Particle acceleration and neutrino emission from radio-quiet active galactic nuclei

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
Murase, Karwin, SSK et al. 2024, ApJL, 961, L34
SSK, Tomida, Murase 2019 MNRAS
SSK et al. in prep.

Seminar @ Chiba U. Dec. 10, 2025

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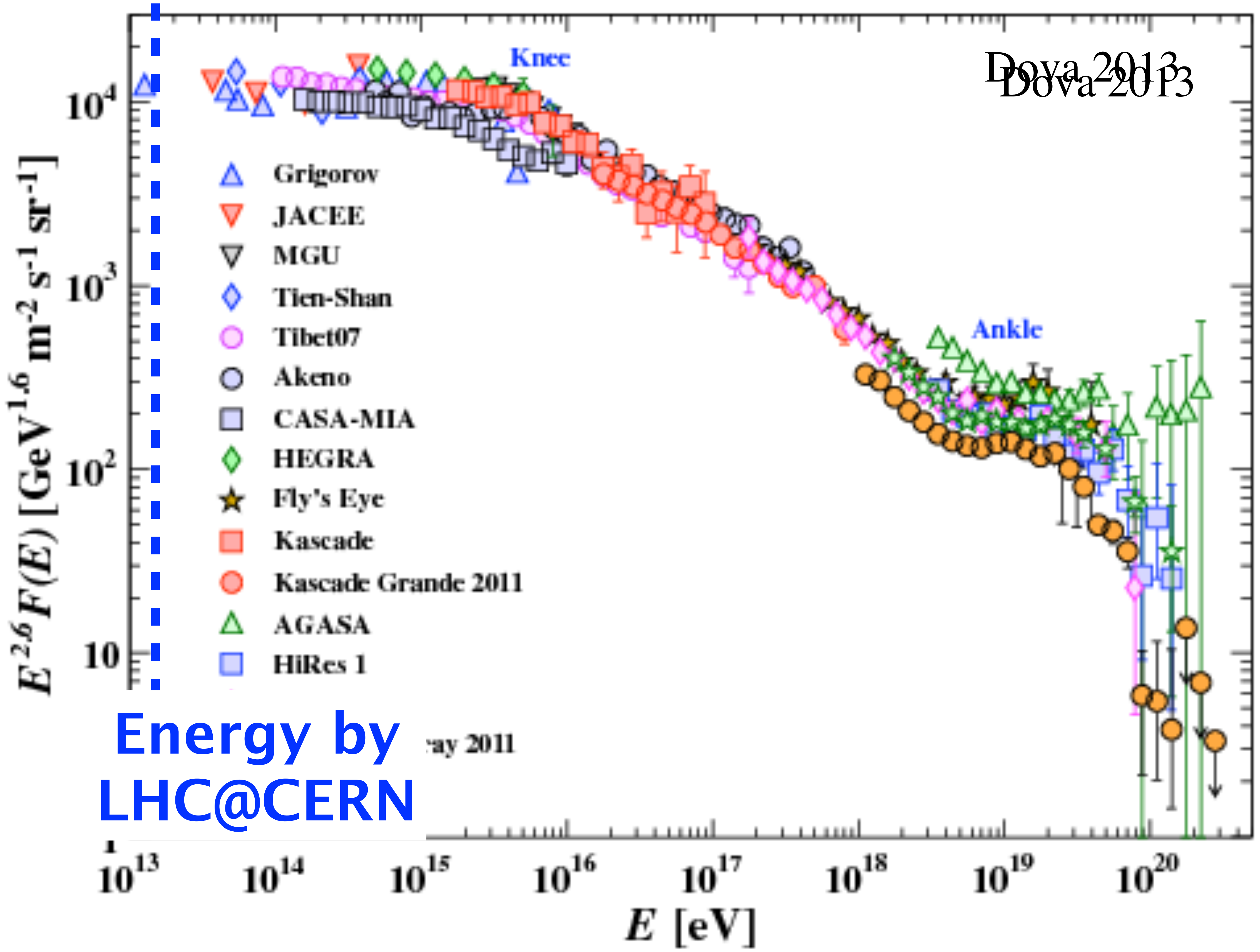
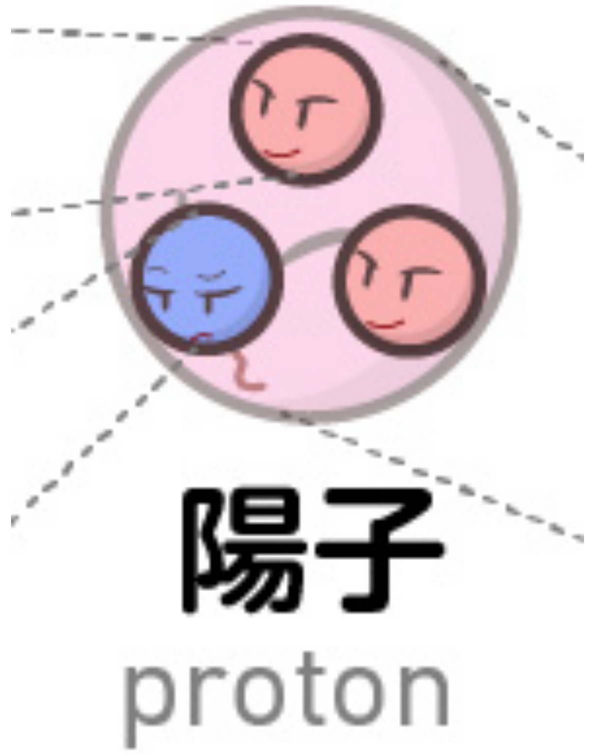
Index

- Introduction to neutrino astrophysics
- CR acceleration in AGN accretion flows
- Neutrino emission modeling
- Summary

Cosmic-Rays (CRs)
：High-energy particles filling the Universe





©Higgstan

Energy of a UHECR

||

Baseball kinetic energy

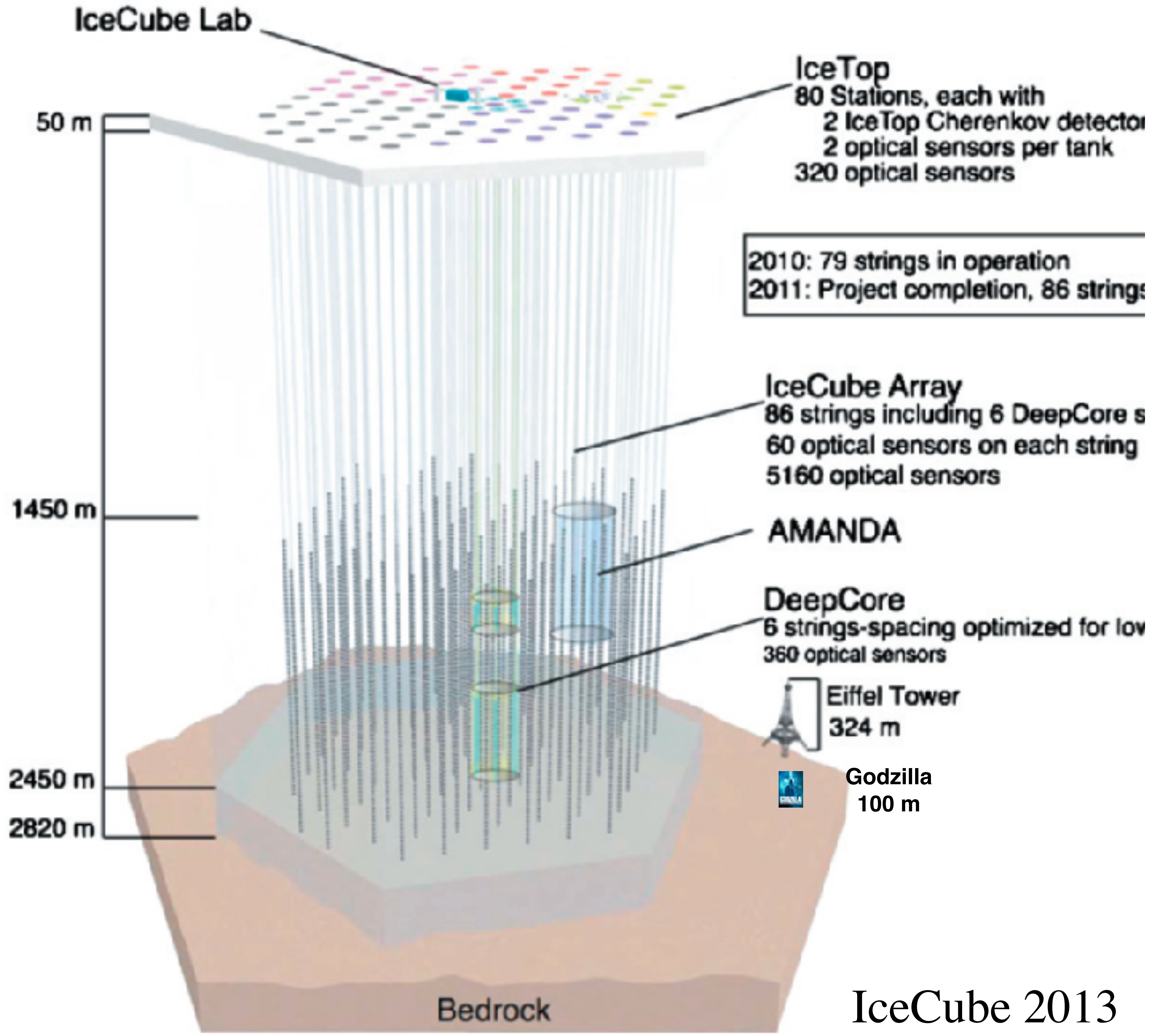
Origins and **production mechanisms** are still **unknown**

