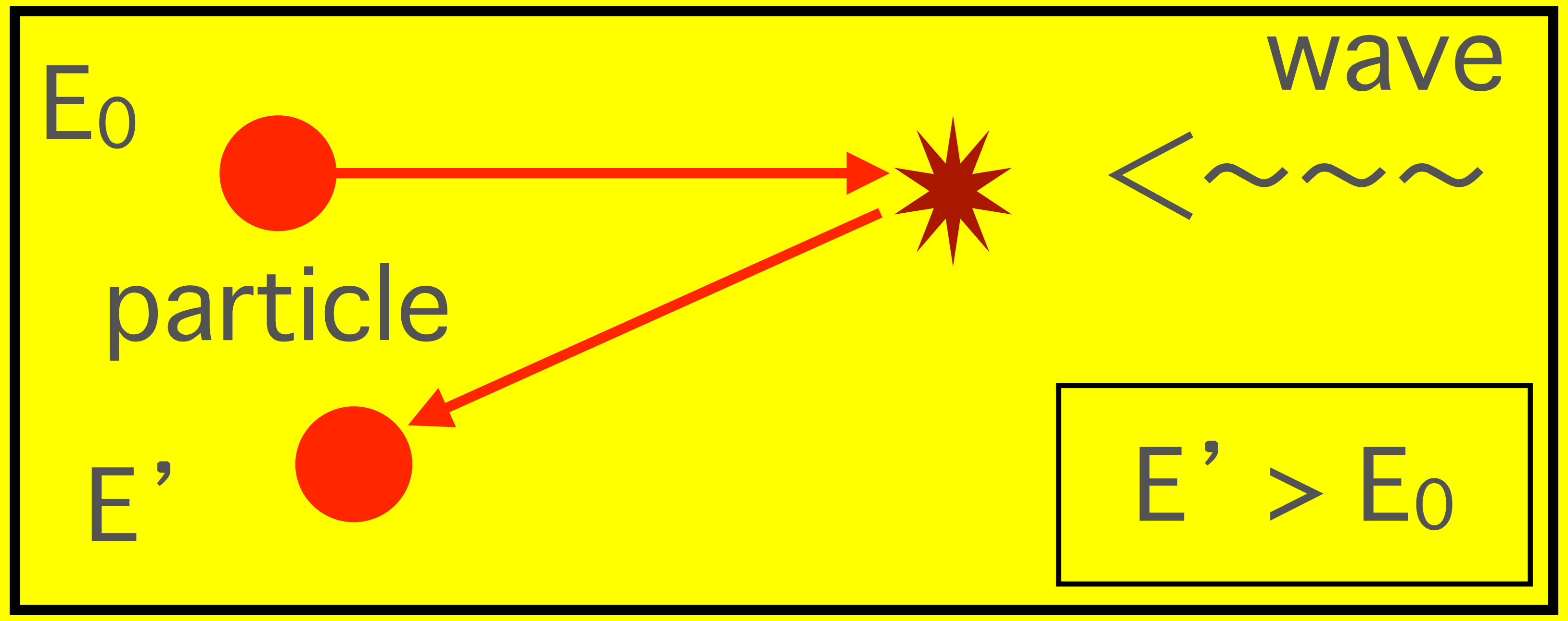
Power-law tail

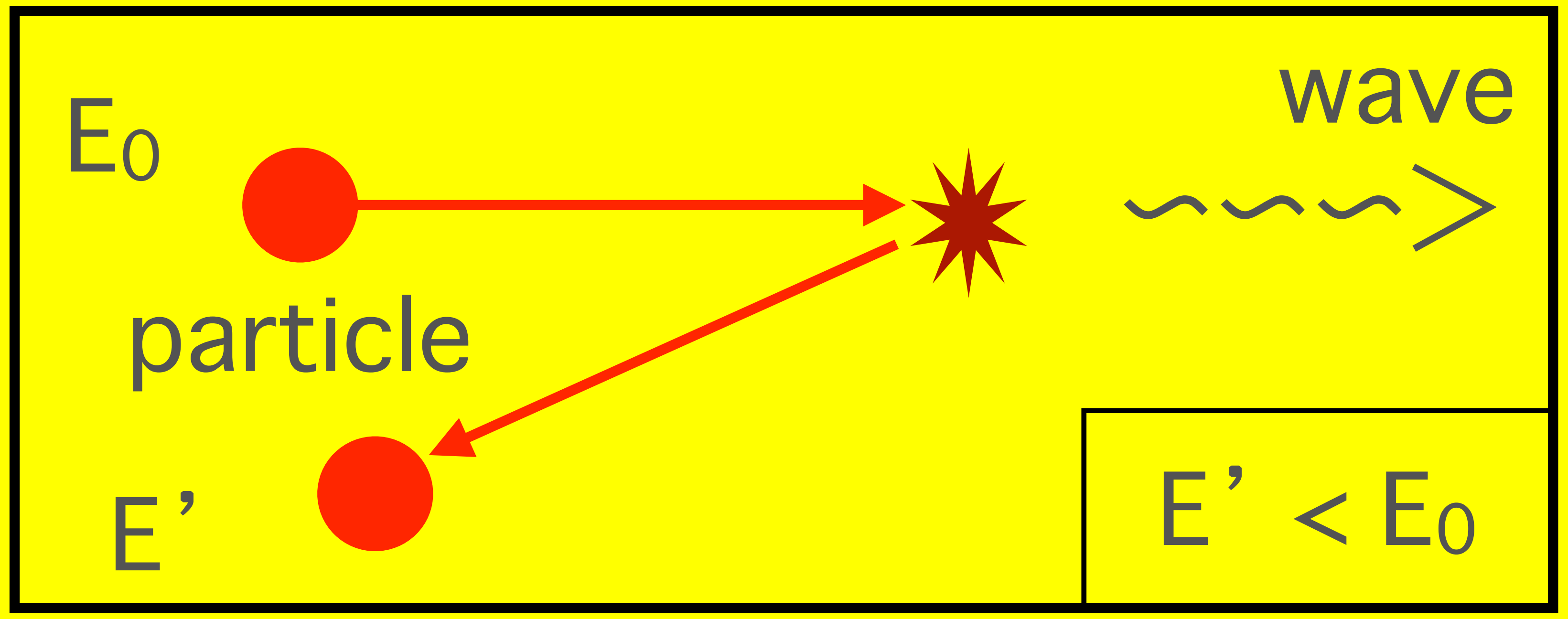
Magnetic reconnection → relativistic particle production
Interaction with Turbulence → further energization