https://www.britannica.com/biography/Shohei-Ohtani

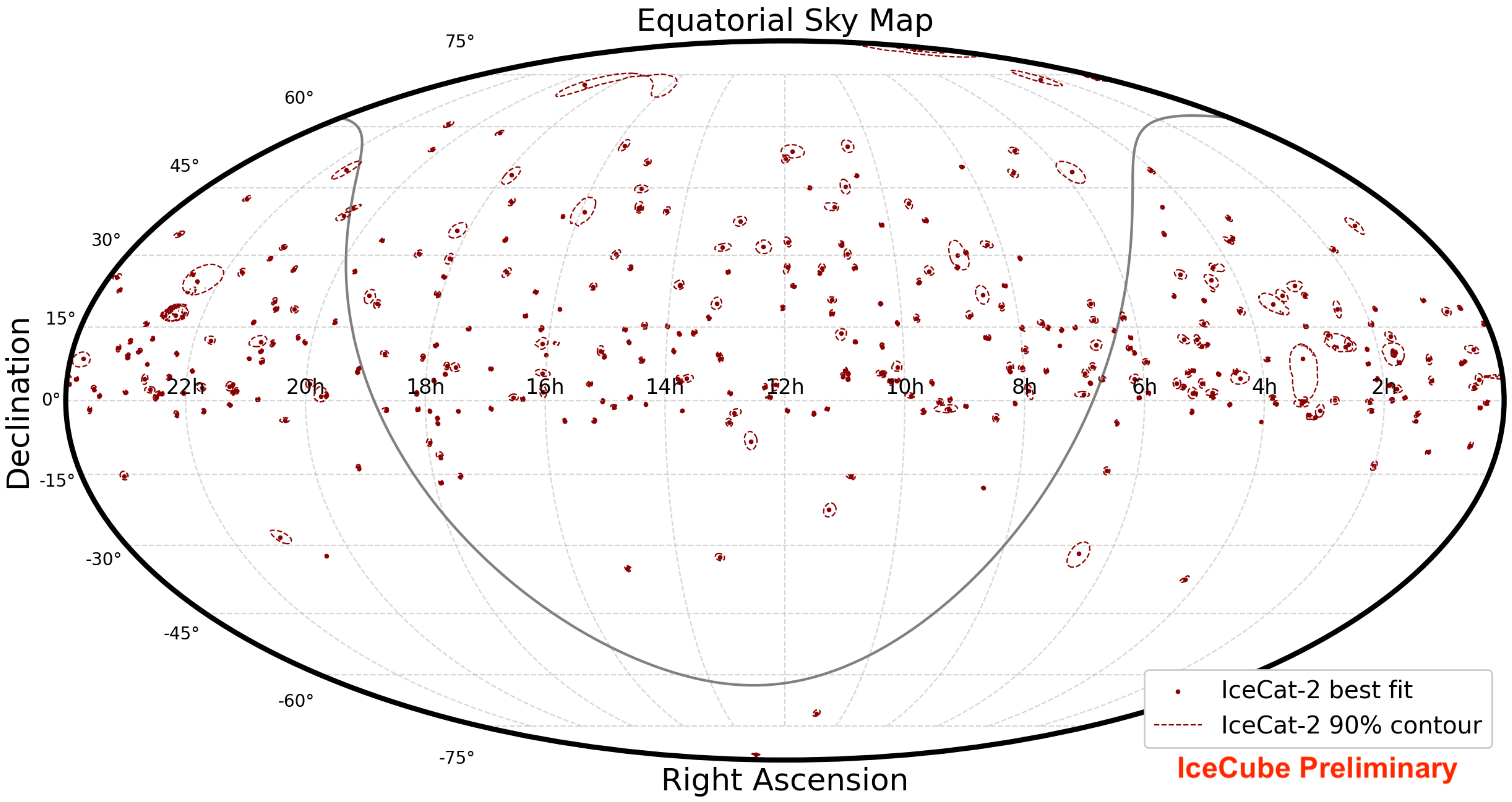
Traditional Astronomy

Multi-messenger Astronomy

IceCube & Cosmic neutrinos



IceCube 2013



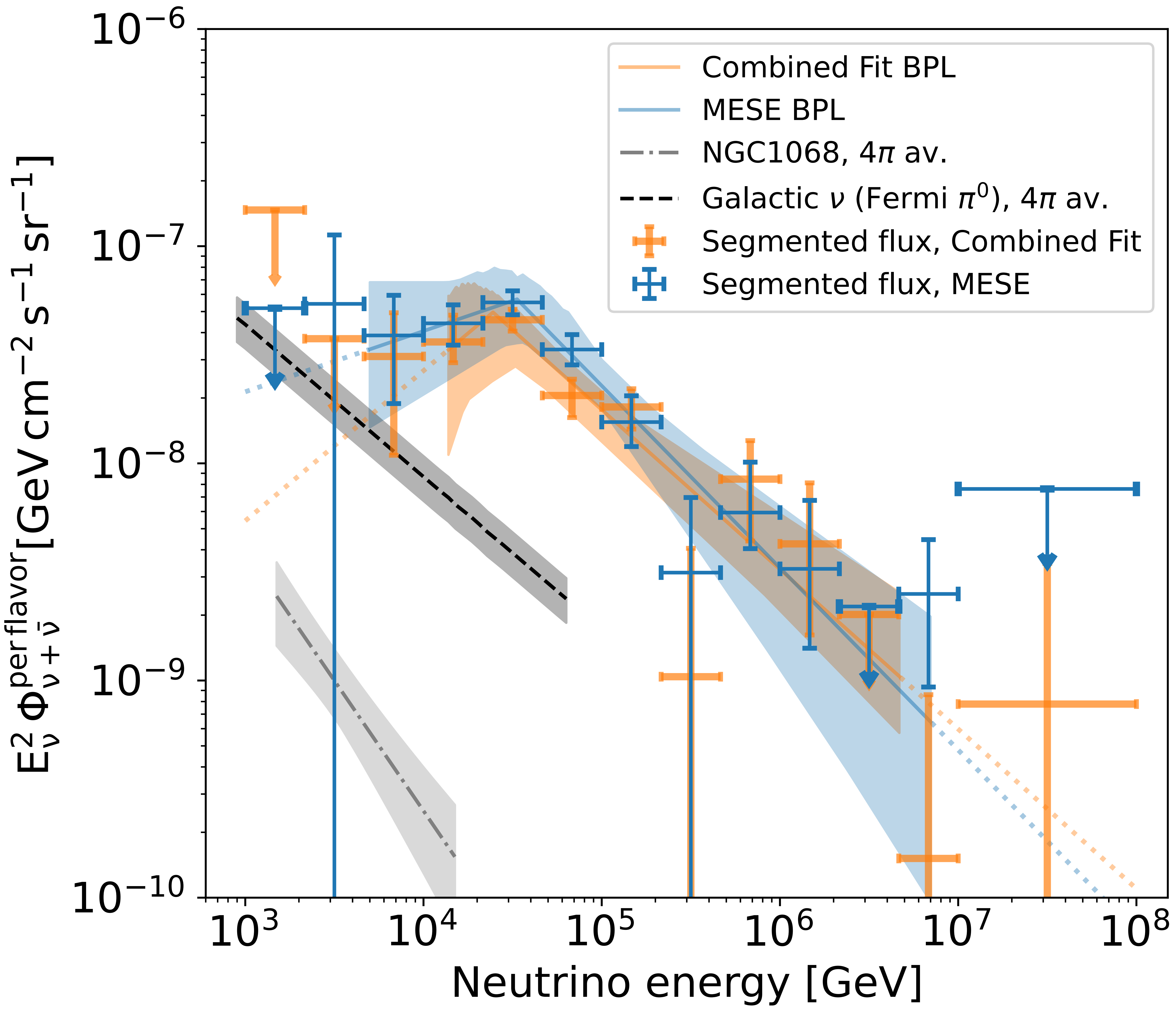
IceCat-2 ICRC 2025

- km³-detector@Antarctica
- **Discovery of cosmic neutrino in 2013**

- Isotropic → Extragalactic origin
- Galactic contribution < 10%

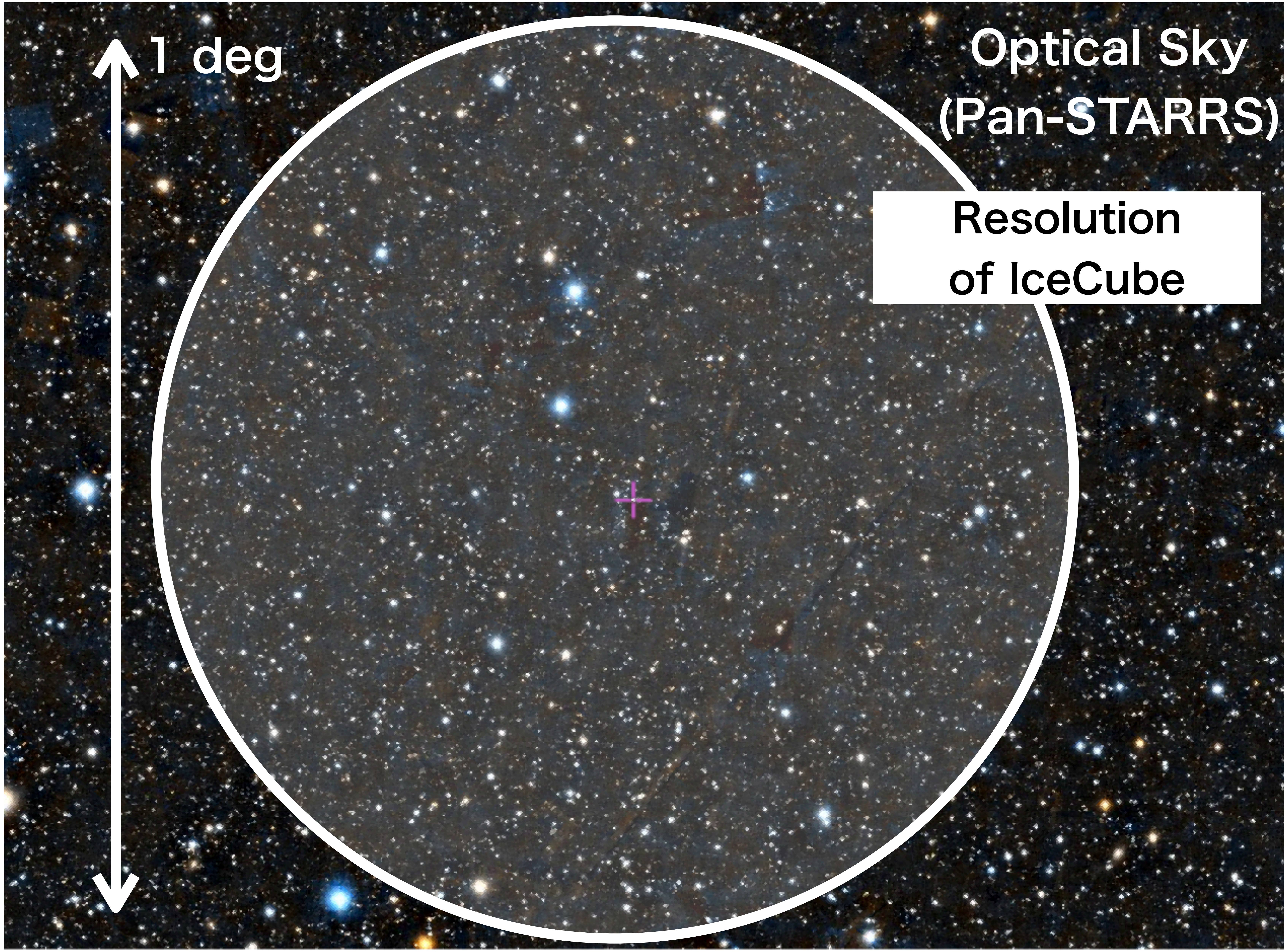
Cosmic Neutrino Background Spectrum

IceCube 2020



- Break in neutrino spectra → **Peak ~ 30 TeV**
- **Origins of astro-neutrinos are a new big mystery**

Difficulty of Identifying Neutrino Sources



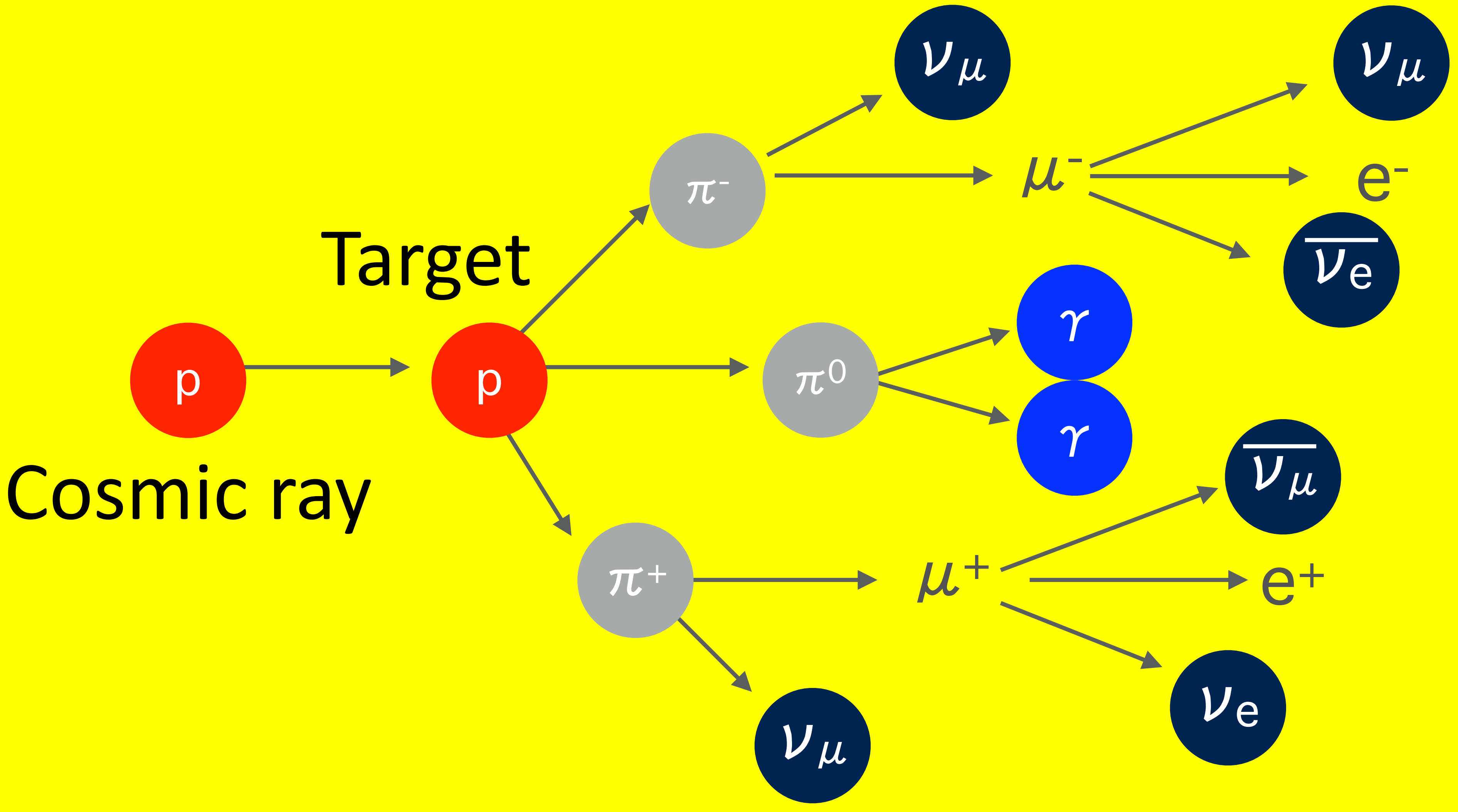
- Ang. Resolution for optical telescope ~ 1 sec
- Ang. resolution for neutrino telescope ~ 1 deg (~ 3600 sec)
- Too many unrelated astrophysical objects

Theoretical support is necessary

https://aladin.u-strasbg.fr/AladinLite/

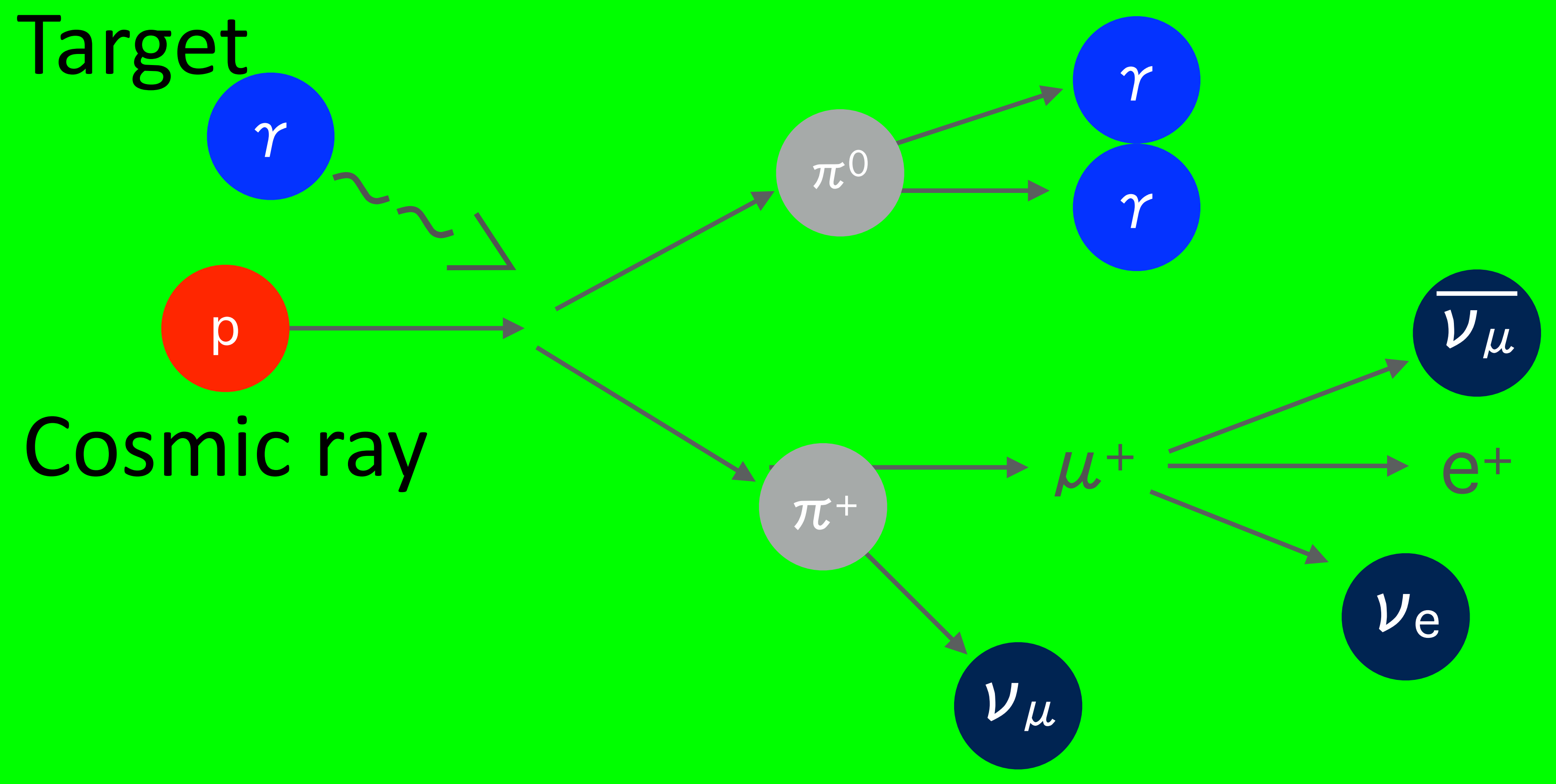
High-energy neutrino production

- pp inelastic collision



- $p+p \rightarrow p+p+\pi$
- $\pi^\pm \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

- Photomeson production ($p\gamma$)

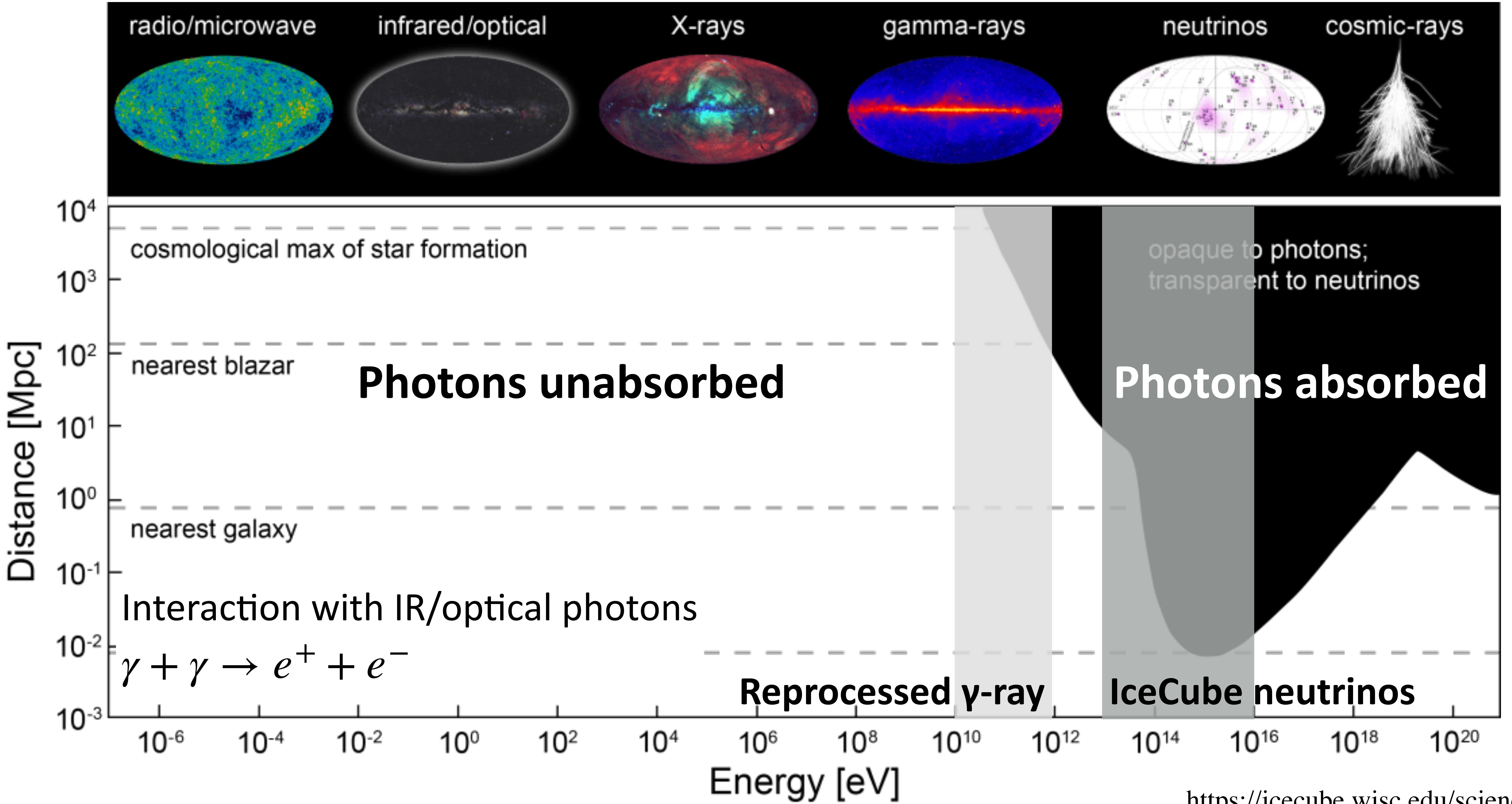


- $p+\gamma \rightarrow p+\pi$
- $\pi^\pm \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

Interaction between CRs & photons/nuclei → Neutrino production

Gamma-rays inevitably accompanied with neutrinos

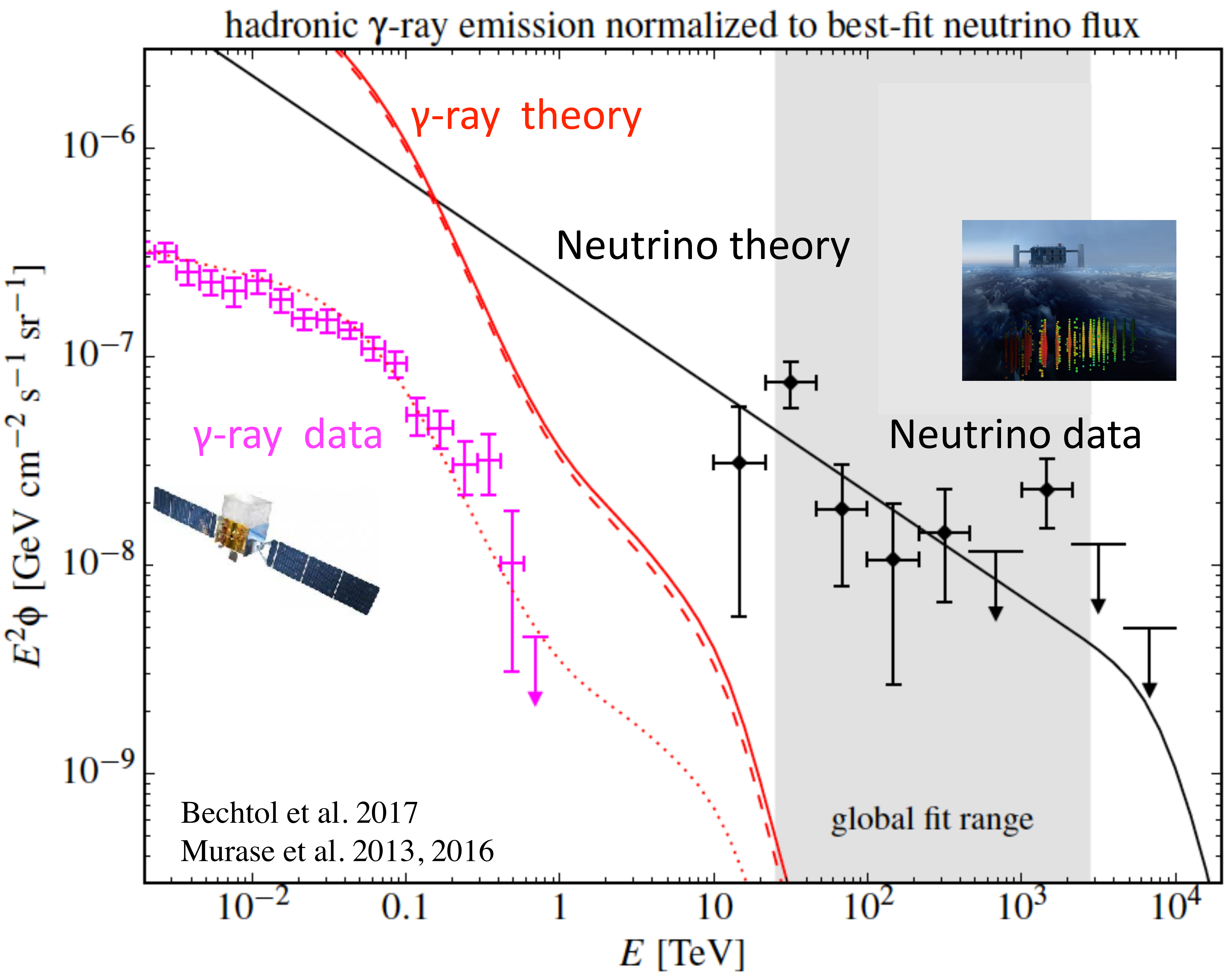
Intergalactic cascade of γ-rays



https://icecube.wisc.edu/science/research/

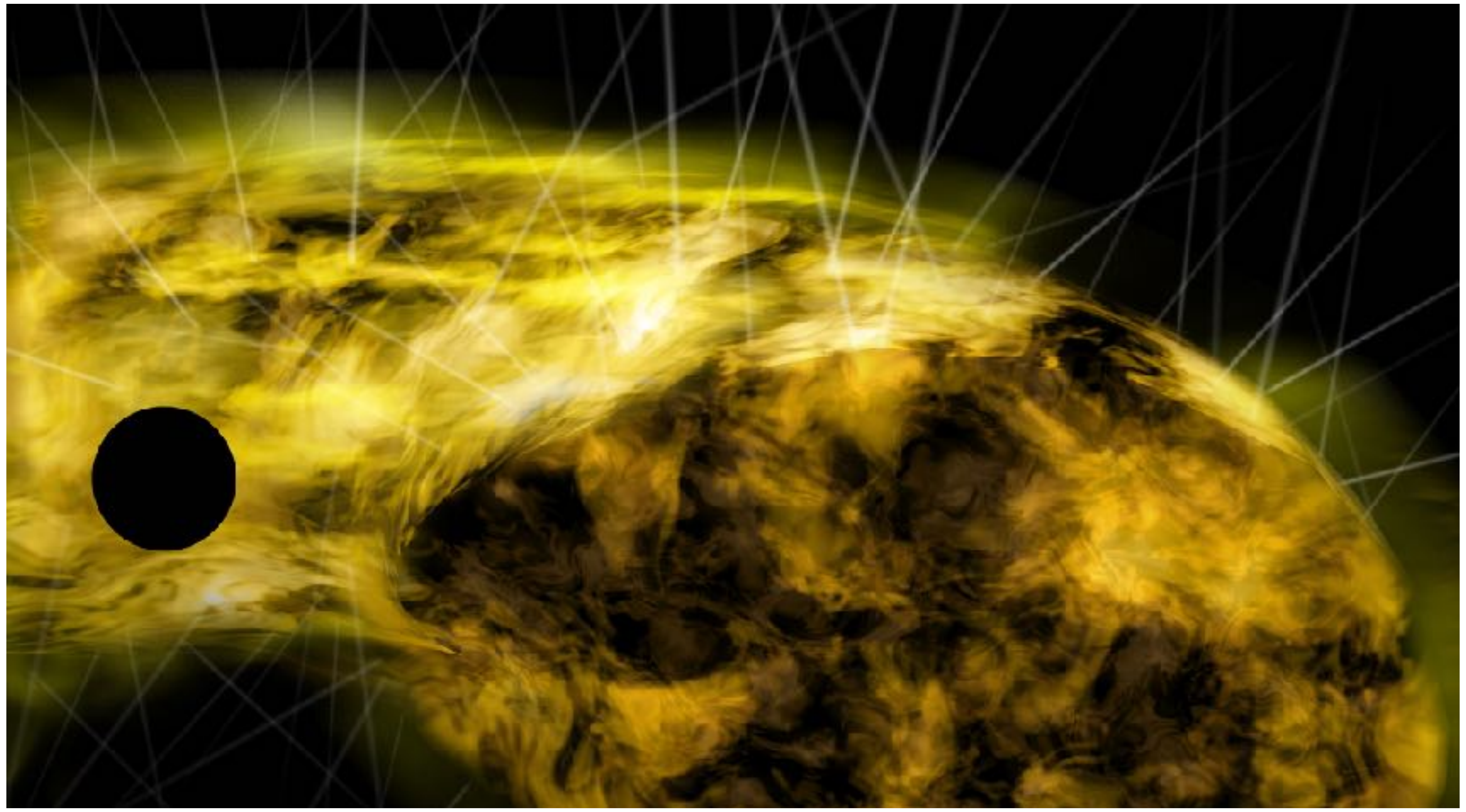
Gamma-ray Constraint on Neutrino Sources