Stochastic Acceleration by MHD Turbulence

CR Acceleration Theory

e.g.) Fermi 1949





Some gain E, others lose E

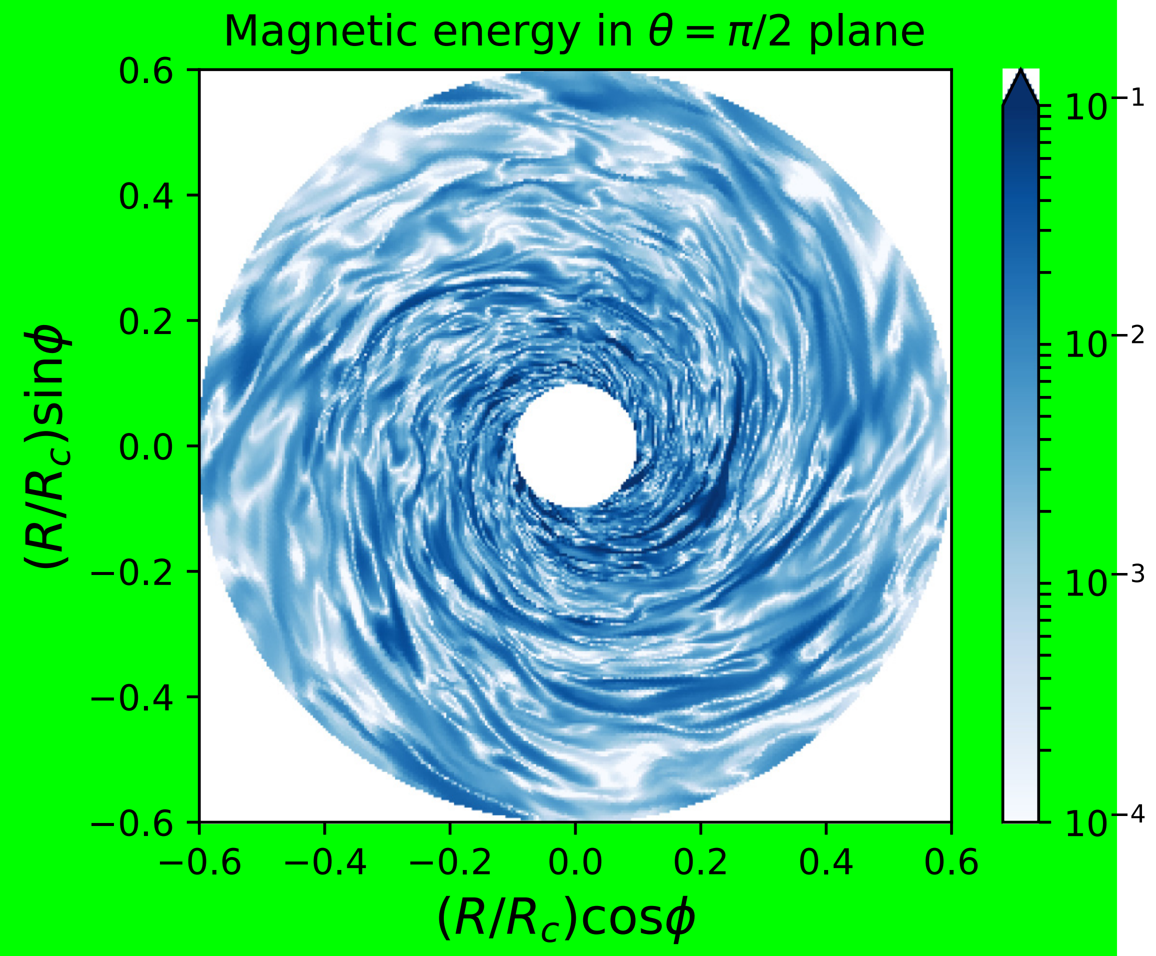
→diffusion in E space

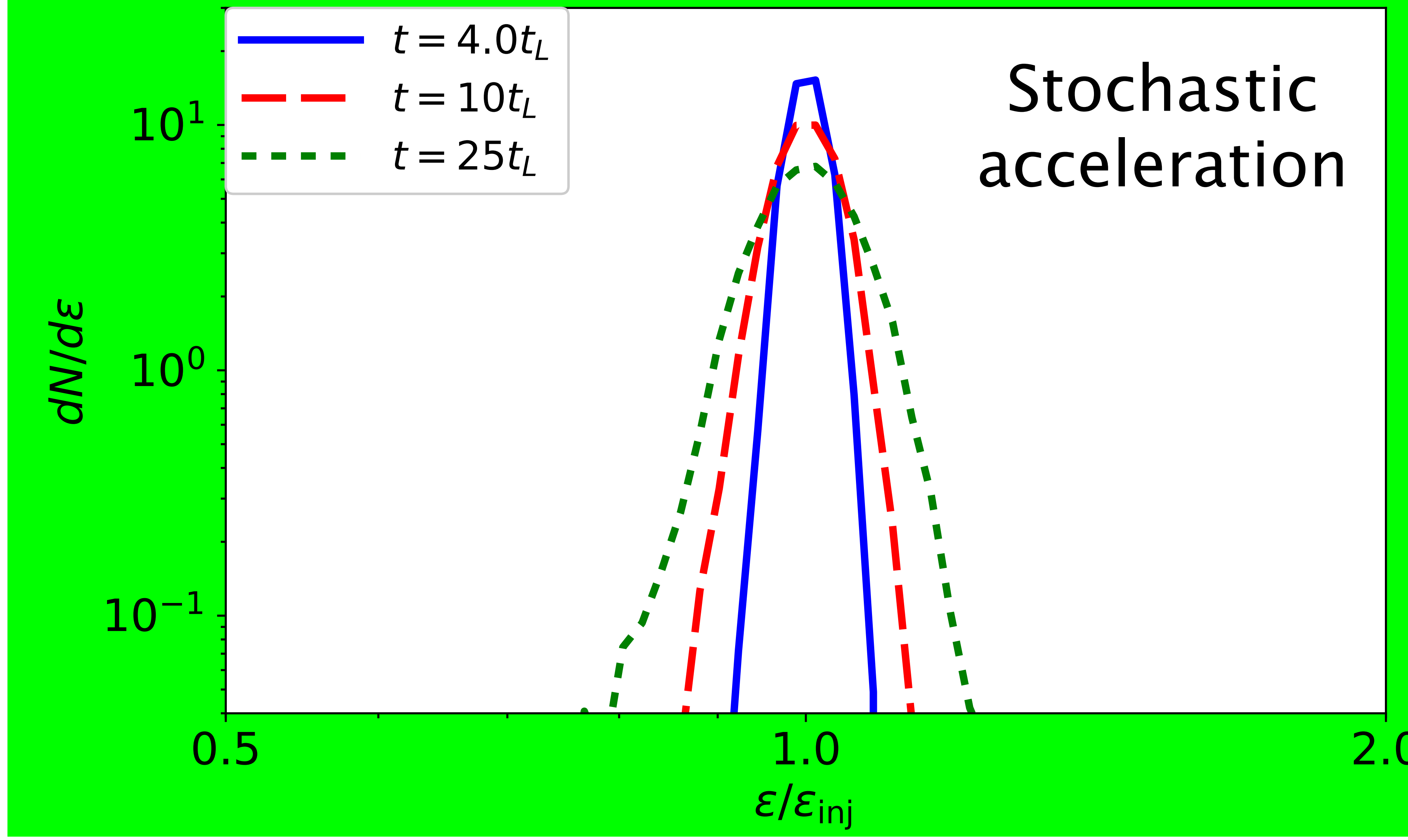
$$\frac{\partial F_p}{\partial t} = \frac{1}{E^2}\frac{\partial}{\partial E}\left(E^2 D_E \frac{\partial F_p}{\partial E}\right)$$