- 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



Hidden Neutrino Source Candidates

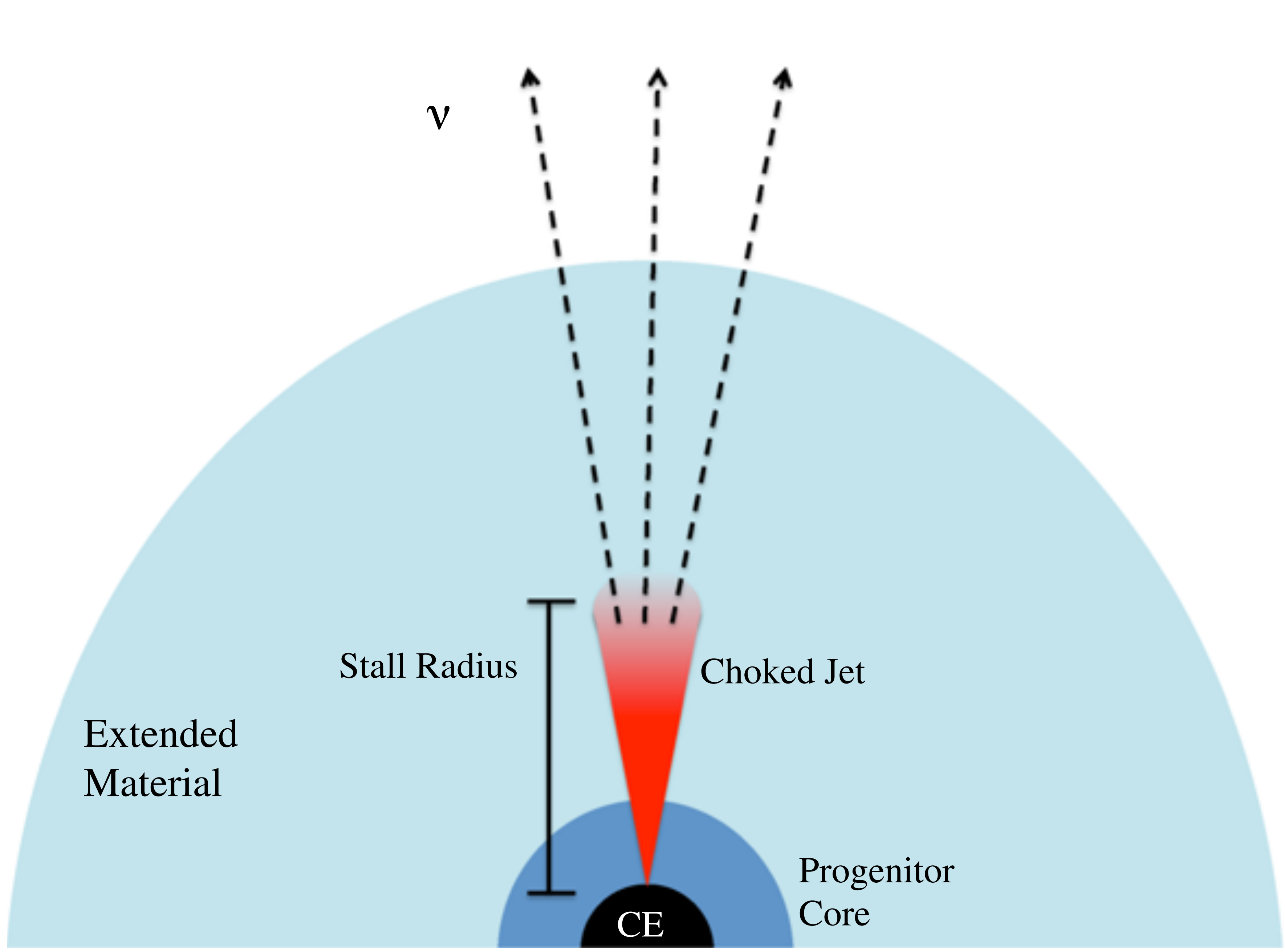
- AGN Core



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

- Choked GRBs

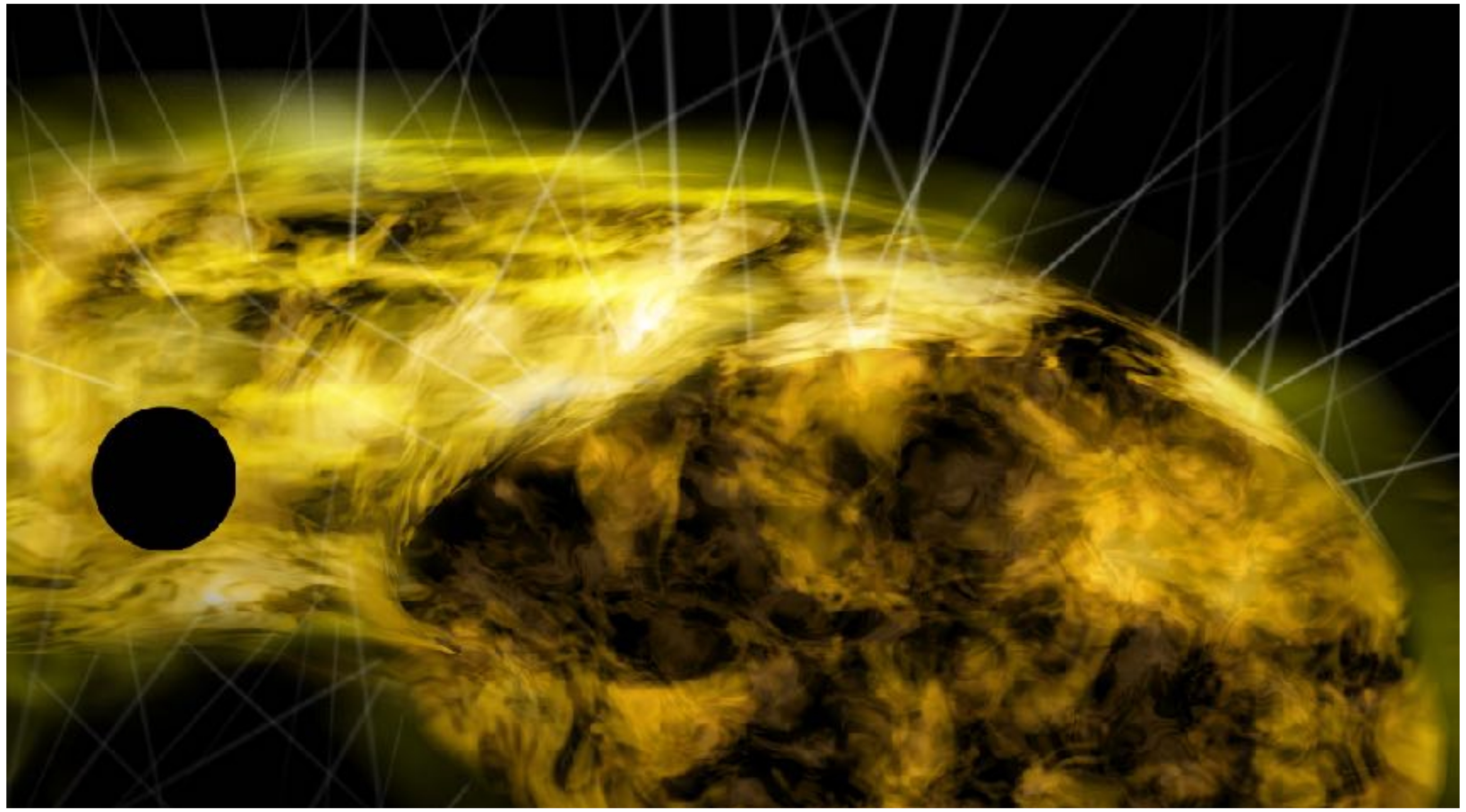
Orphan Neutrinos



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

Hidden Neutrino Source Candidates

- AGN Core



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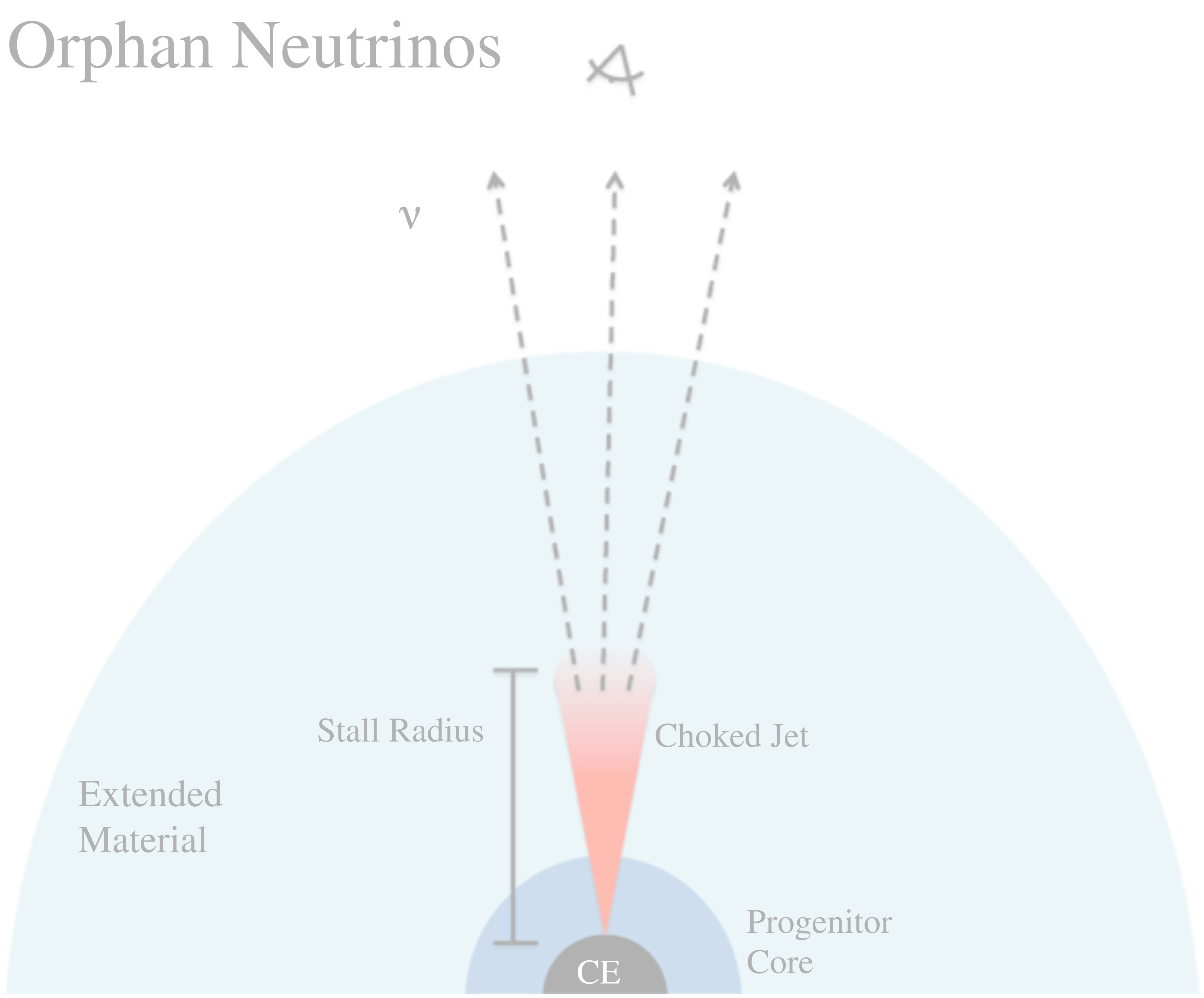
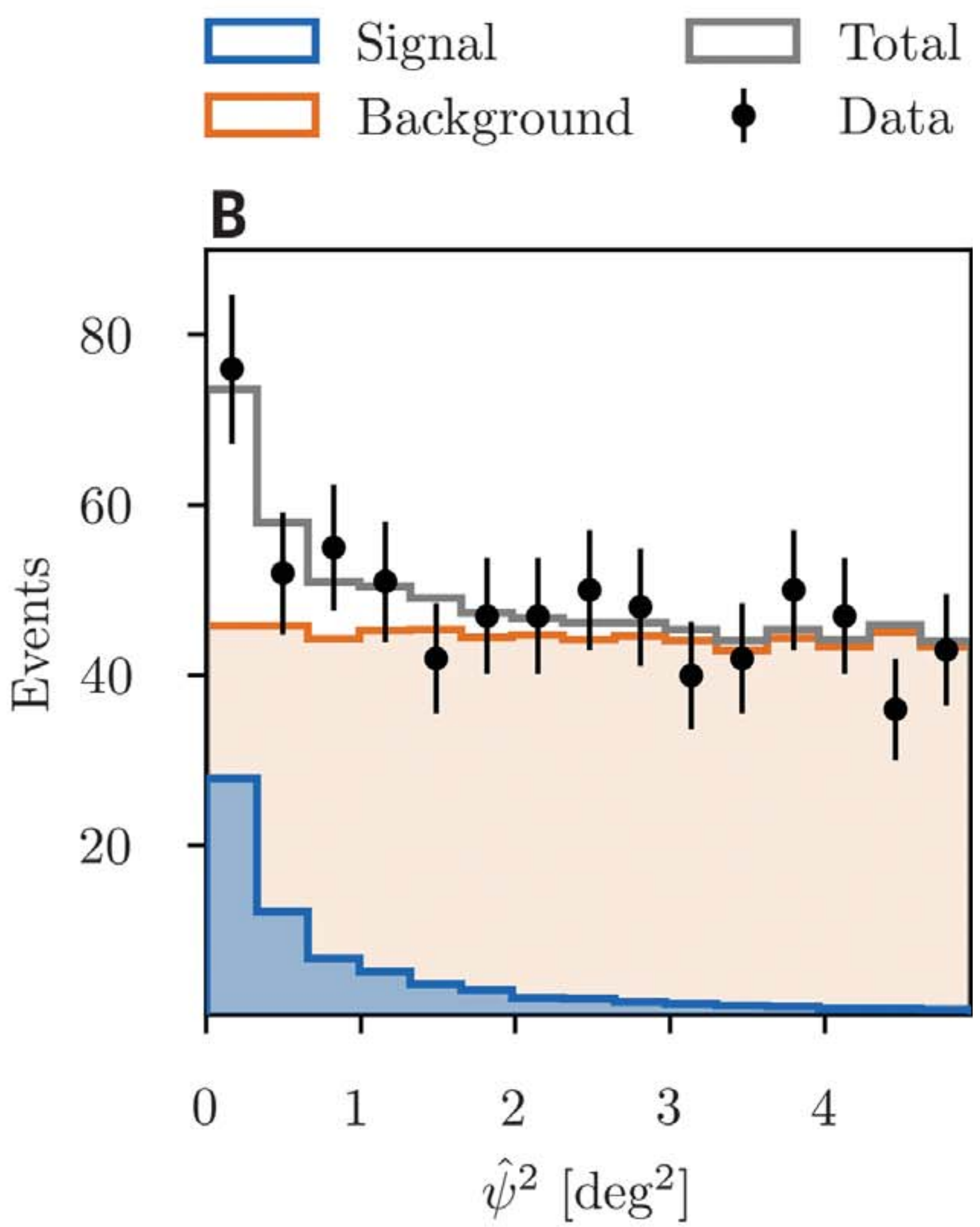
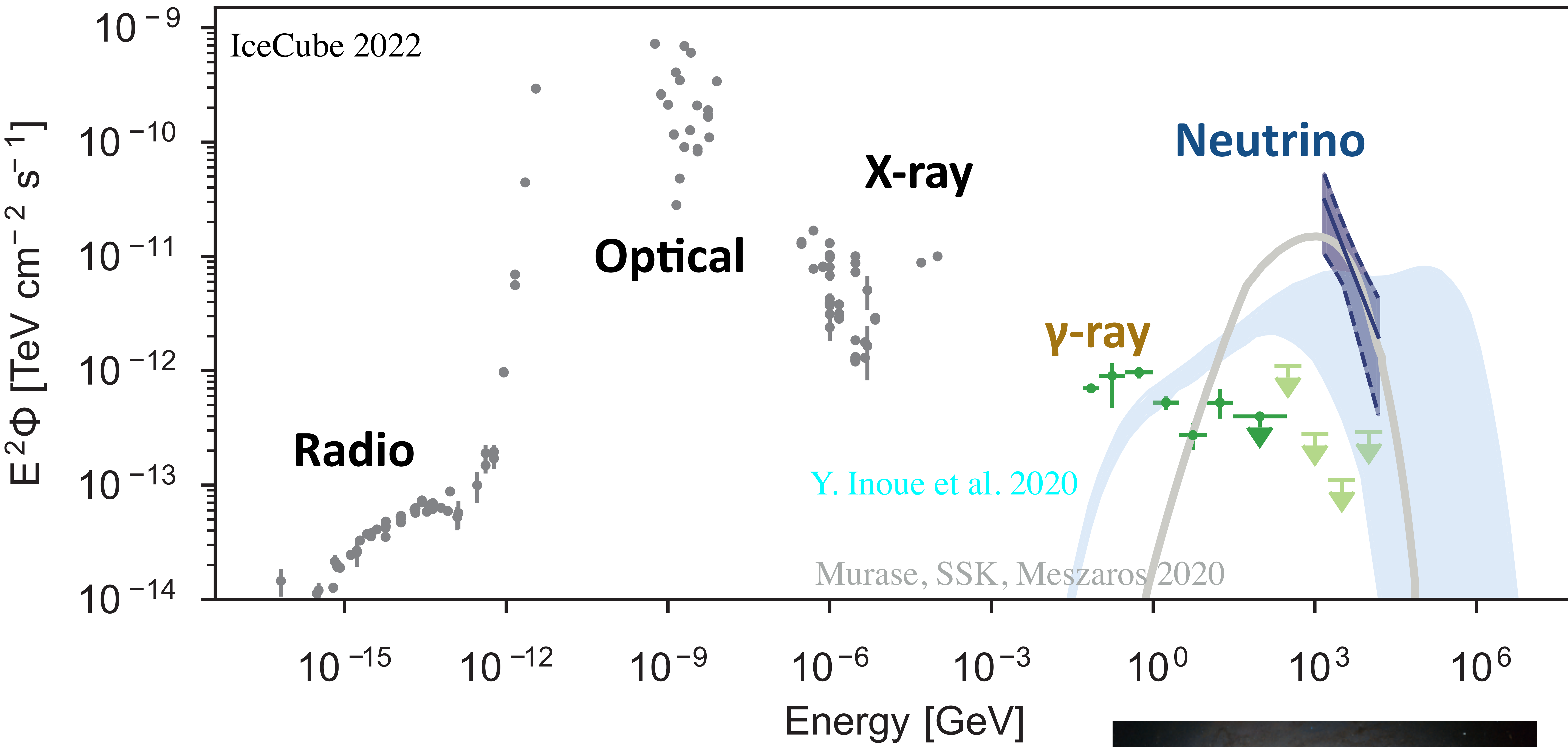


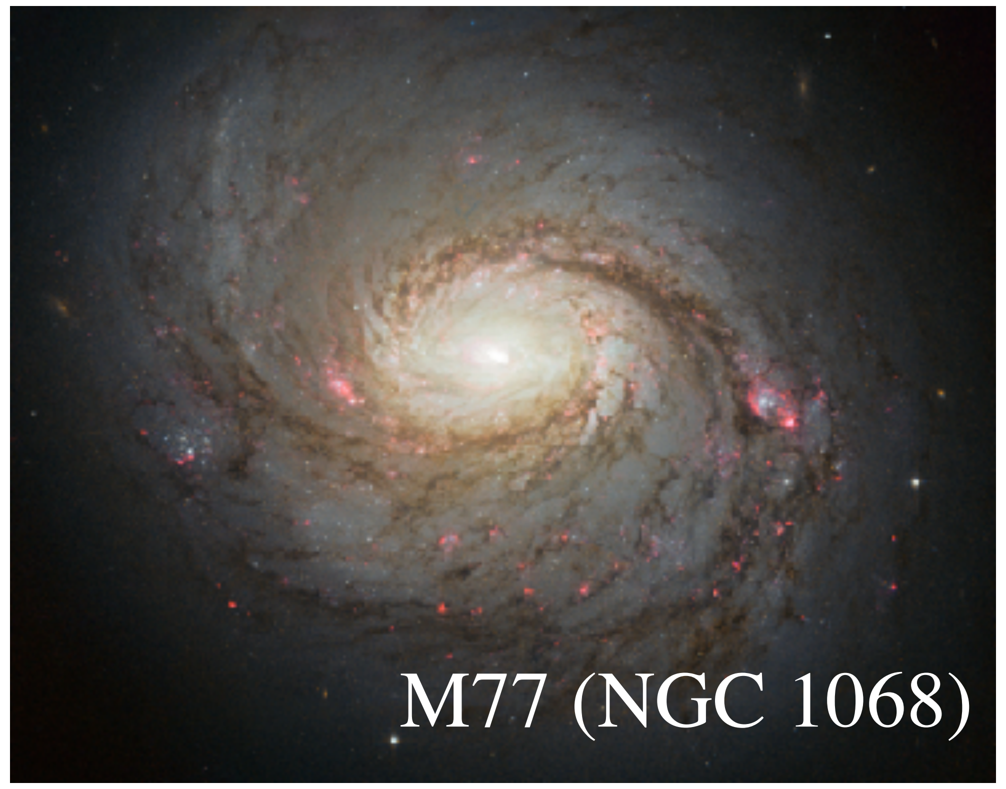
- GRBs failed to penetrate stellar envelope
- Stellar envelope absorbs γ-rays
- $p + \gamma \rightarrow p + e^+ + e^-$

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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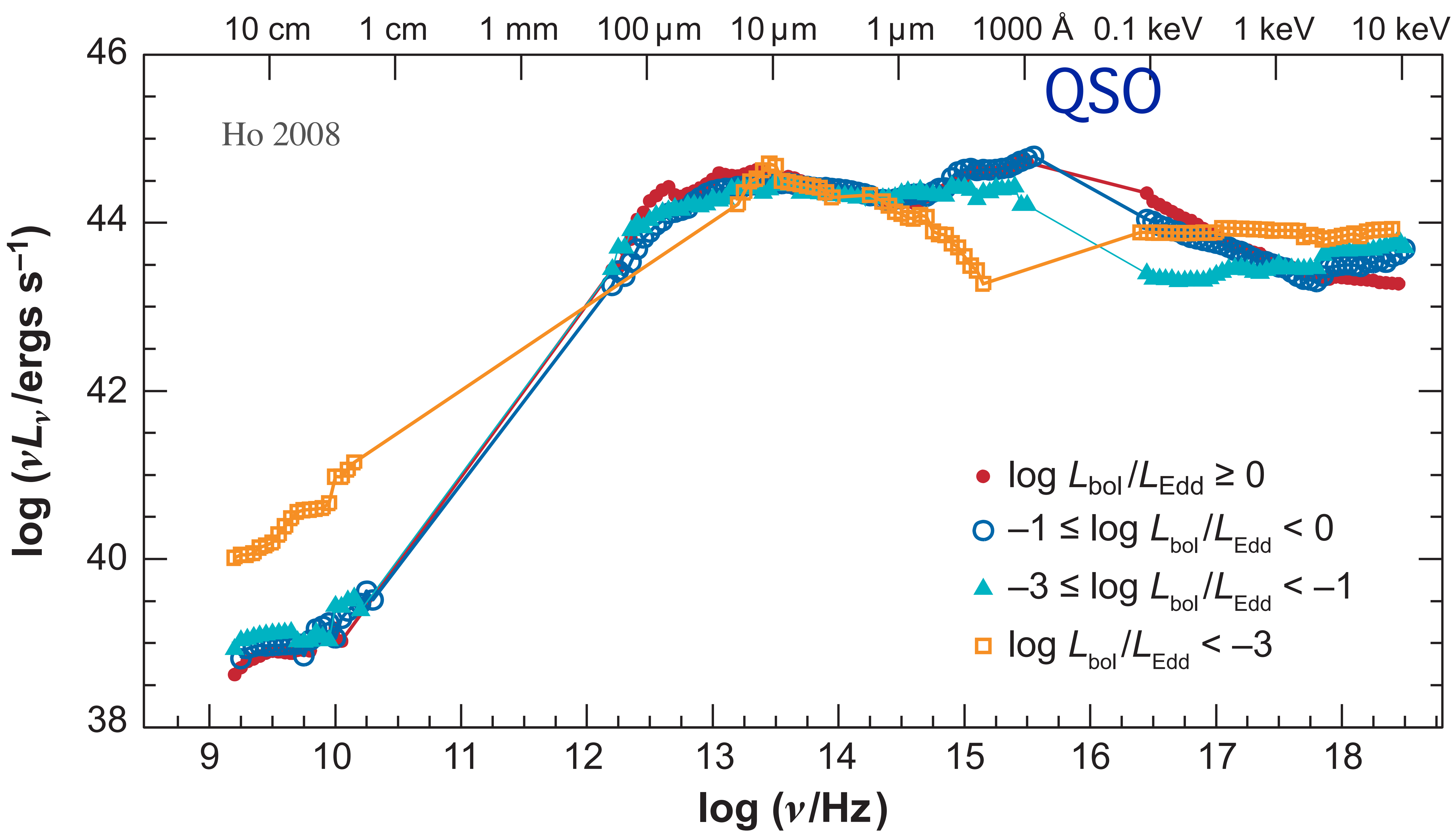
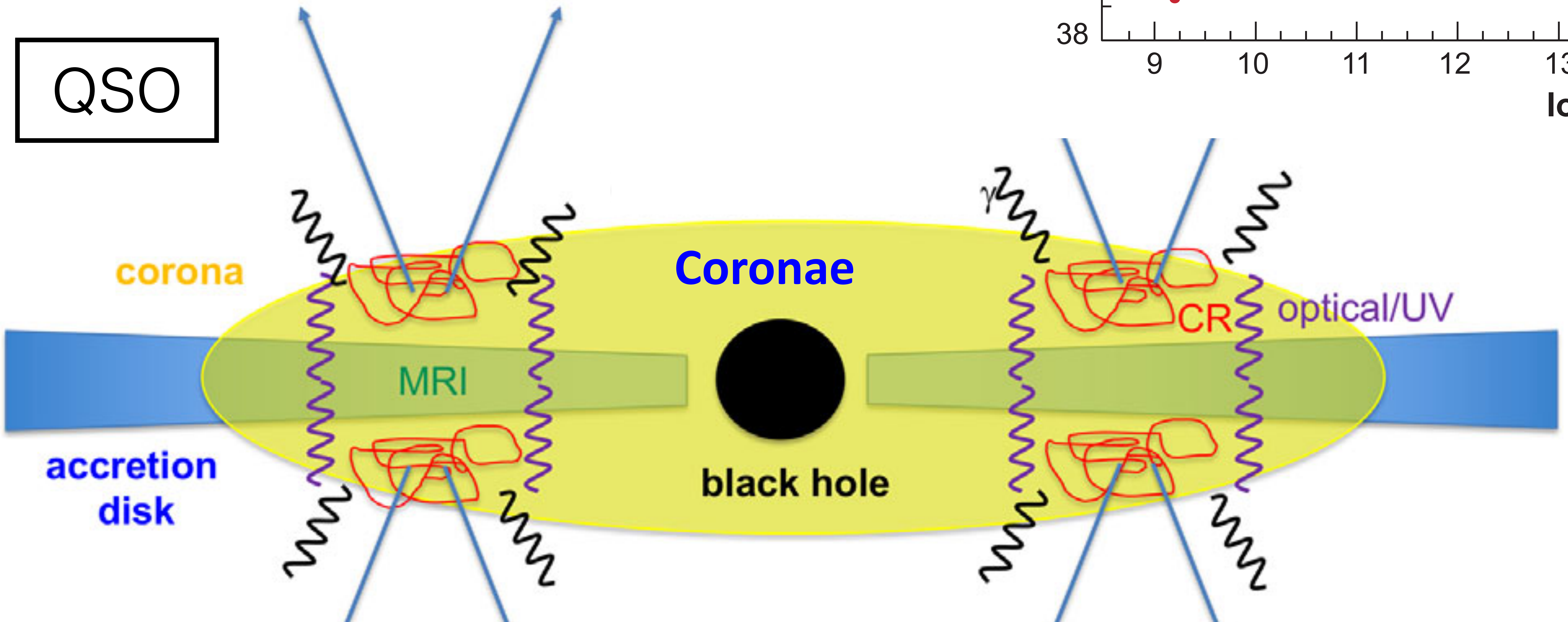
AGN Accretion Flows