MHD + Test Particle Simulations

SSK+ 2016 ApJ, 2019 MNRAS; Sun & Bai 2021

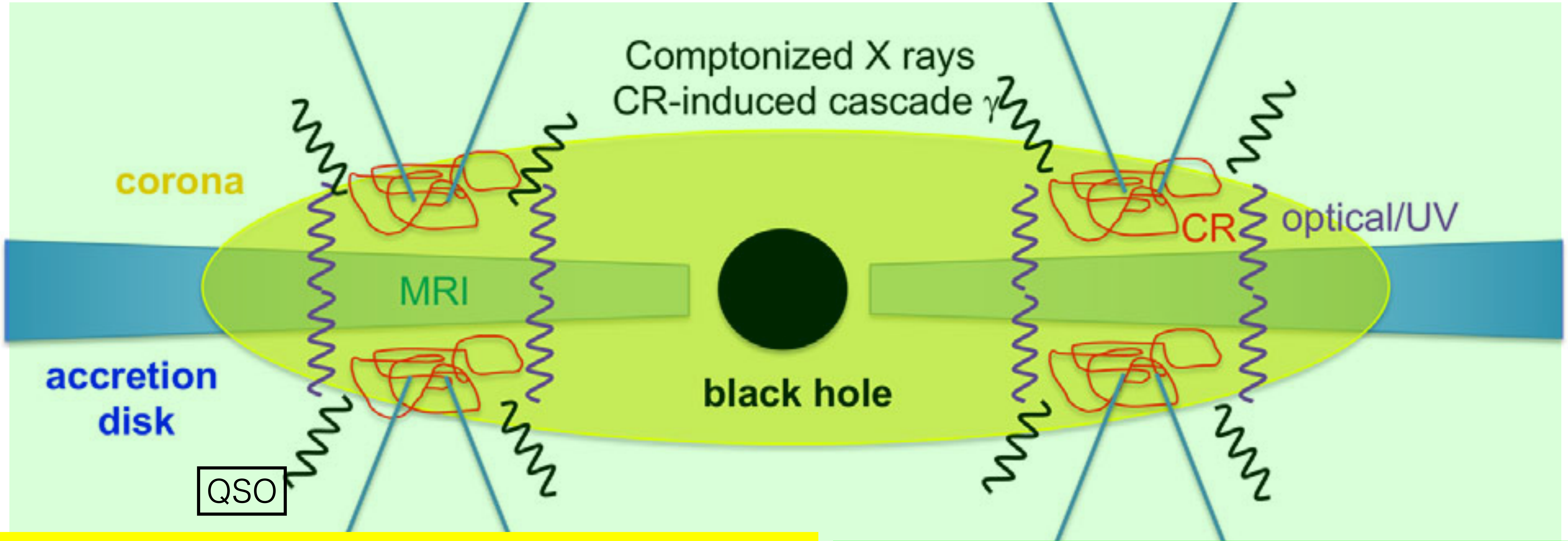
MRI turbulence





AGN Corona Model

Murase, SSK, Meszaros 2020



- 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

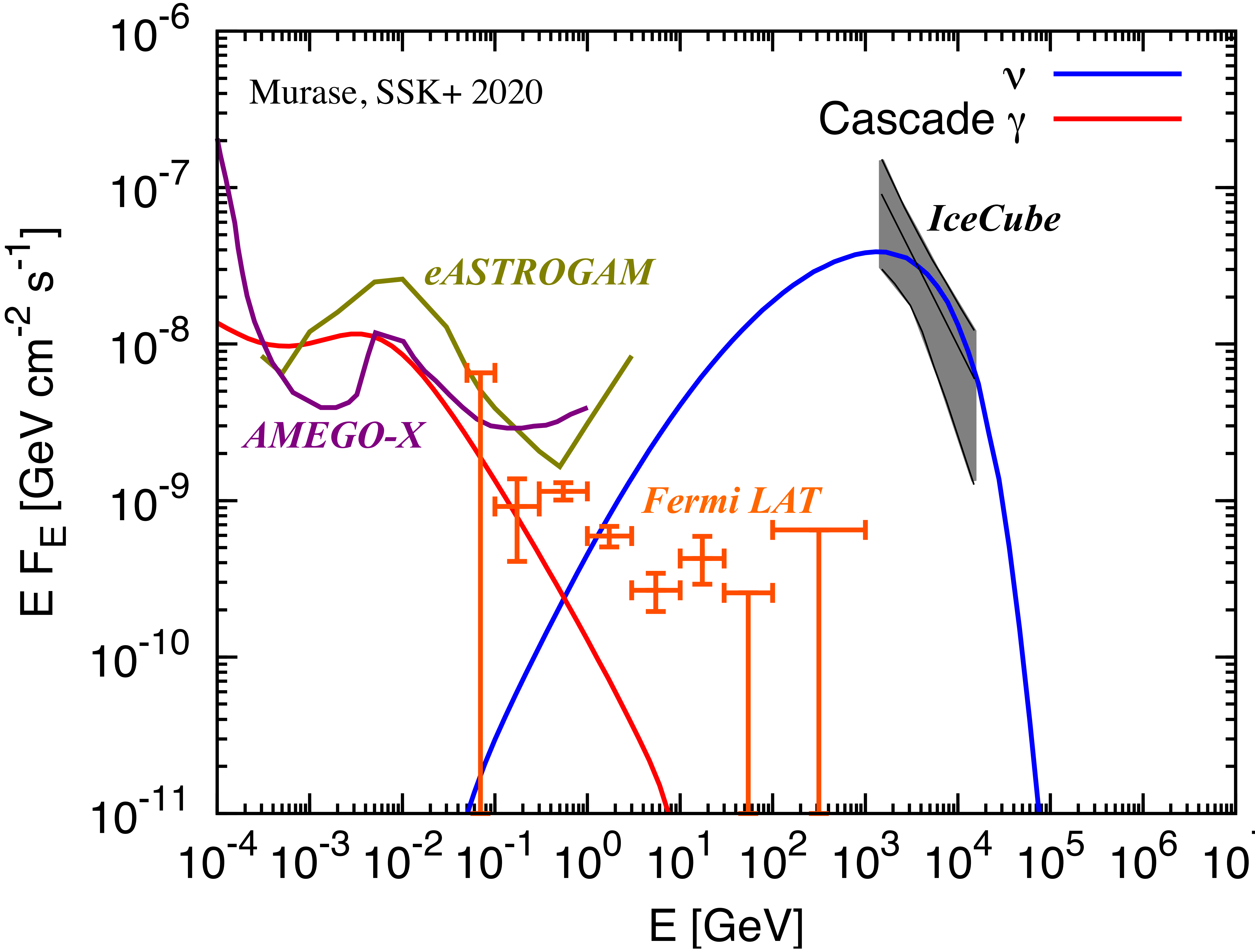
$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\mathrm{esc}}} + \dot{n}^{(\mathrm{IC})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{ff})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{syn})}_{\varepsilon_\gamma}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

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

See also SSK+ 2019; SSK+ 2021; 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 Bethe-Heitler process with UV photons
- Both pp & pγ (with X-rays) contribute to resulting neutrino flux
- **Cascade emission at 10 MeV**
  —>Testable by MeV γ ray satellites

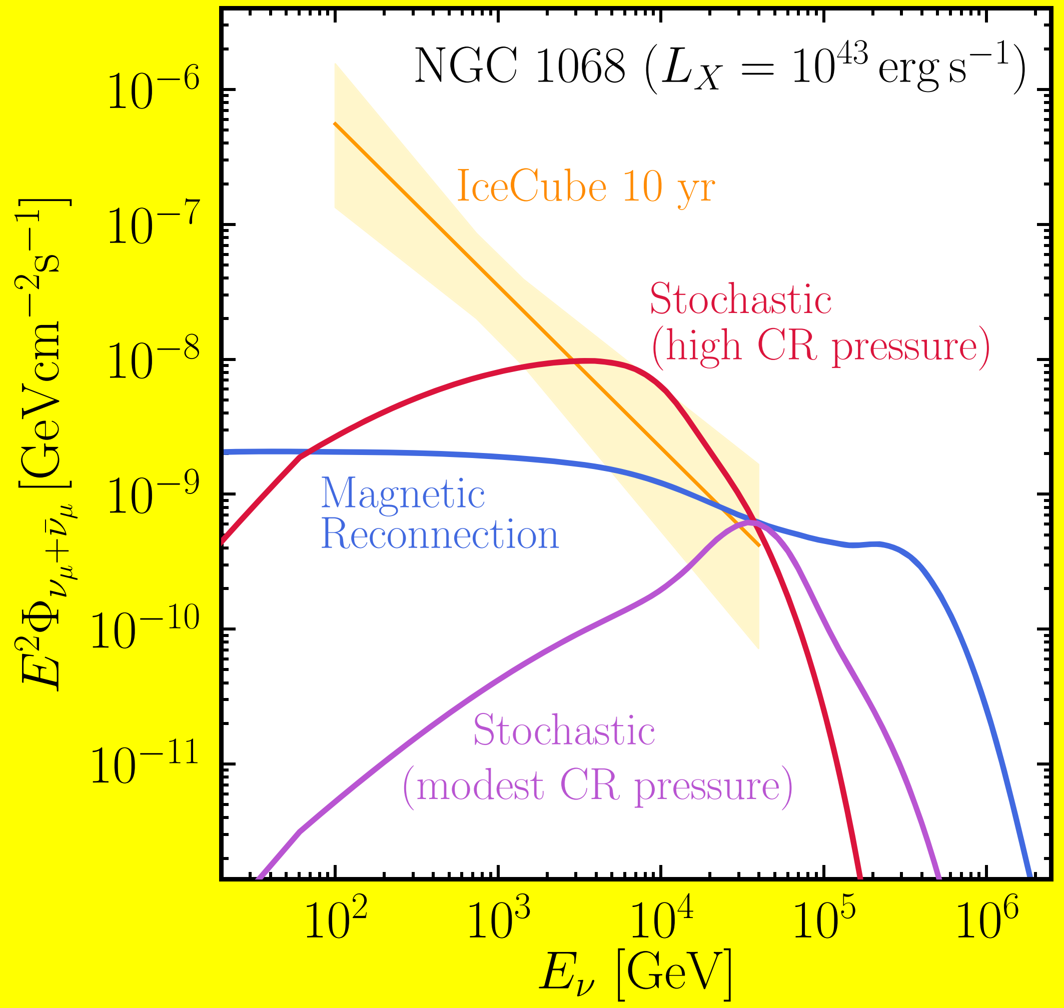


Nearby Seyfert galaxies

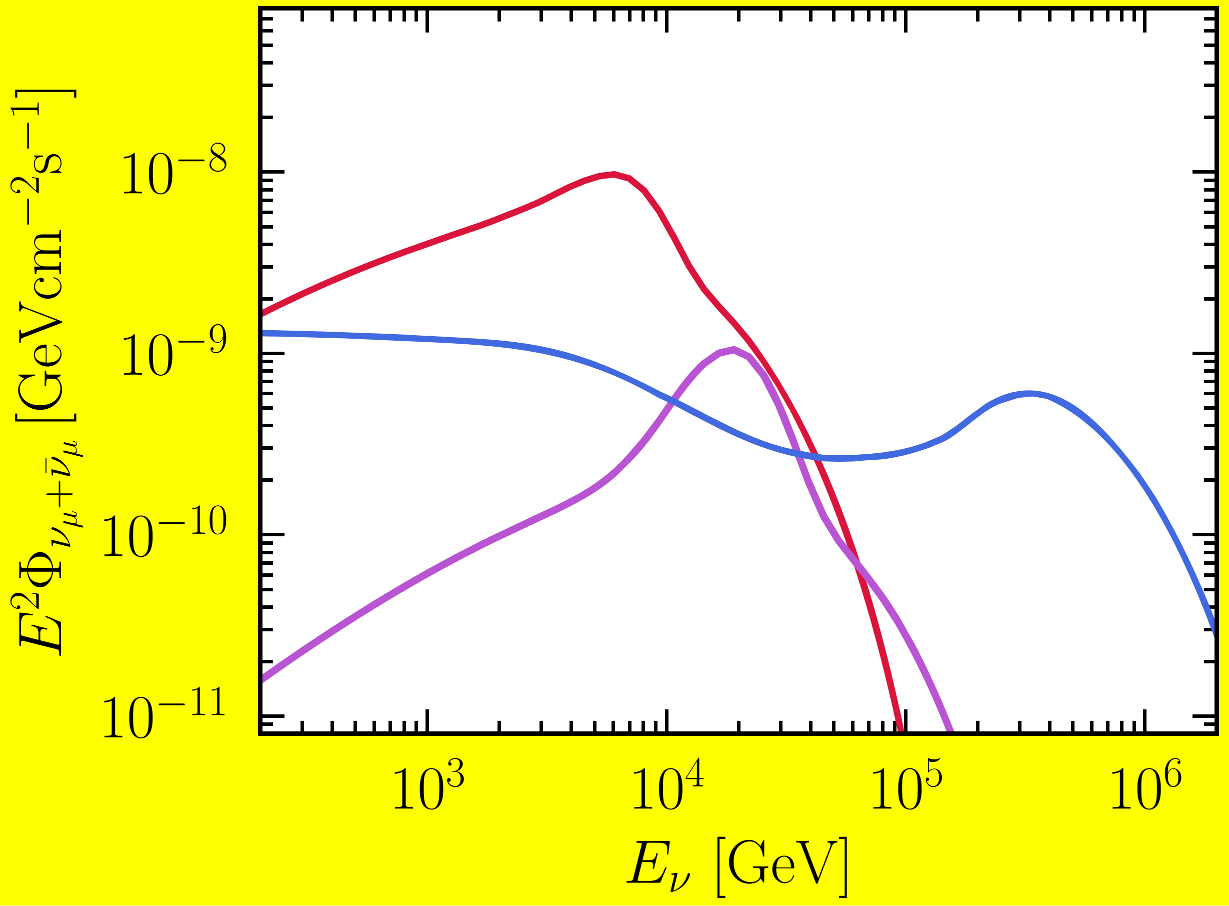
Kheirandish, Murase, SSK 2021

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

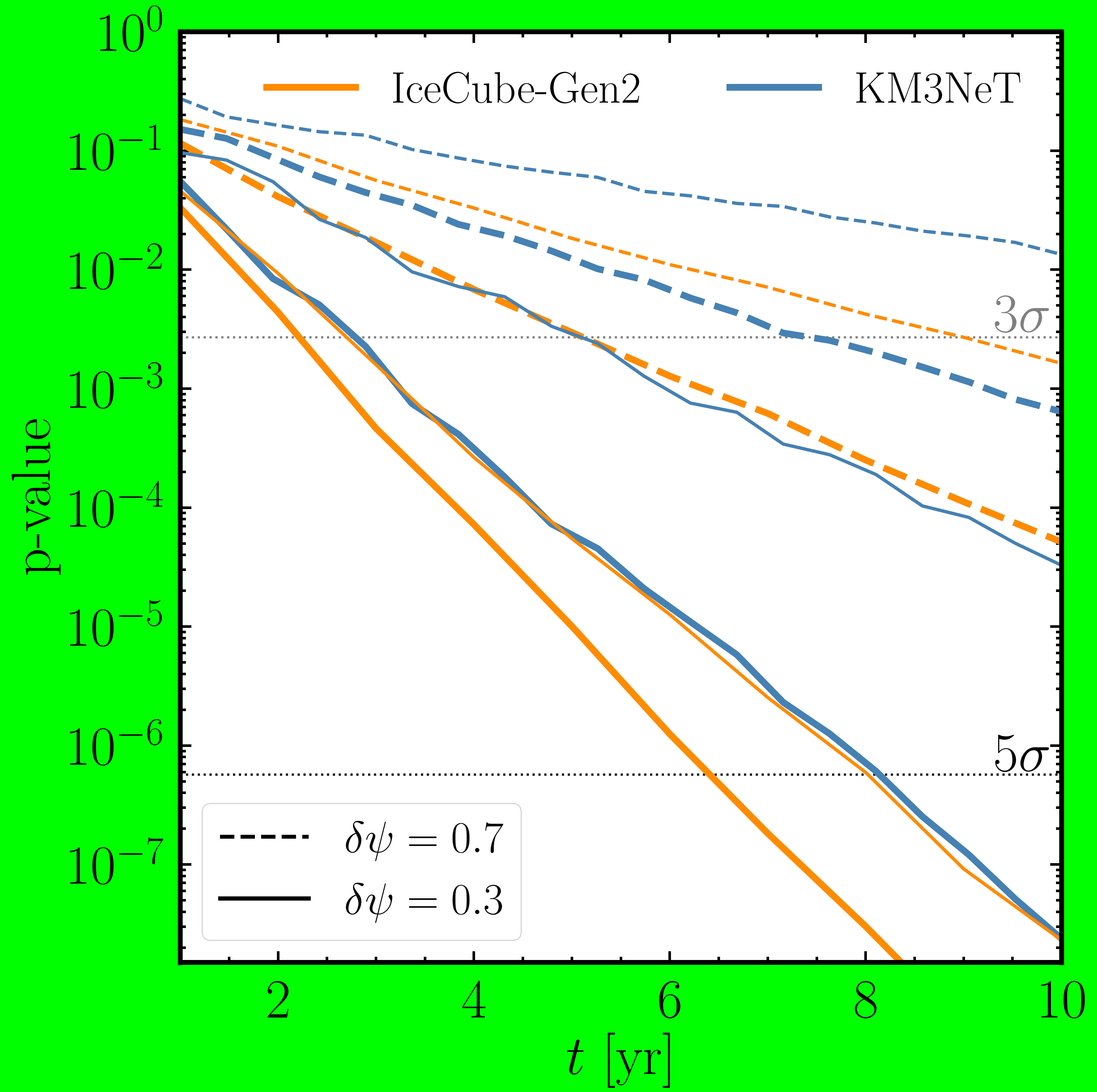
Source
Cen A
Circinus Galaxy
ESO 138-1
NGC 7582
NGC 1068
NGC 4945
NGC 424
UGC 11910
CGCG 164-019
NGC 1275