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



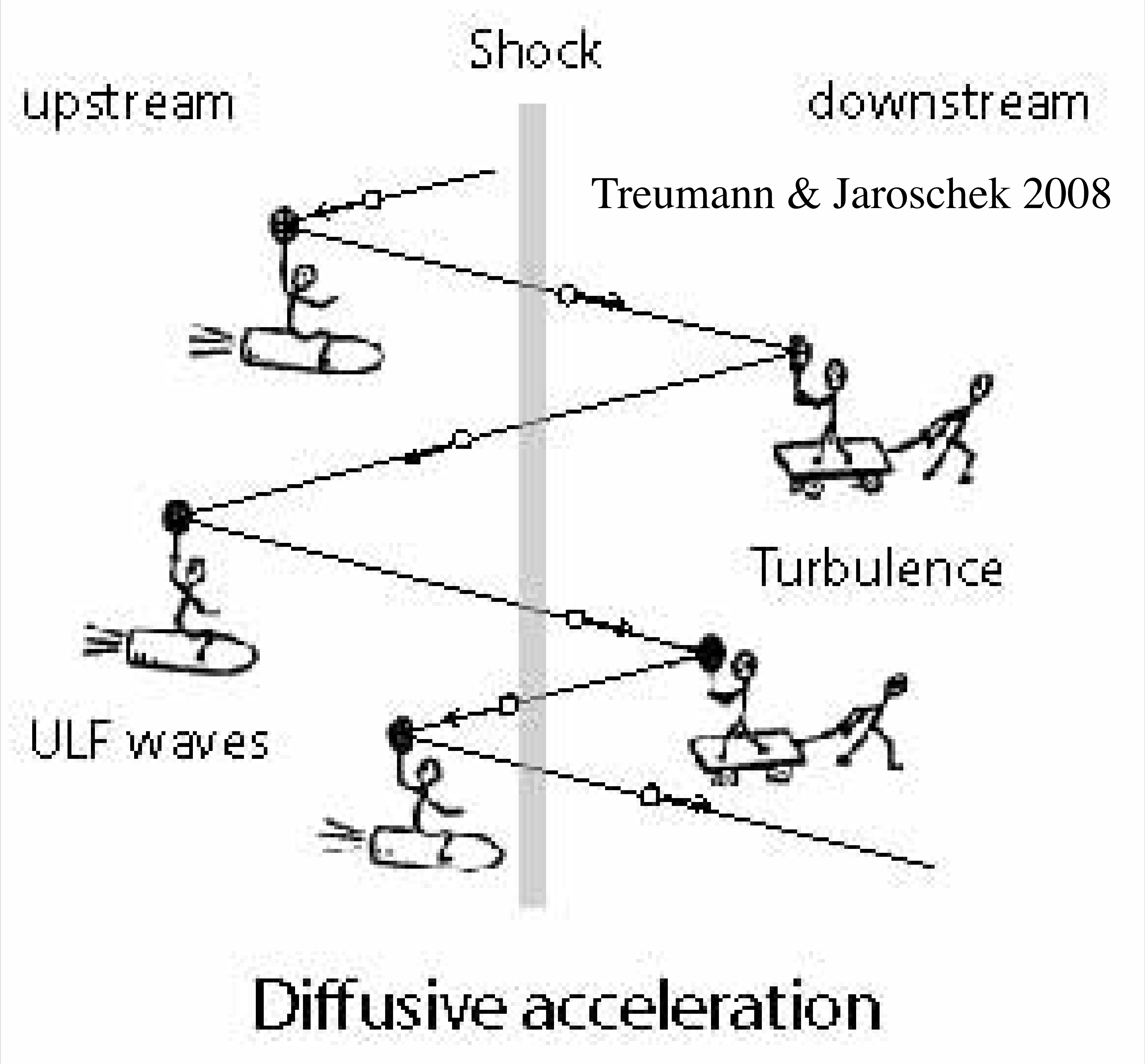
QSO



Cosmic-ray acceleration

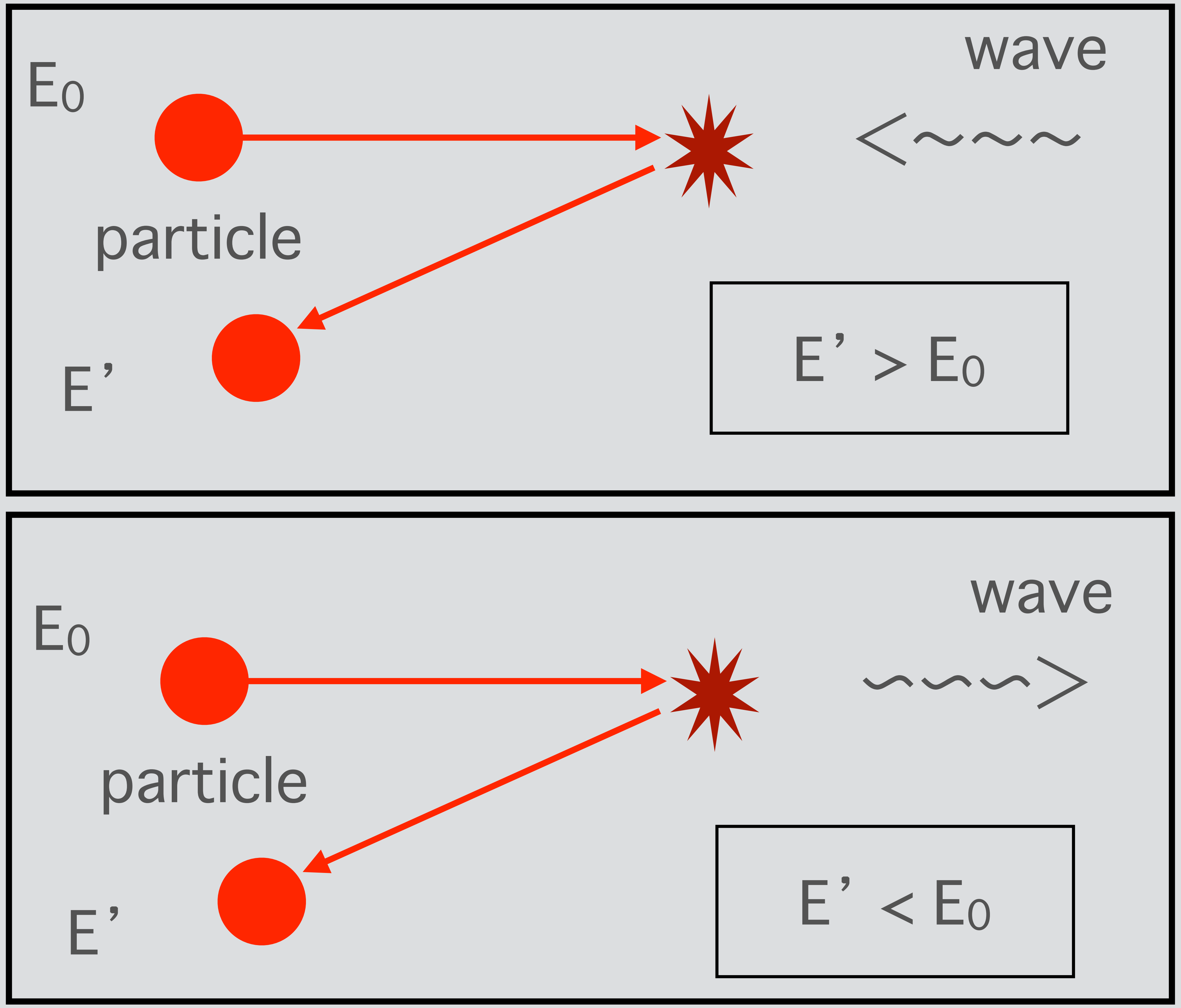
Blandford & Eichler 1987

- Diffusive Shock Acceleration



CRs gain energy by crossing a shock

- Stochastic acceleration in turbulence

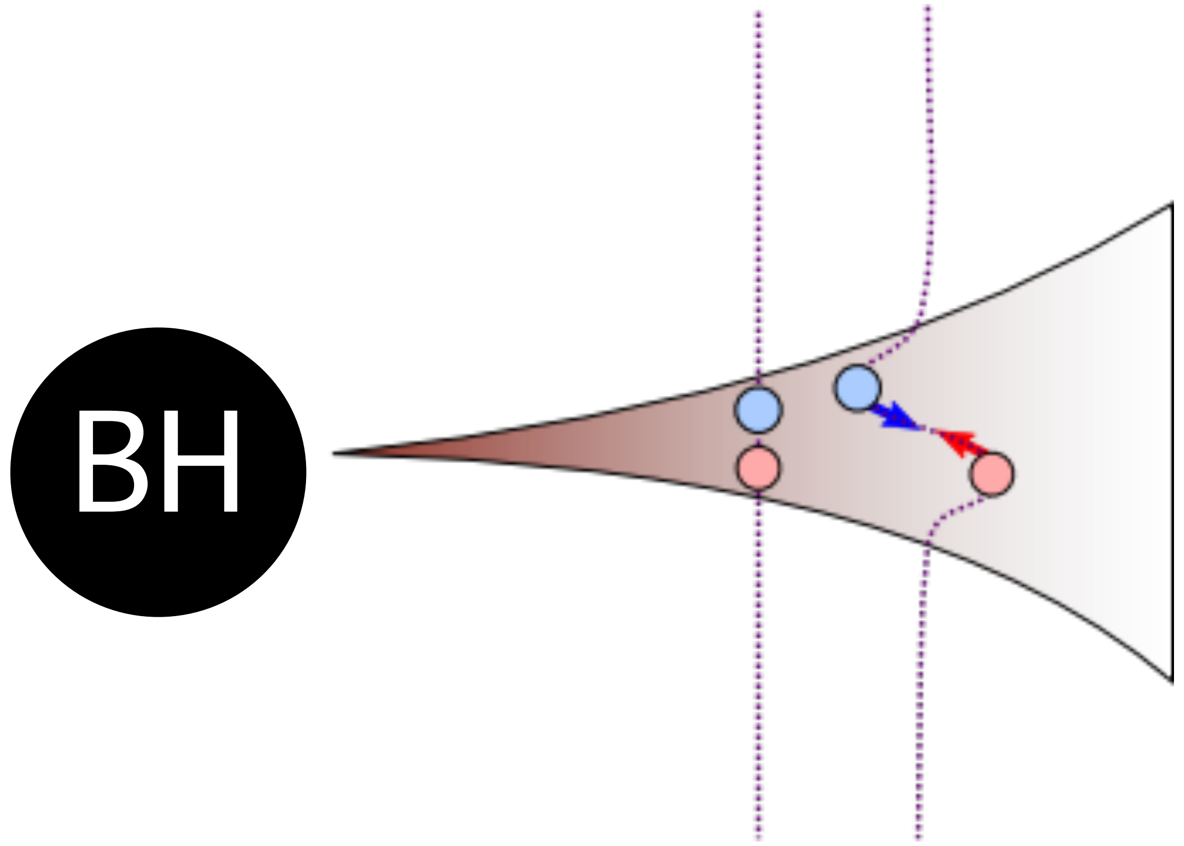


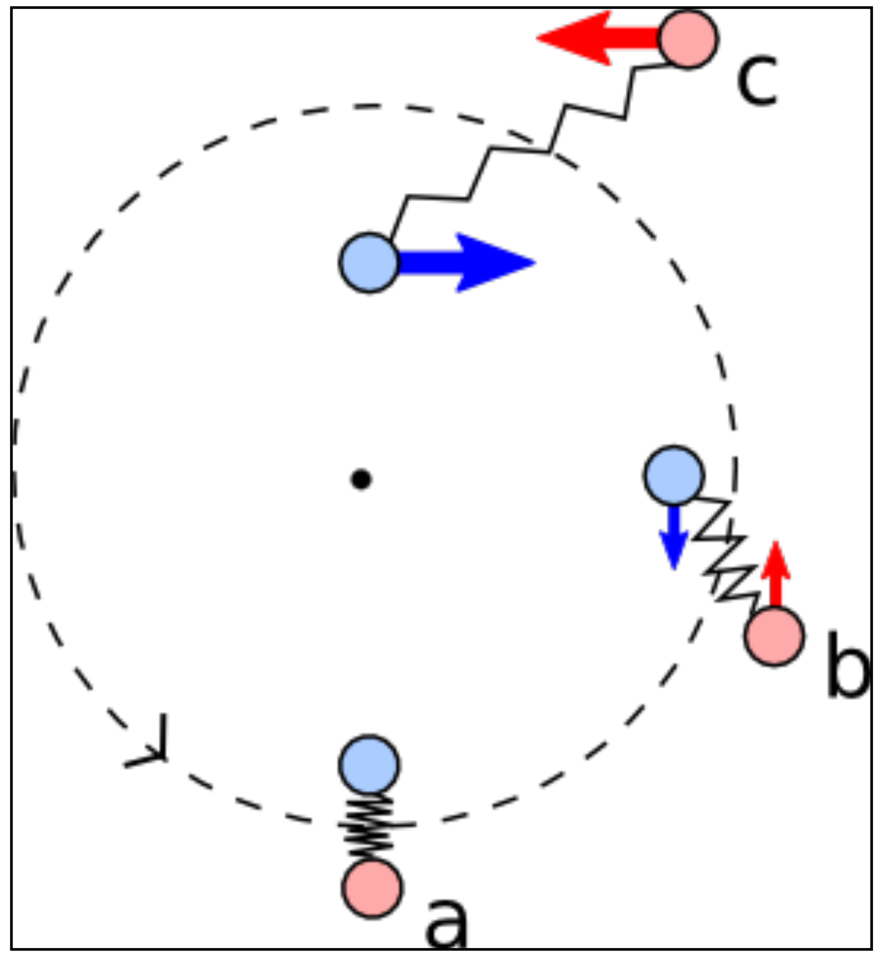
CRs gain energy by interaction with waves

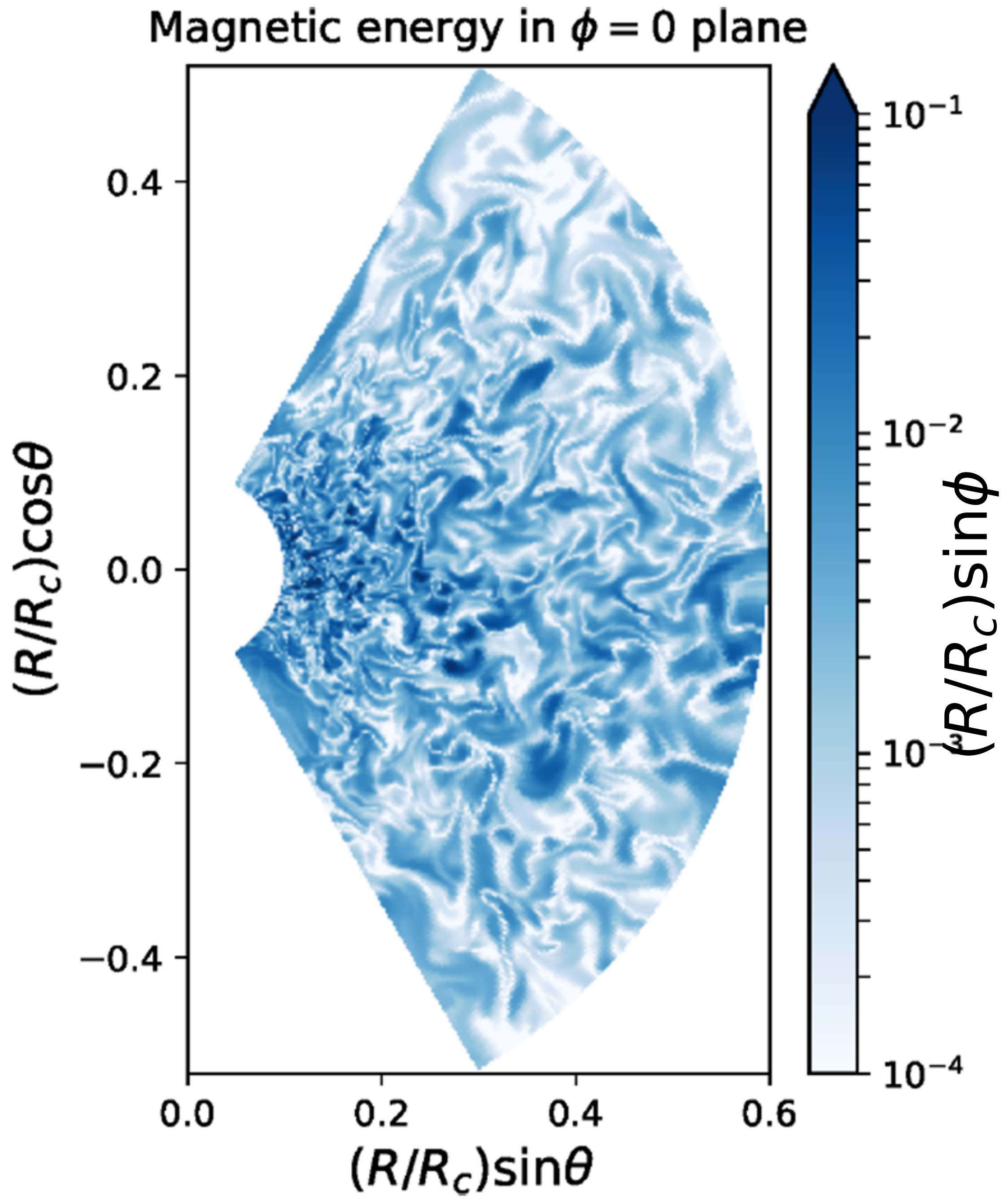
Magneto-Rotational Instability (MRI)