ESO 138-1



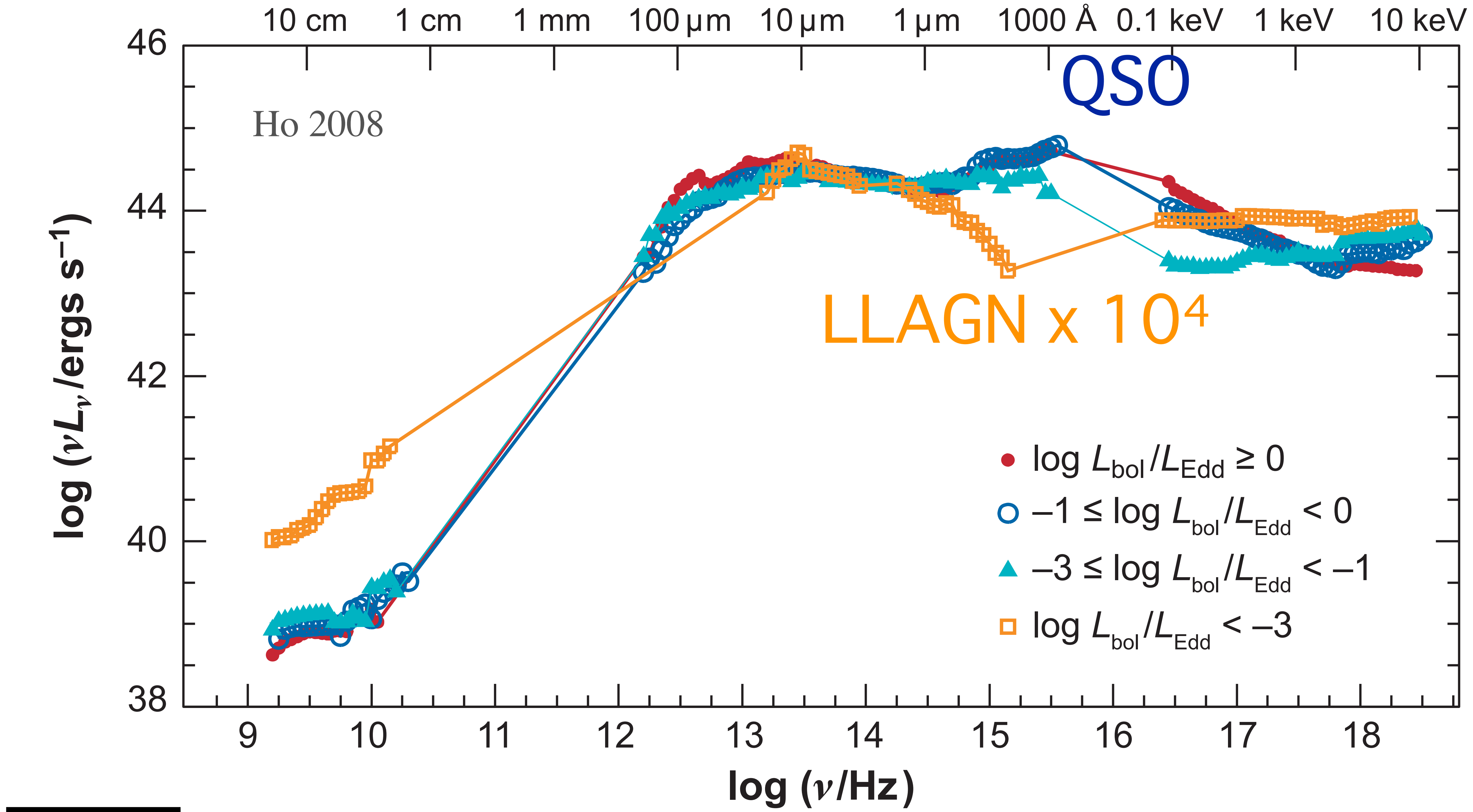
- Stacking nearby Seyferts

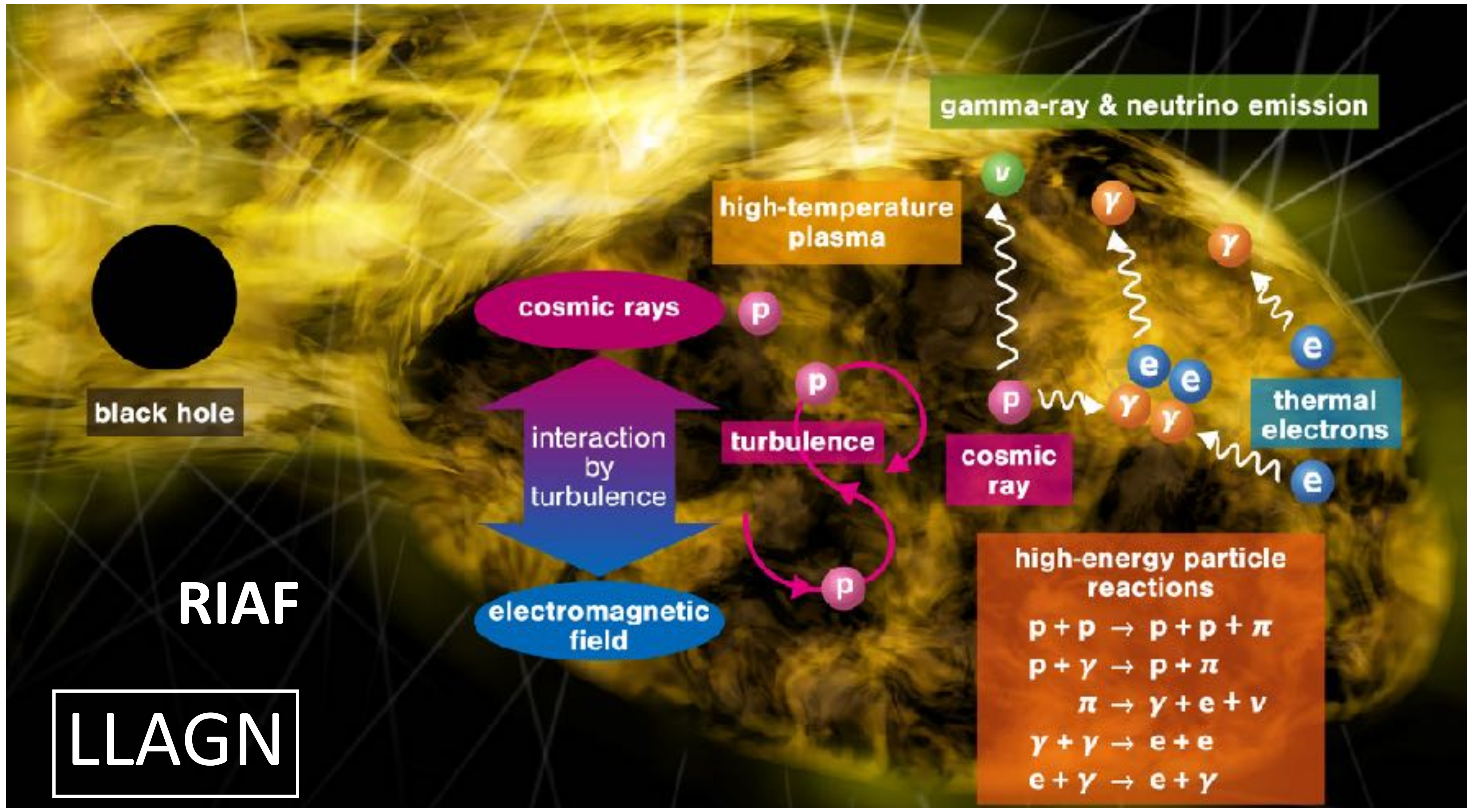


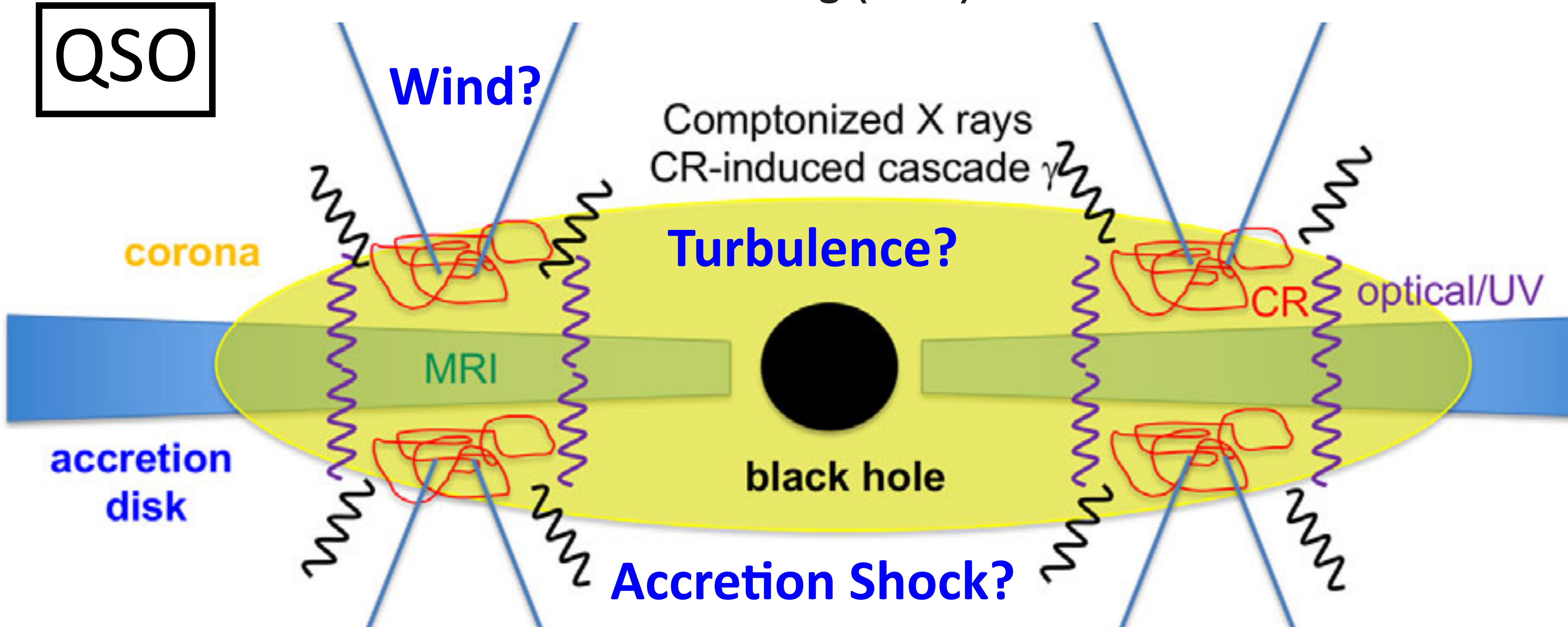
- Future detectors should detect ν from AGN
  —> **testable by future neutrino experiments**

RIAFs in LLAGN

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

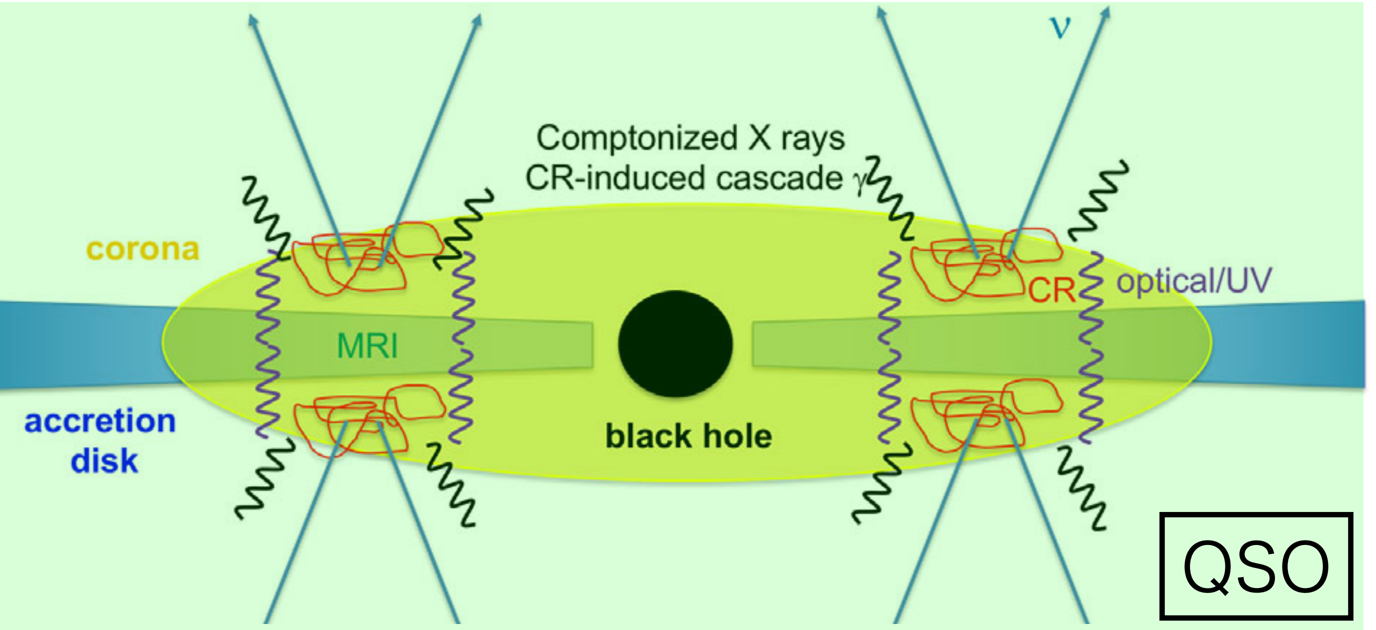




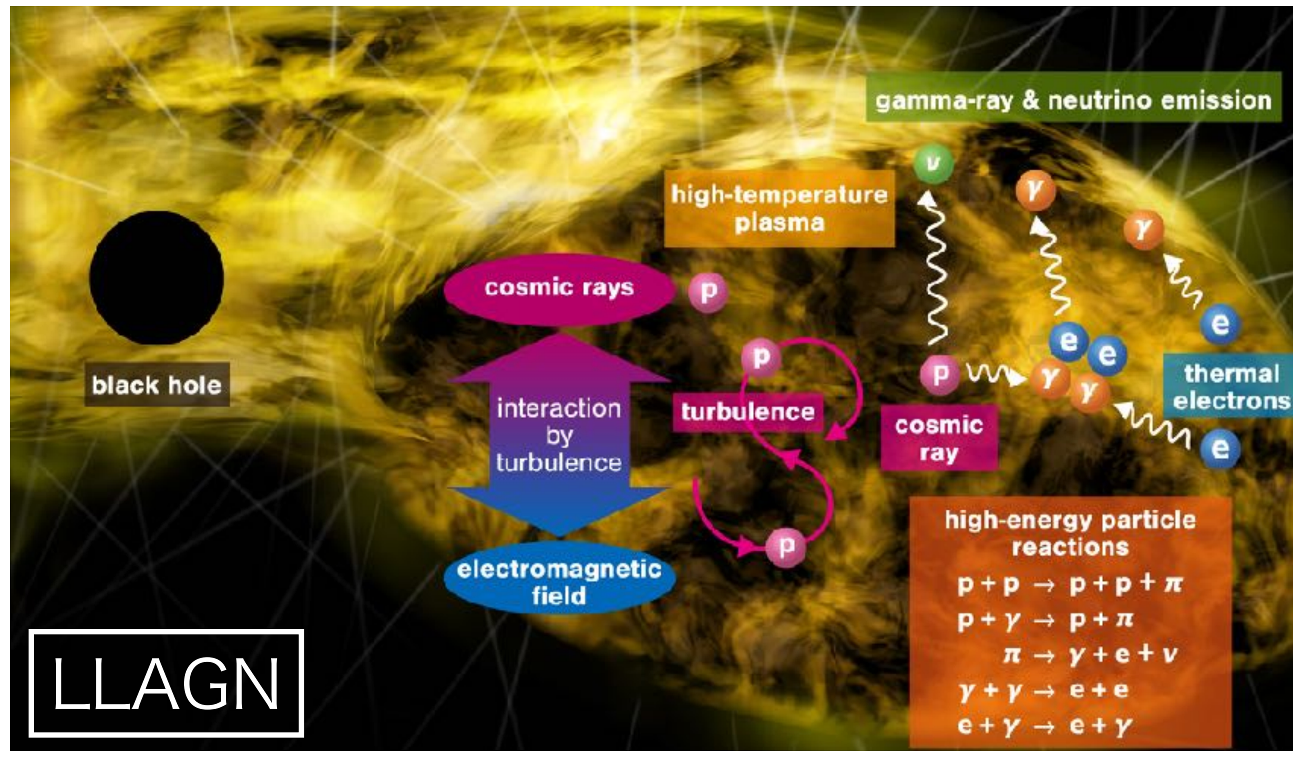


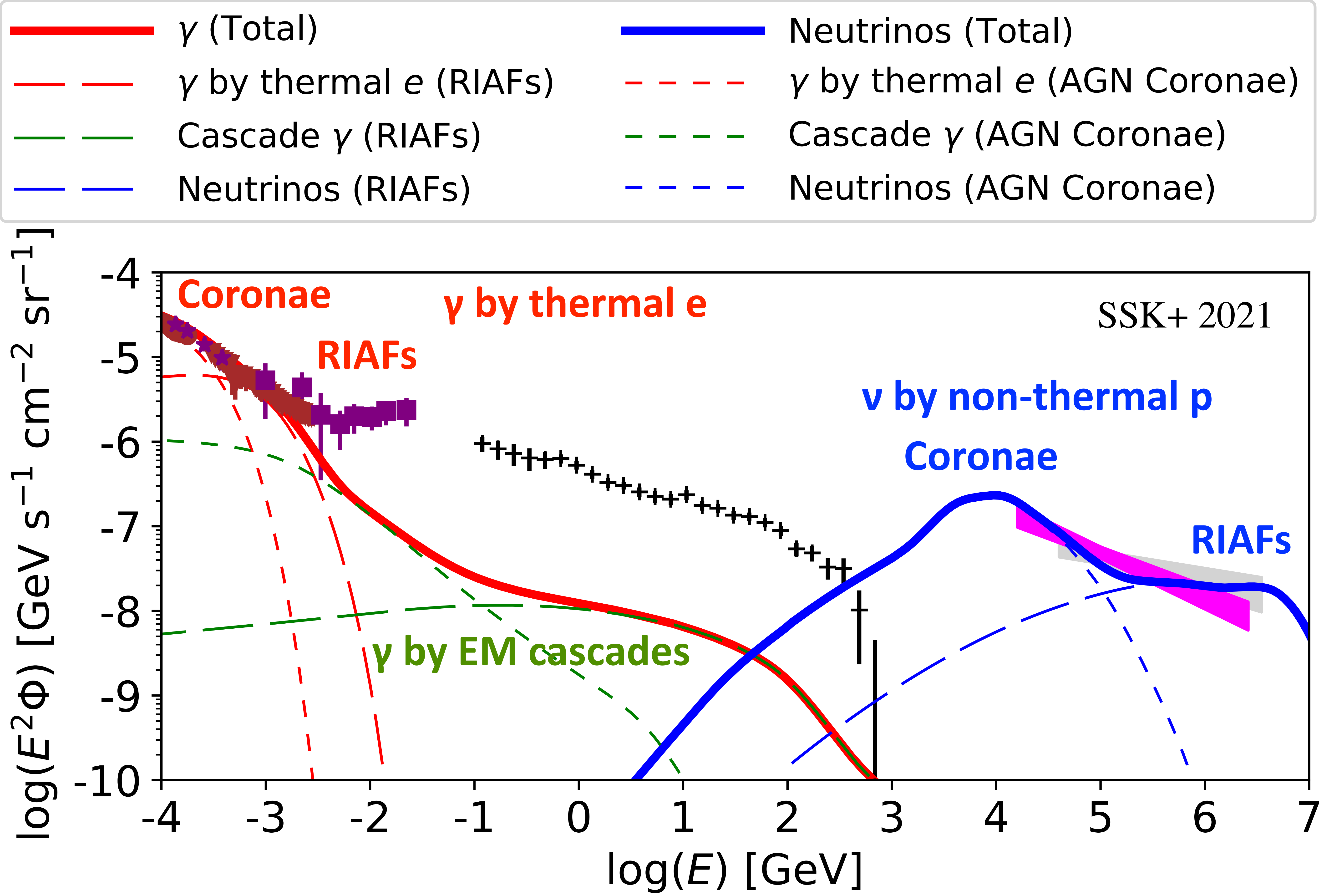
Protons in coronae & RIAFs are collisionless → Non-thermal proton production