Gas accretion with angular momentum
→ formation of rotationally supported disks

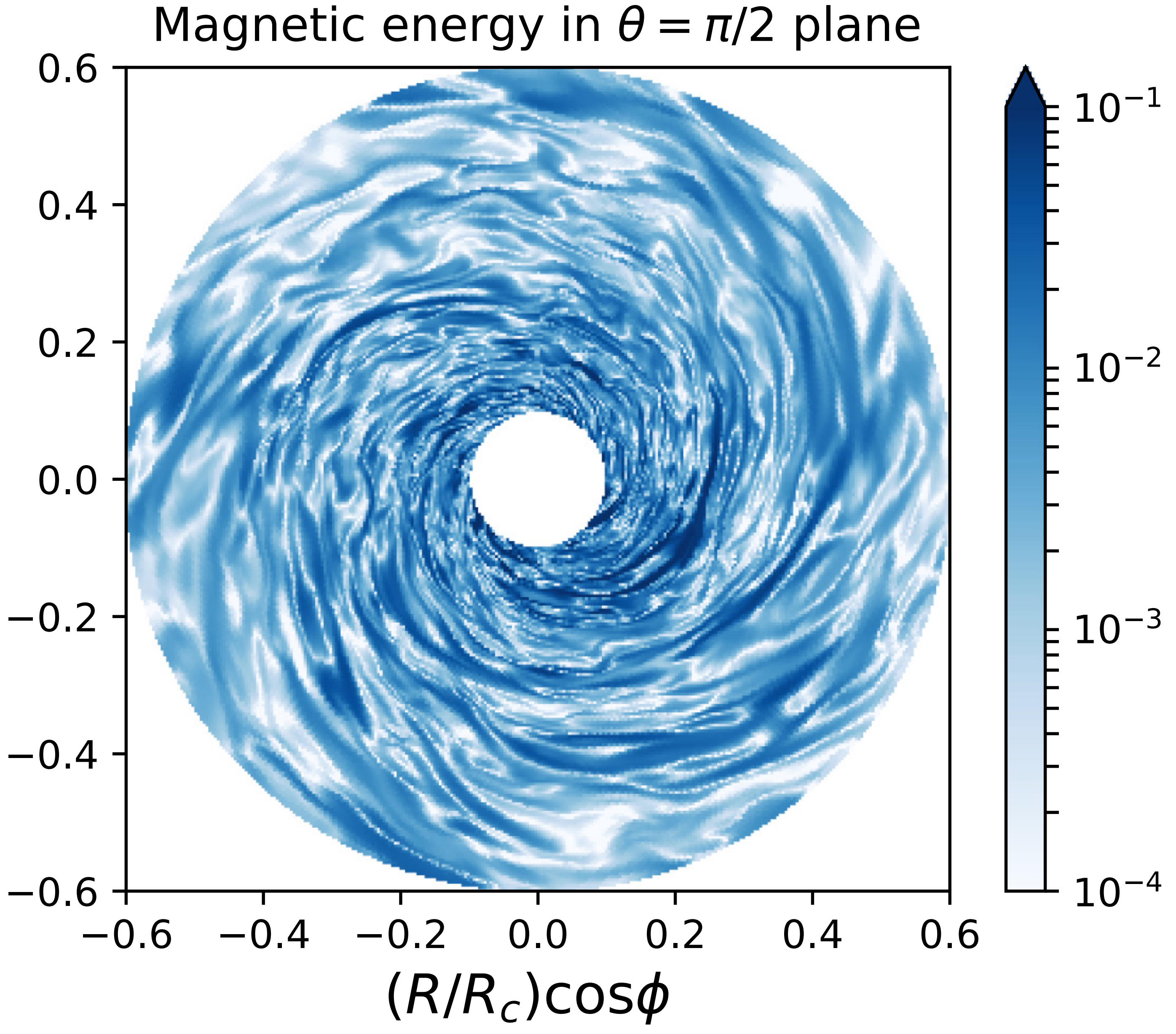
Velikhov '59
Balbus & Hawley '91







Kimura et al. 2019

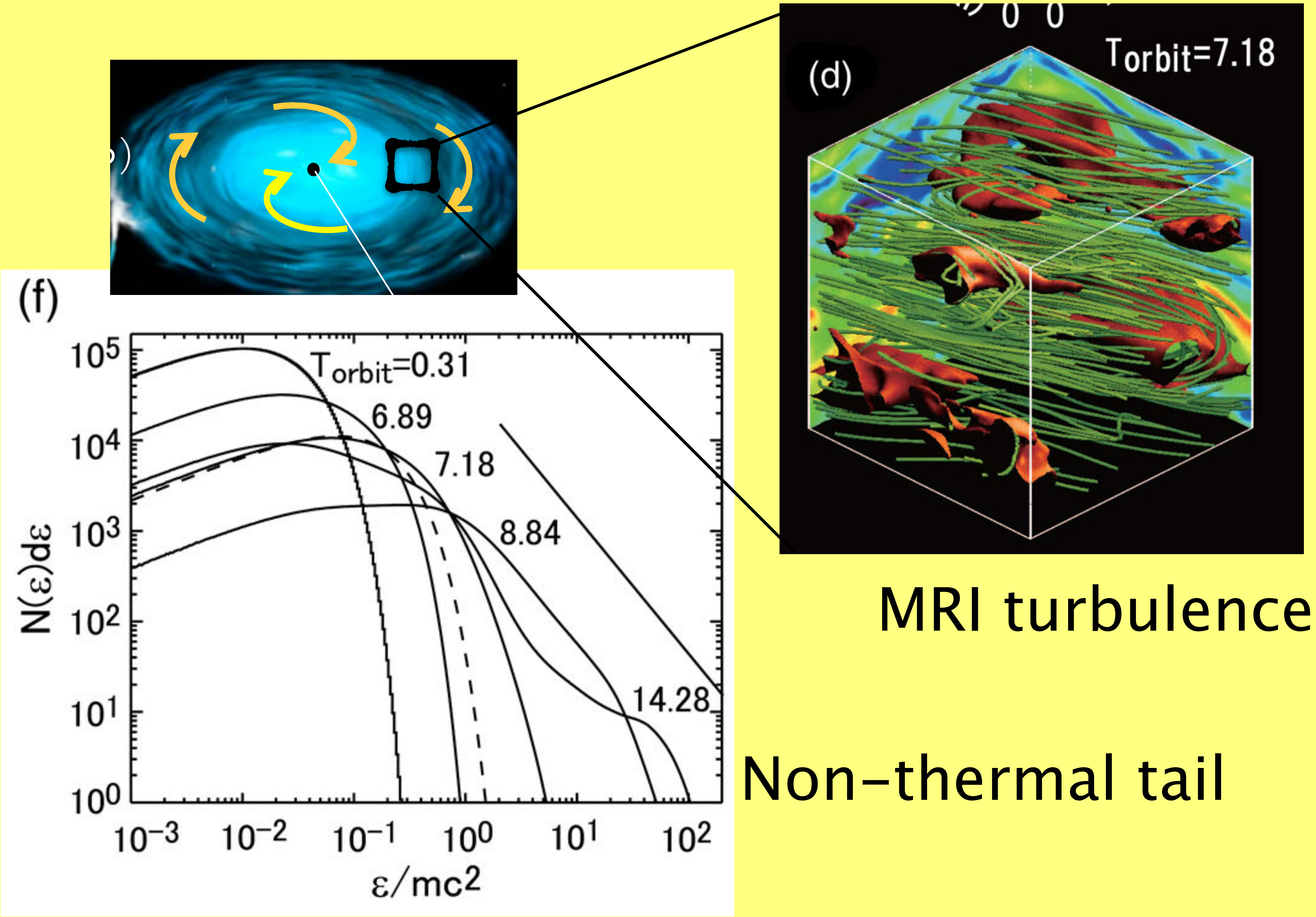


MRI :mechanism of
angular momentum transport

Particle Acceleration in Corona

Particle-In-Cell Simulations in shearing box

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

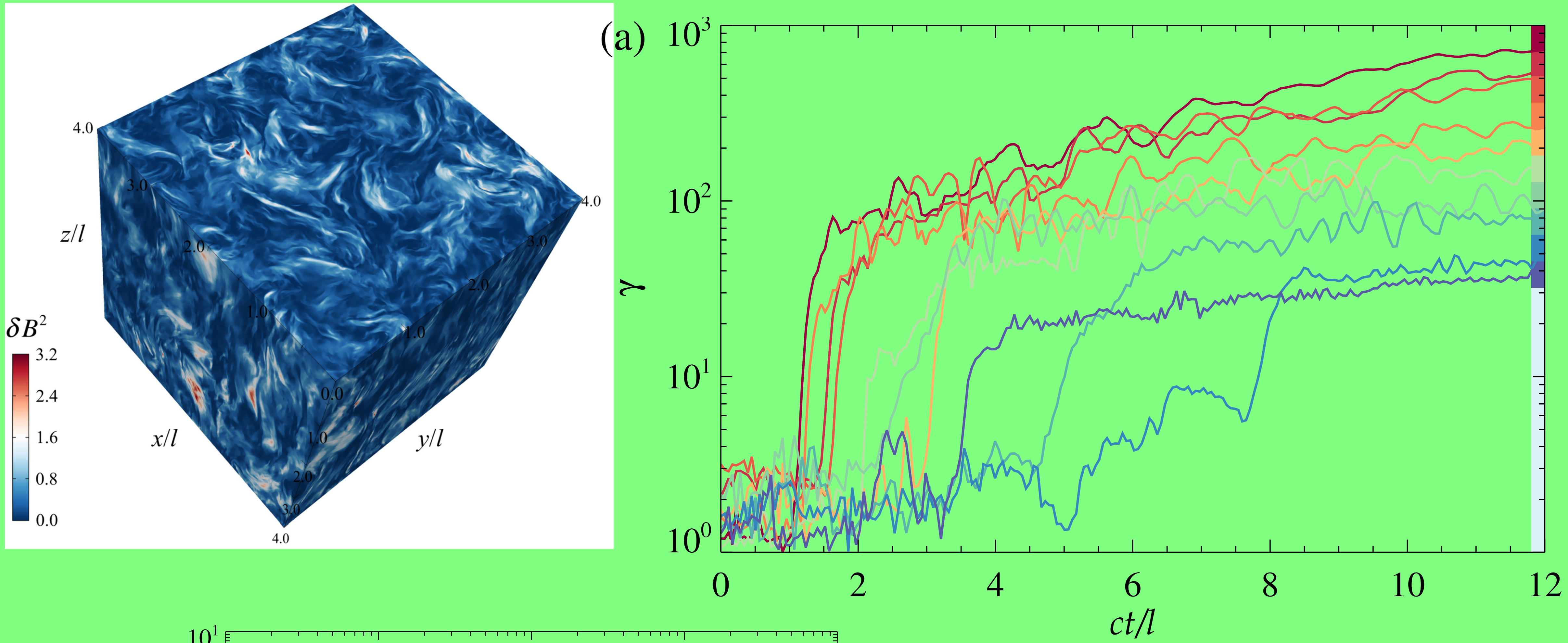


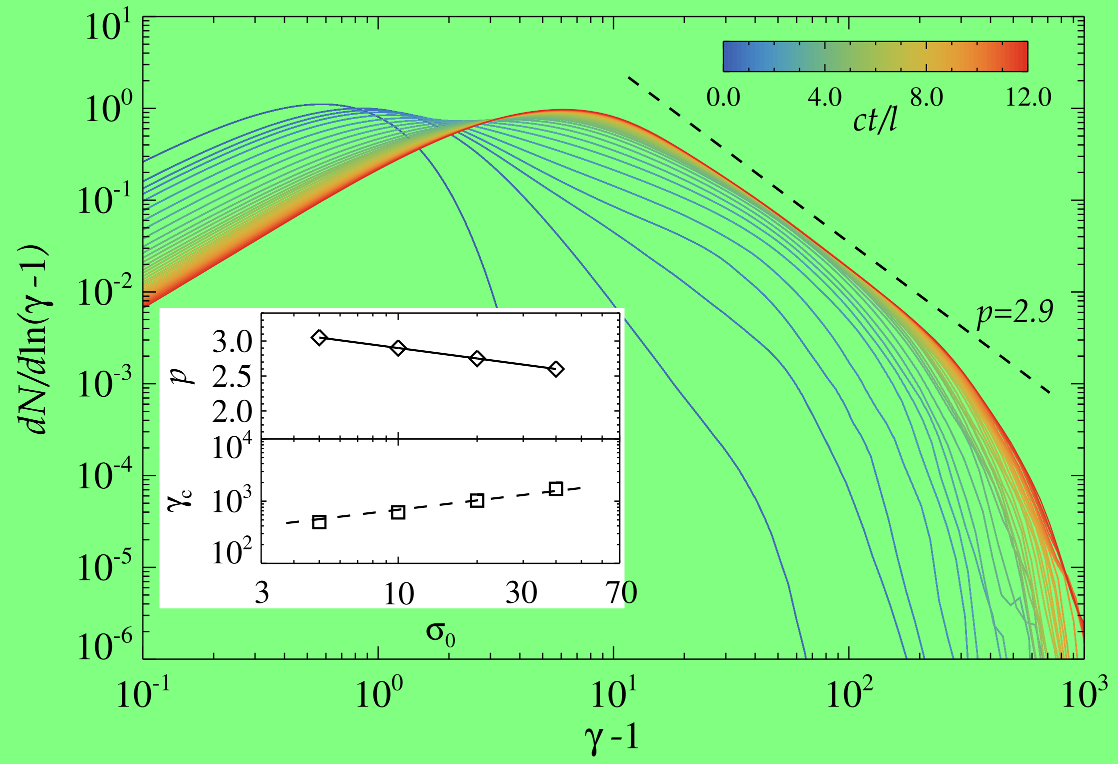
MRI turbulence

Non-thermal tail

Particle-In-Cell Simulations with turbulence

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





Stochastic acceleration

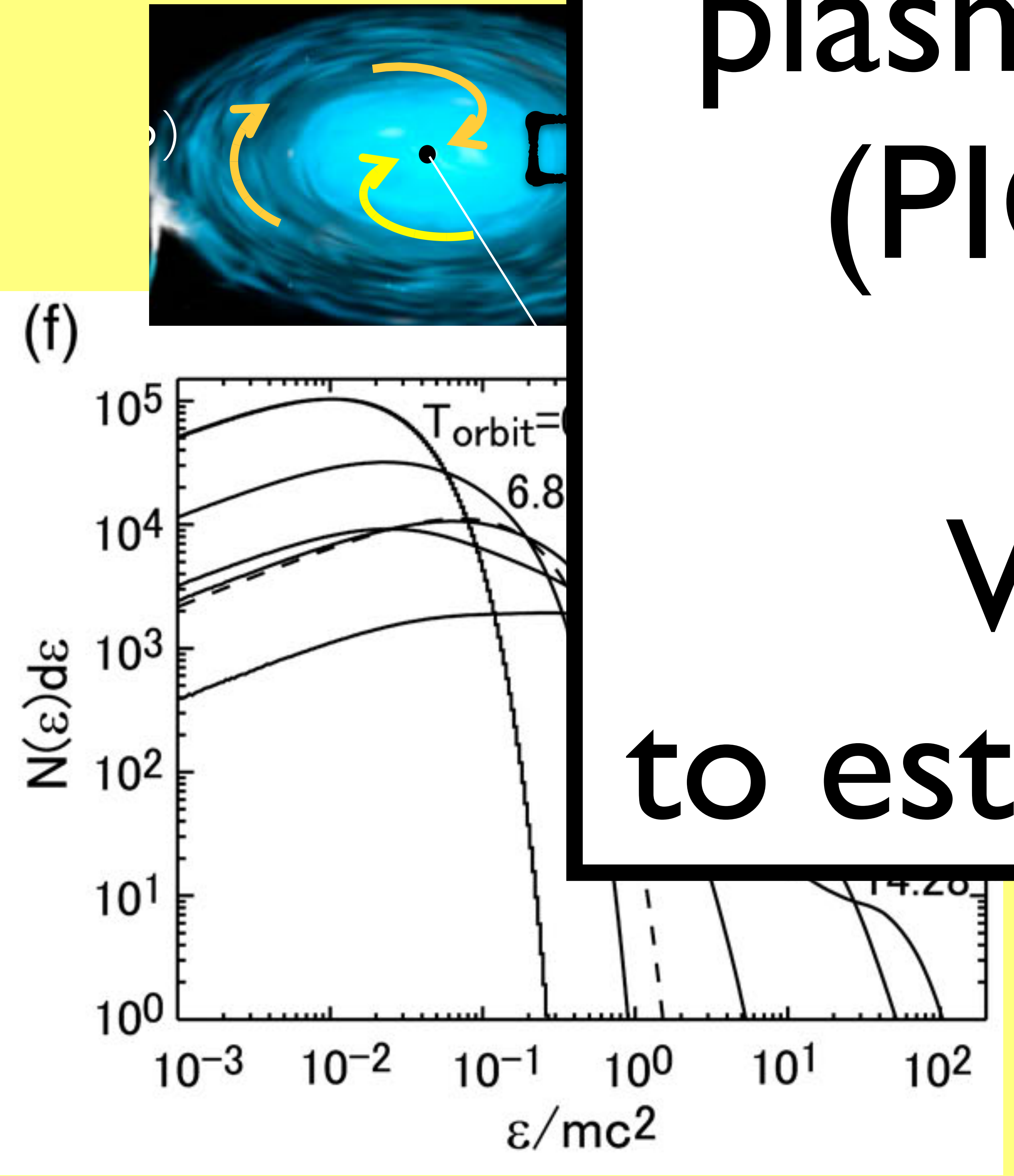
Power-law tail

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

Particle Acceleration in Corona

Particle-In-Cell Simulations in shearing box

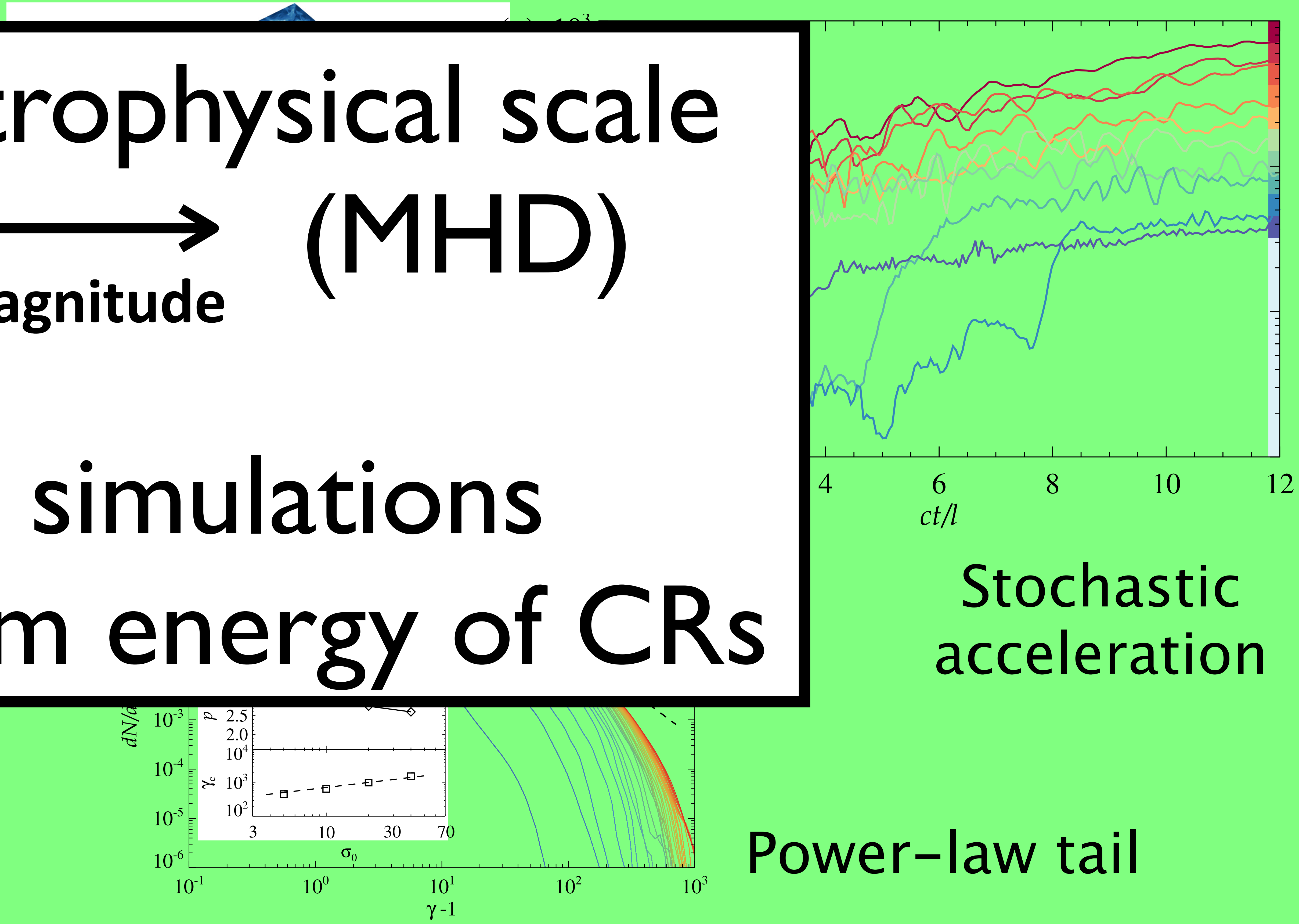
Hoshino 2013, 2015; Riquelme et al. 2012; Kuntz et al. 2016



Non-thermal tail

Particle-In-Cell Simulations with turbulence

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



Stochastic acceleration

Power-law tail

plasma scale << astrophysical scale

(PIC) ⟷ (MHD)

~ **10 orders of magnitude**

We need MHD simulations to estimate maximum energy of CRs

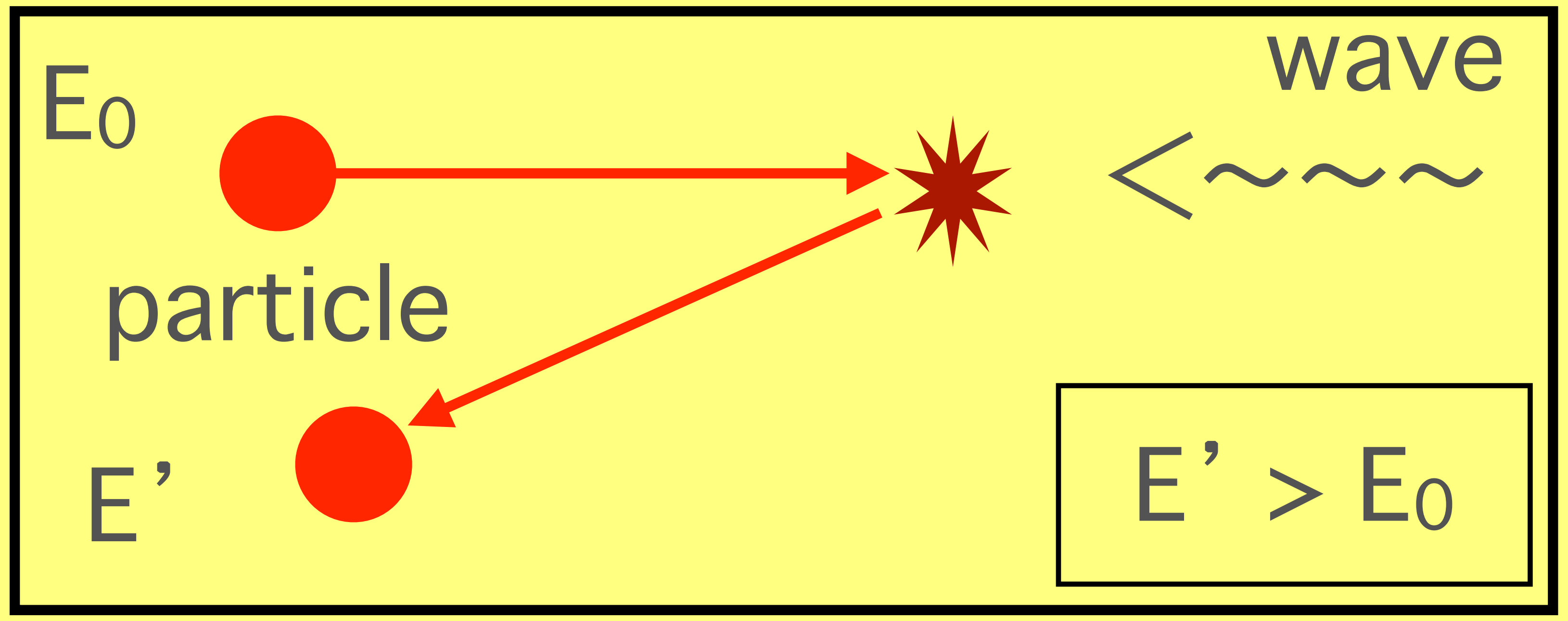
Magnetic reconnection → relativistic particle production