Cosmic High-energy Background from RQ AGNs



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





- 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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- Neutrino emission models in Seyfert galaxies
- Neutrino emission from AGN coronae
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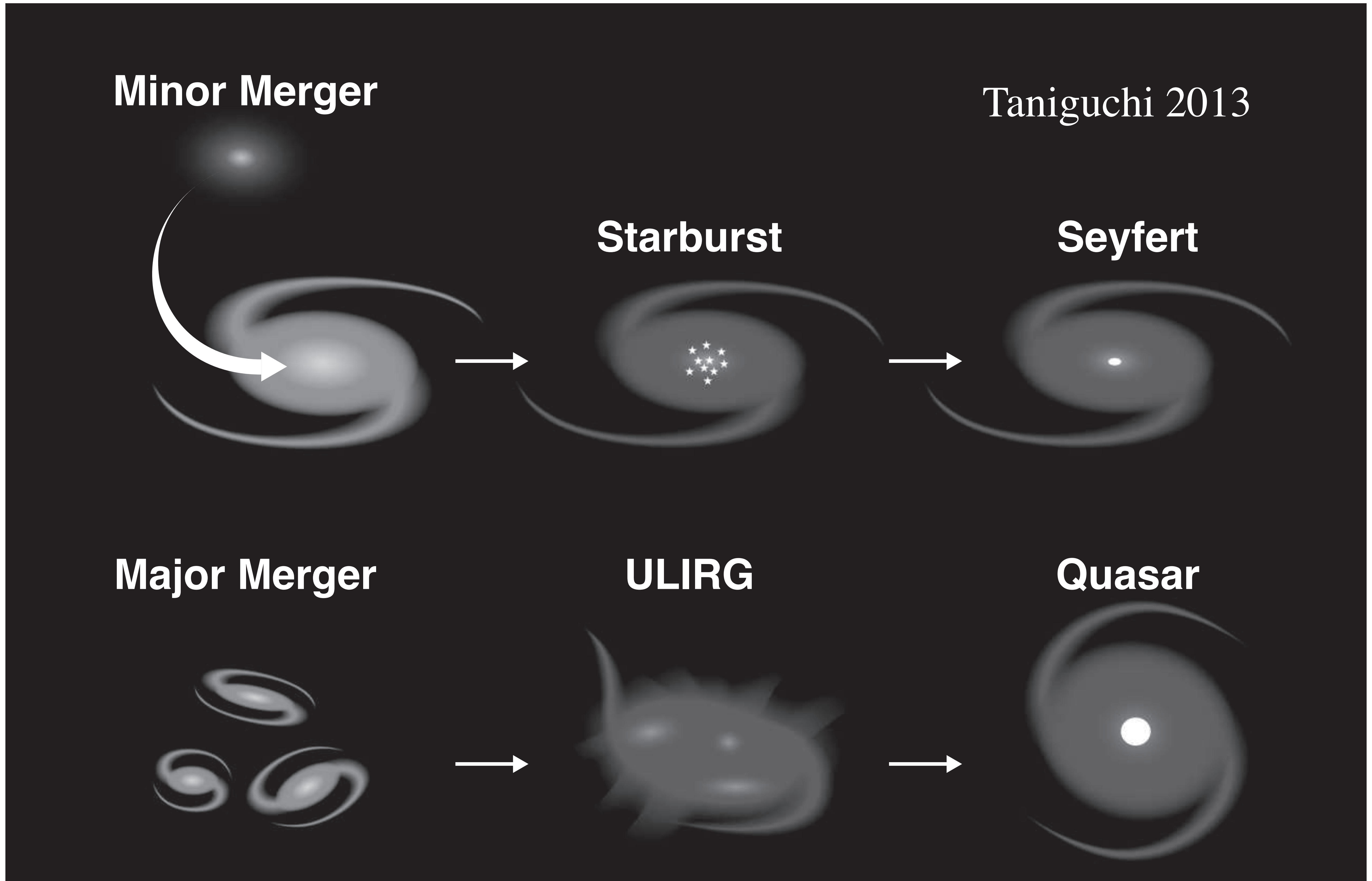
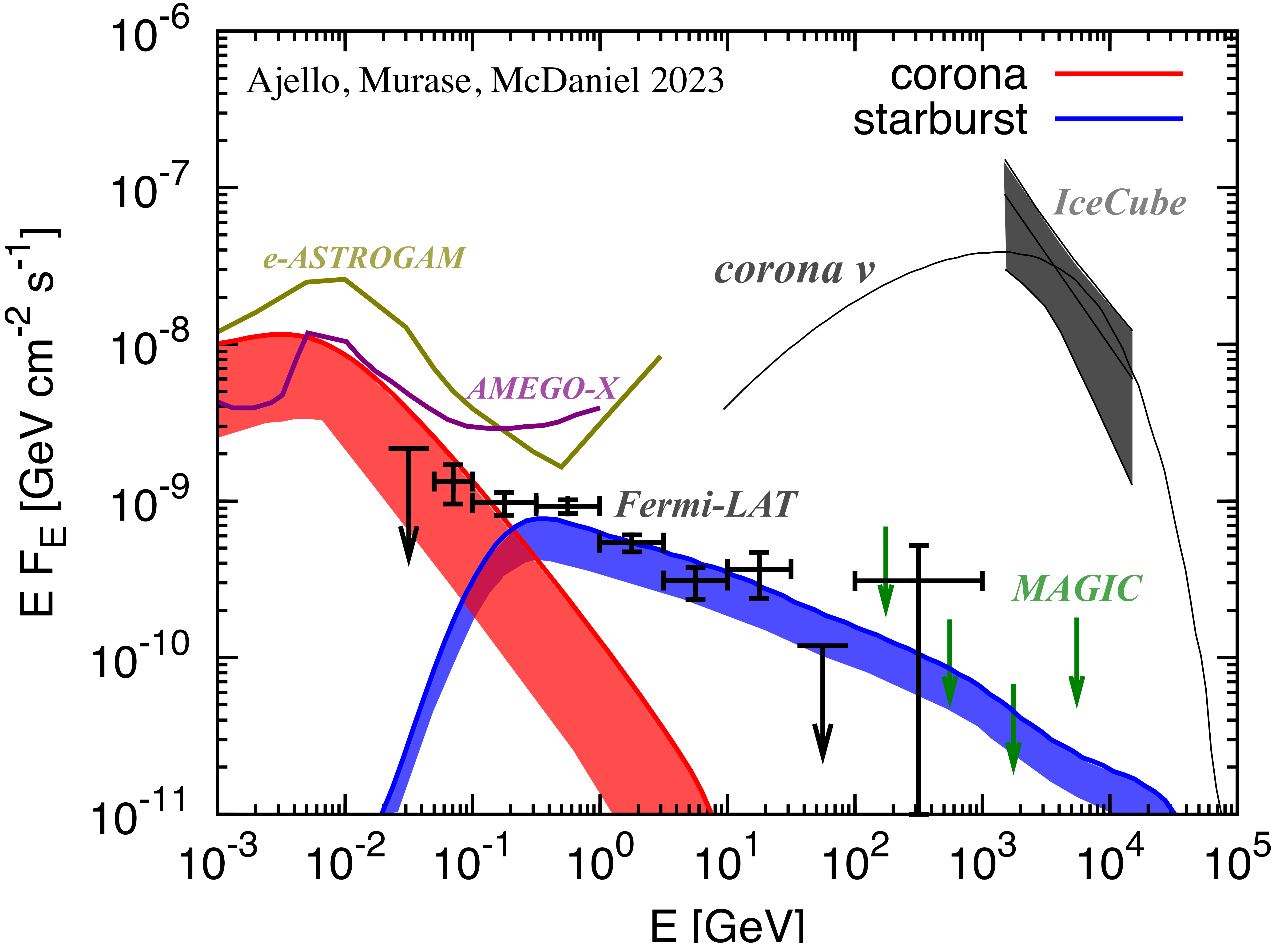
AGN-Starburst connection

- Many Seyfert galaxies are forming stars in central regions
- Star-formation activity can produce cosmic-rays, leading to gamma-ray and neutrino productions
- Famous example:
  NGC 1068, Arp 220, **NGC 4945, Circinus galaxy**



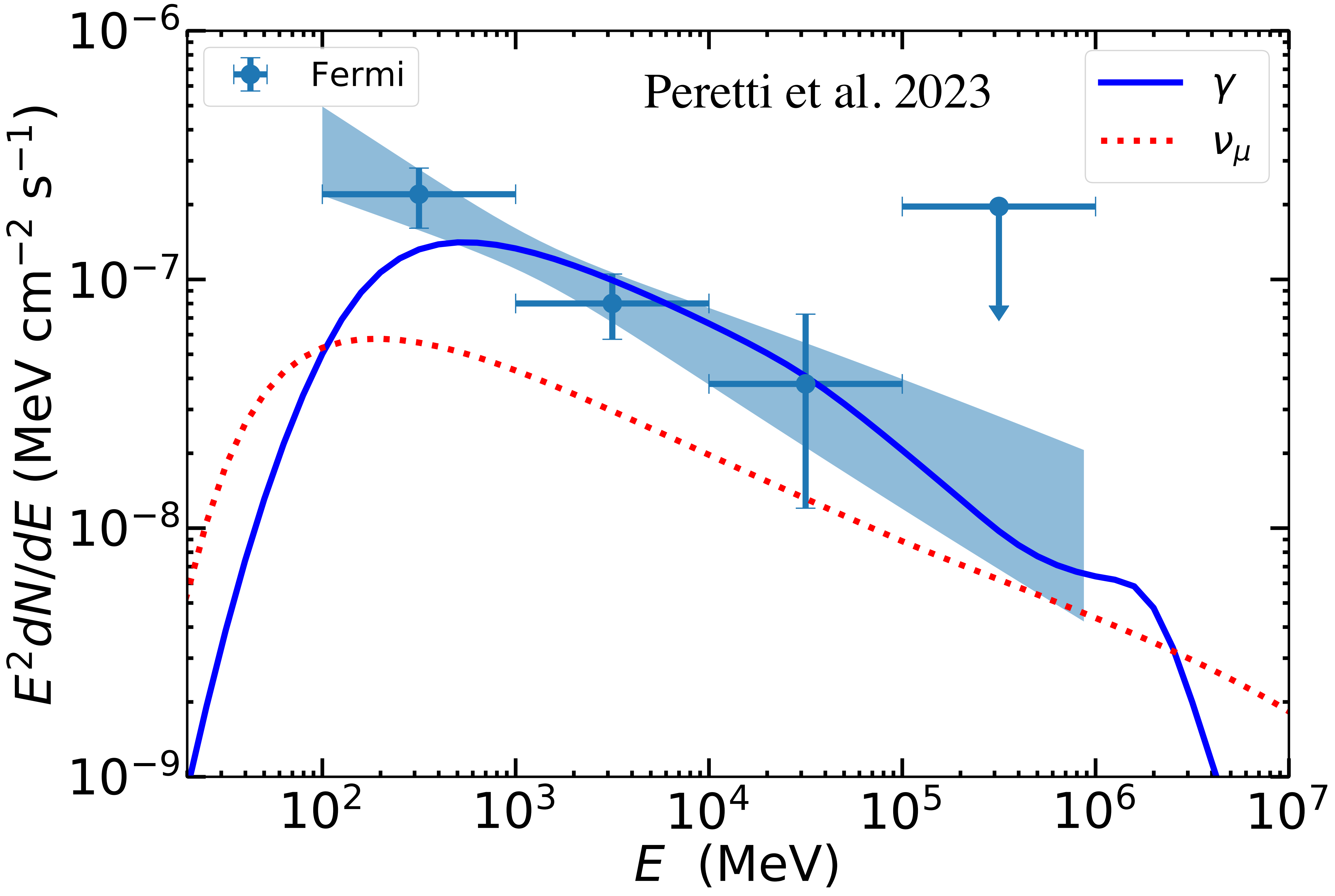
Gamma rays from NGC 1068



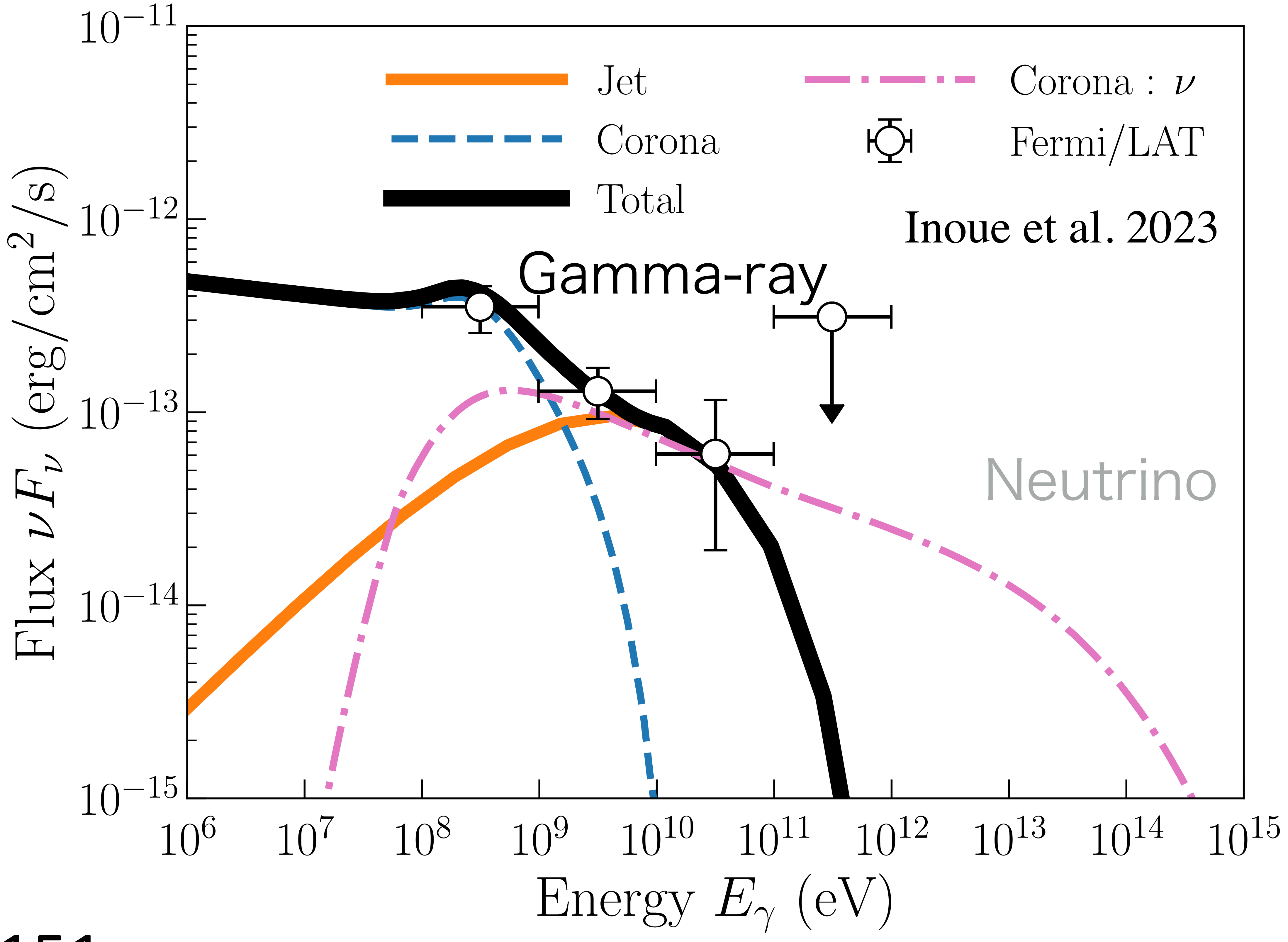
- Gamma rays by starburst activity: low-E cutoff at sub-GeV by pion decay
- Sub-GeV γ-ray spectrum in NGC1068: extending to ward lower energies —> need additional component
- **Gamma-ray flux consistent with hadronic cascade by corona model**

Gamma rays from NGC 4151?

- UFO scenario

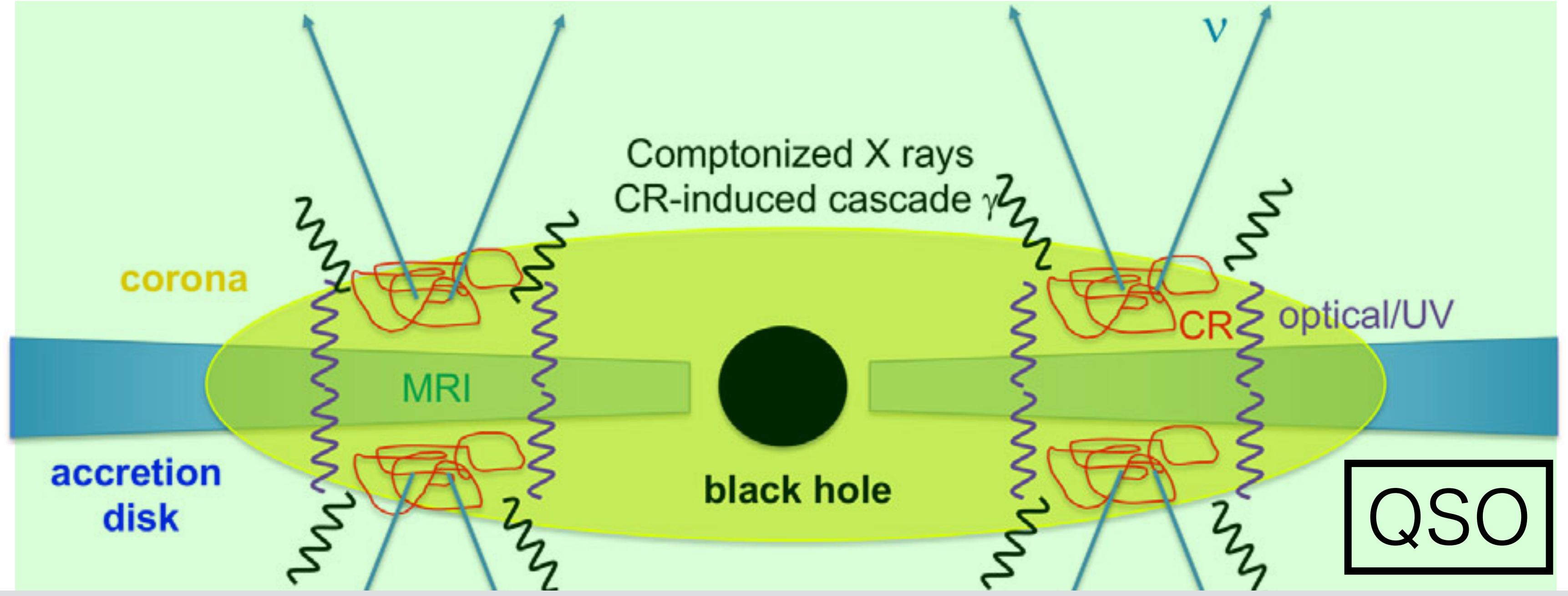


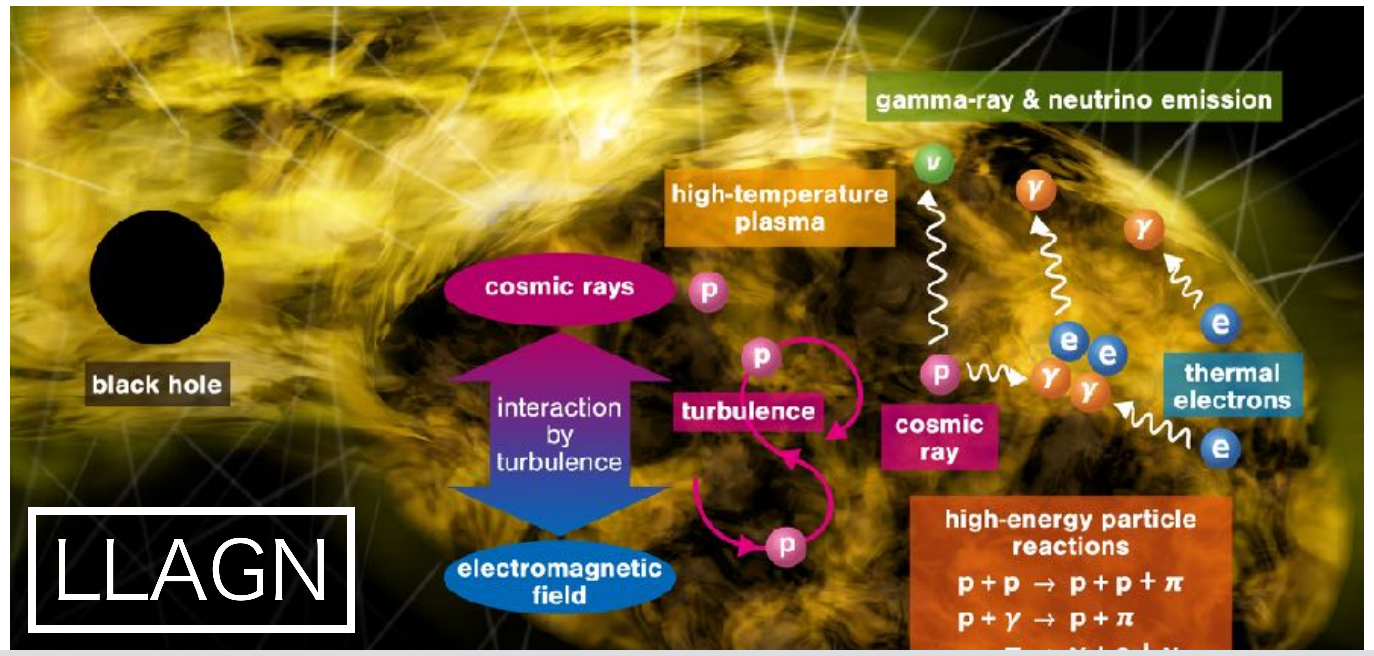
- Accretion-shock + Jet scenario



- Perretti et al. reported gamma-rays from NGC 4151
- Gamma-rays can be explained by the ultrafast outflow
- The gamma-ray flux is low and neutrino cannot be detected based on accretion shock scenario

Summary





- IceCube discovered evidence of neutrino signal from Seyfert galaxy
- Accretion shock & failed wind scenario can explain ν data,
  but they need to assume inefficient acceleration parameters
- Coronae around SMBH can explain ν data for NGC 1068 without overshooting γ data and future neutrino & MeV γ-ray observations will provide a robust test
- Combining a contribution from LLAGN, AGN accretion flows can be the source of the cosmic neutrino background for all the energy range (1 TeV - 10 PeV)
- Starburst activity can explain γ-rays of E > GeV,
  but cannot explain neutrinos & sub-GeV gamma-ray data