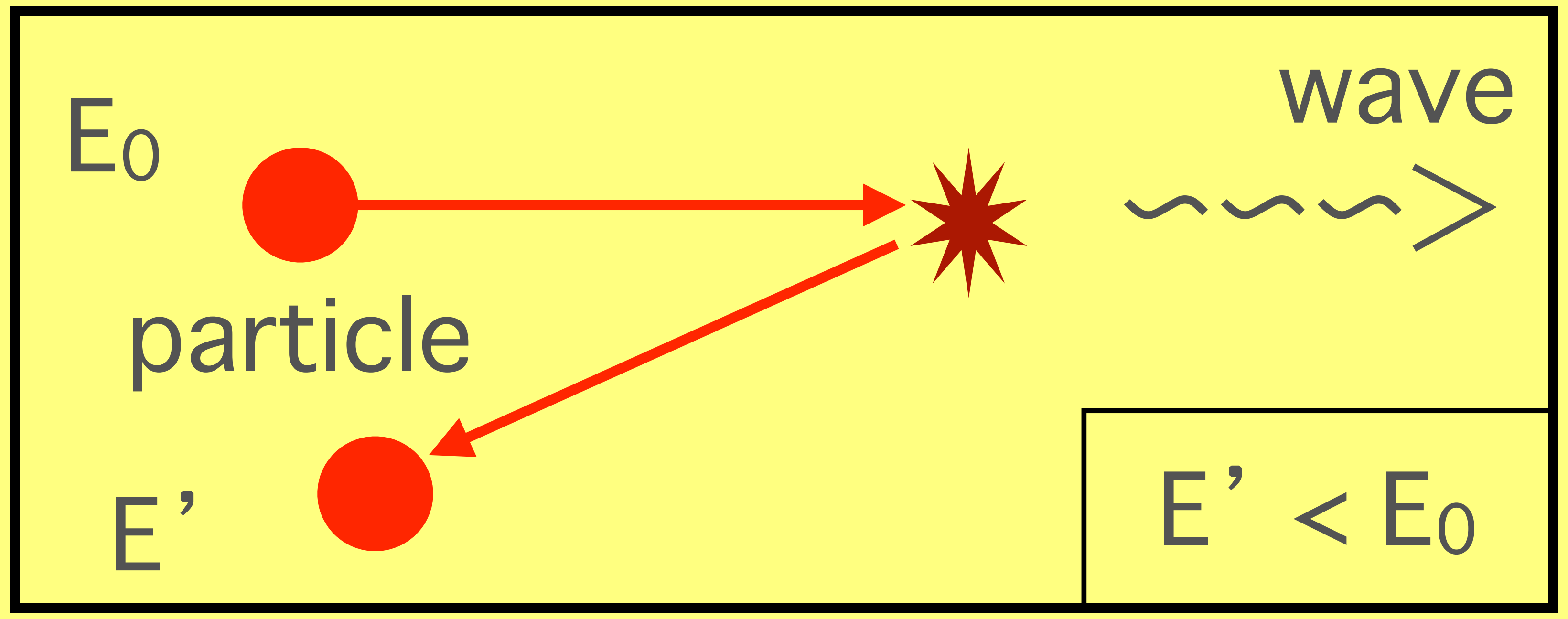
Interaction with Turbulence → further energization

Stochastic Acceleration by MHD Turbulence

CR Acceleration Theory

e.g.) Fermi 1949





Some gain E, others lose E

→diffusion in E space

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

Does this equation describe evolution of cosmic-ray energy distribution?

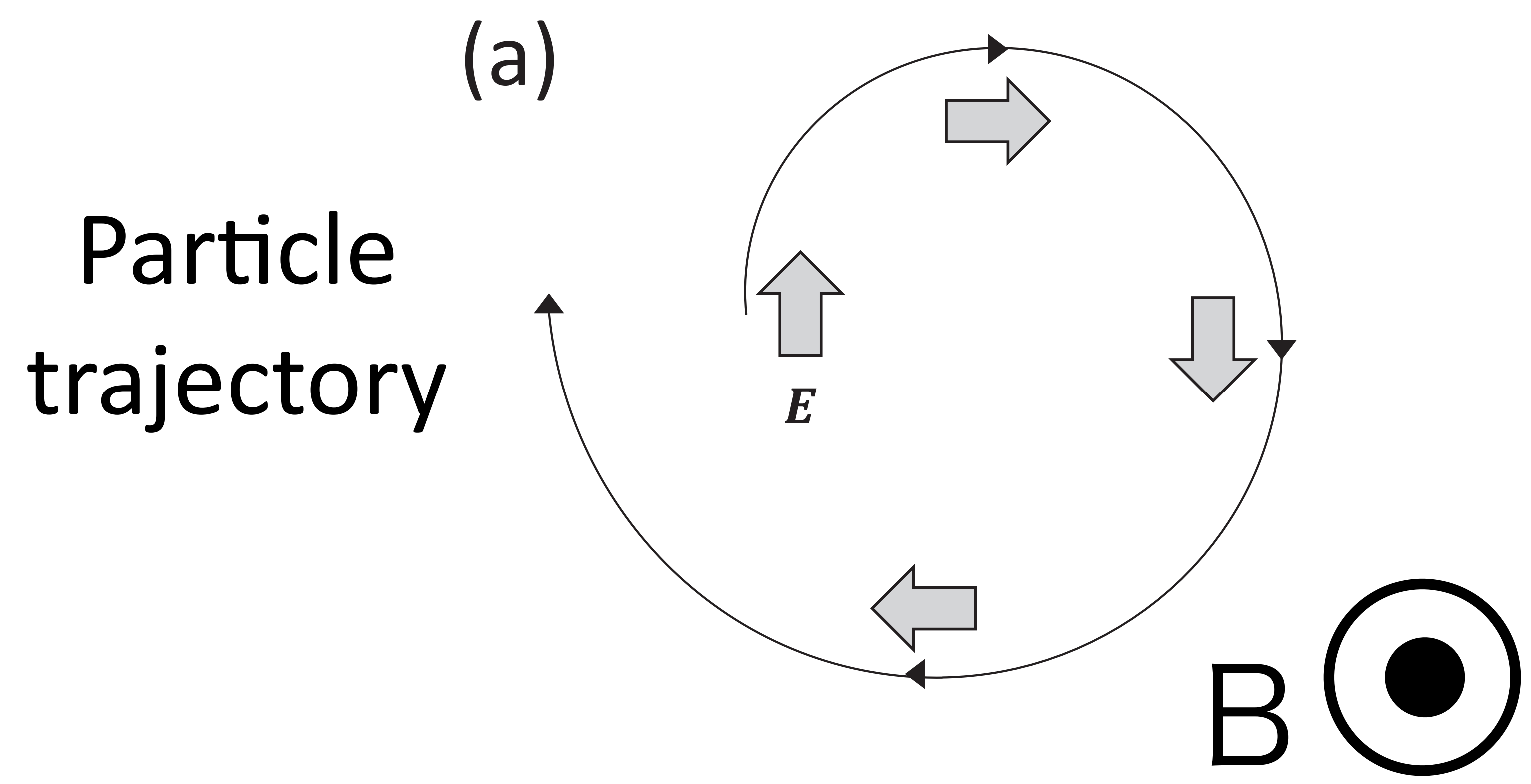
Wave-particle Interaction

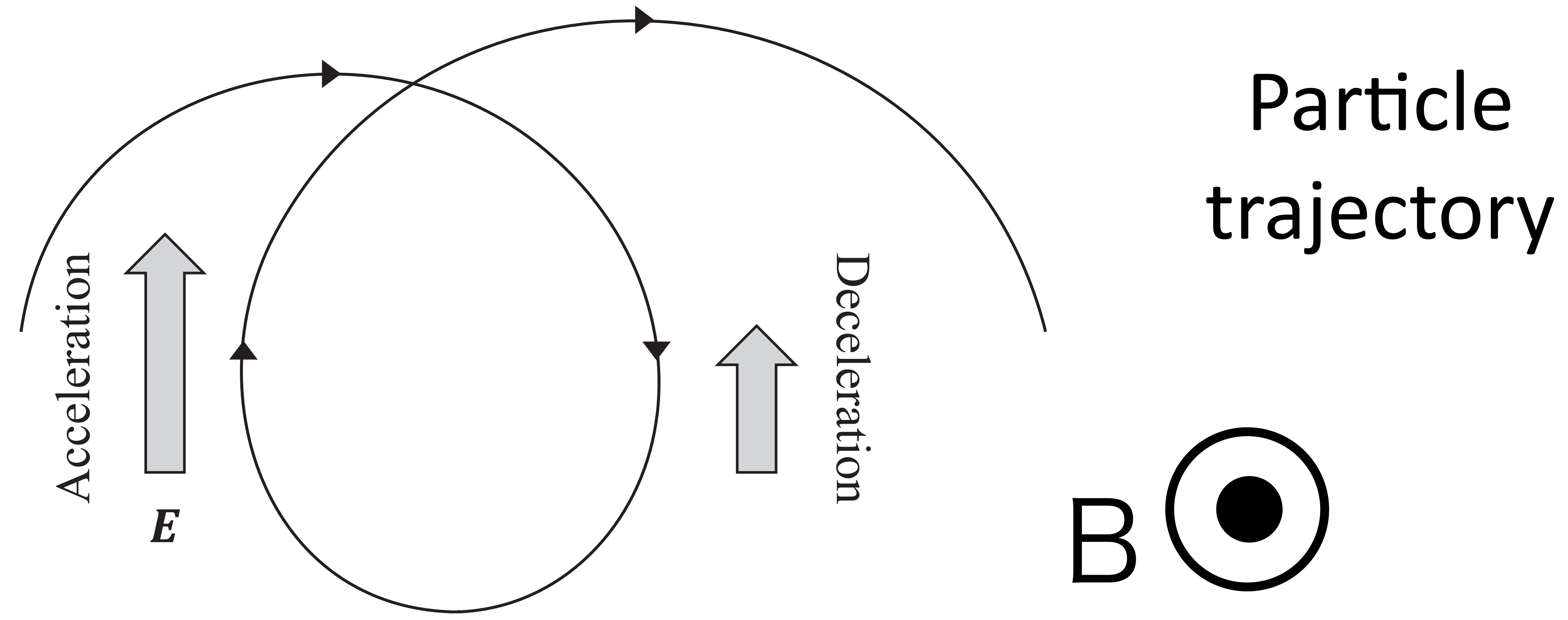
- **Resonant Condition:** $\omega - k_{\parallel} v_{\parallel} = n\Omega_L$

e.g.) Teraki & Asano 2019

- **Gyro-resonance**：$n = \pm 1, \ \pm 2, \ldots$
  - $n = \pm 1$ —> $\omega - k_{\parallel} v_{\parallel} = \Omega_L$
  - $v_{\parallel} \gg \omega / k_{\parallel}$ —> $k_{\parallel} \approx r_L$
    → Interaction rate depends on scale
  - $D_{pp} \propto \beta_A^2 p^q \qquad (P_k \propto k^{-q})$

- **Transit Time Damping (TTD)**：$n = 0$
  - Resonant condition: $\omega / k_{\parallel} \propto v_{\parallel}$
  - Inefficient for $v_{\parallel} \gg \omega / k_{\parallel}$?
    →Resonant broadening
  - $D_{pp} \propto \beta_{\rm turb}^2 p^2$





MHD simulations + Test Particle Simulations

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

Stone et al. 2020

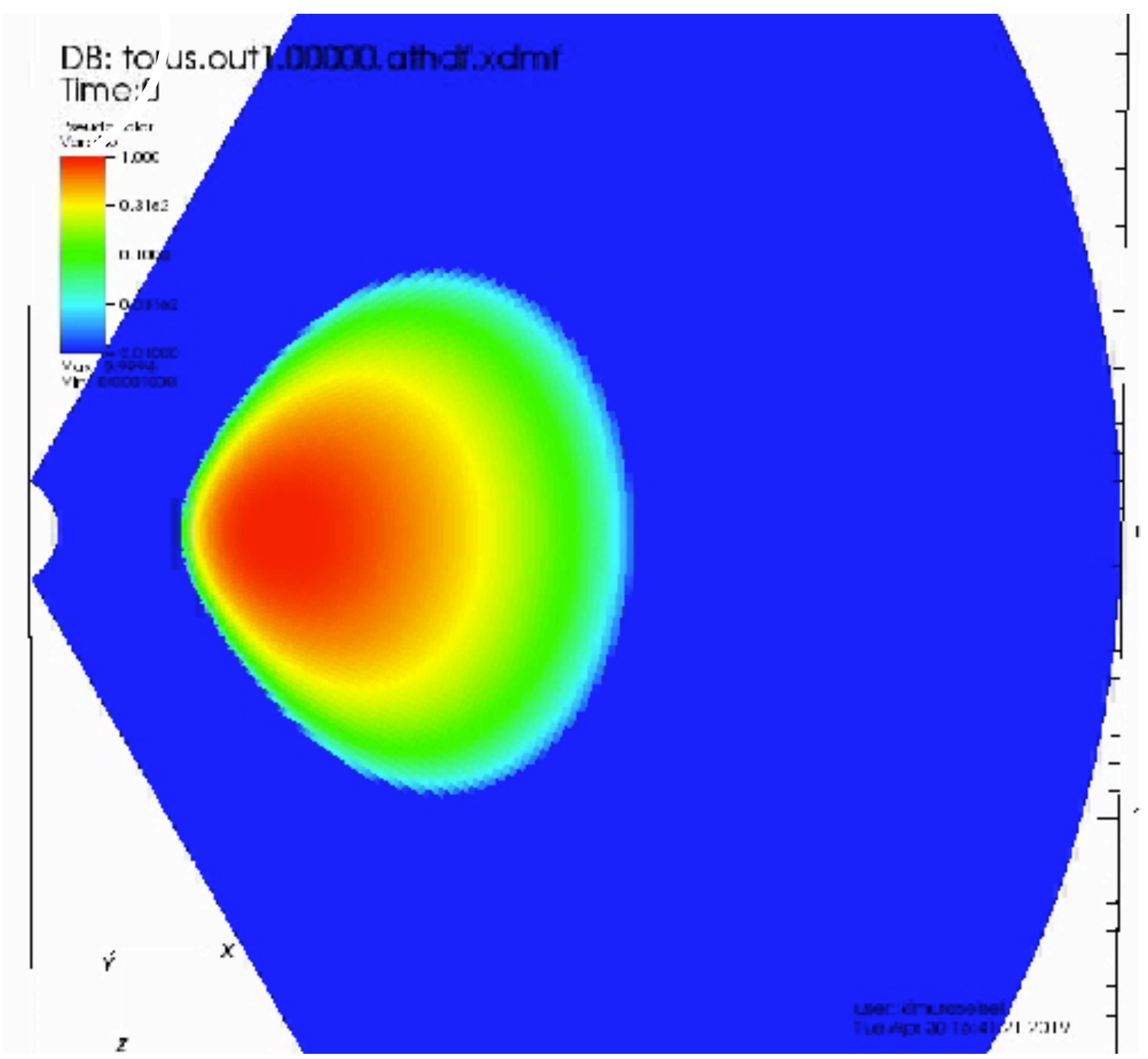
SSK et al. 2019 MNRAS

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

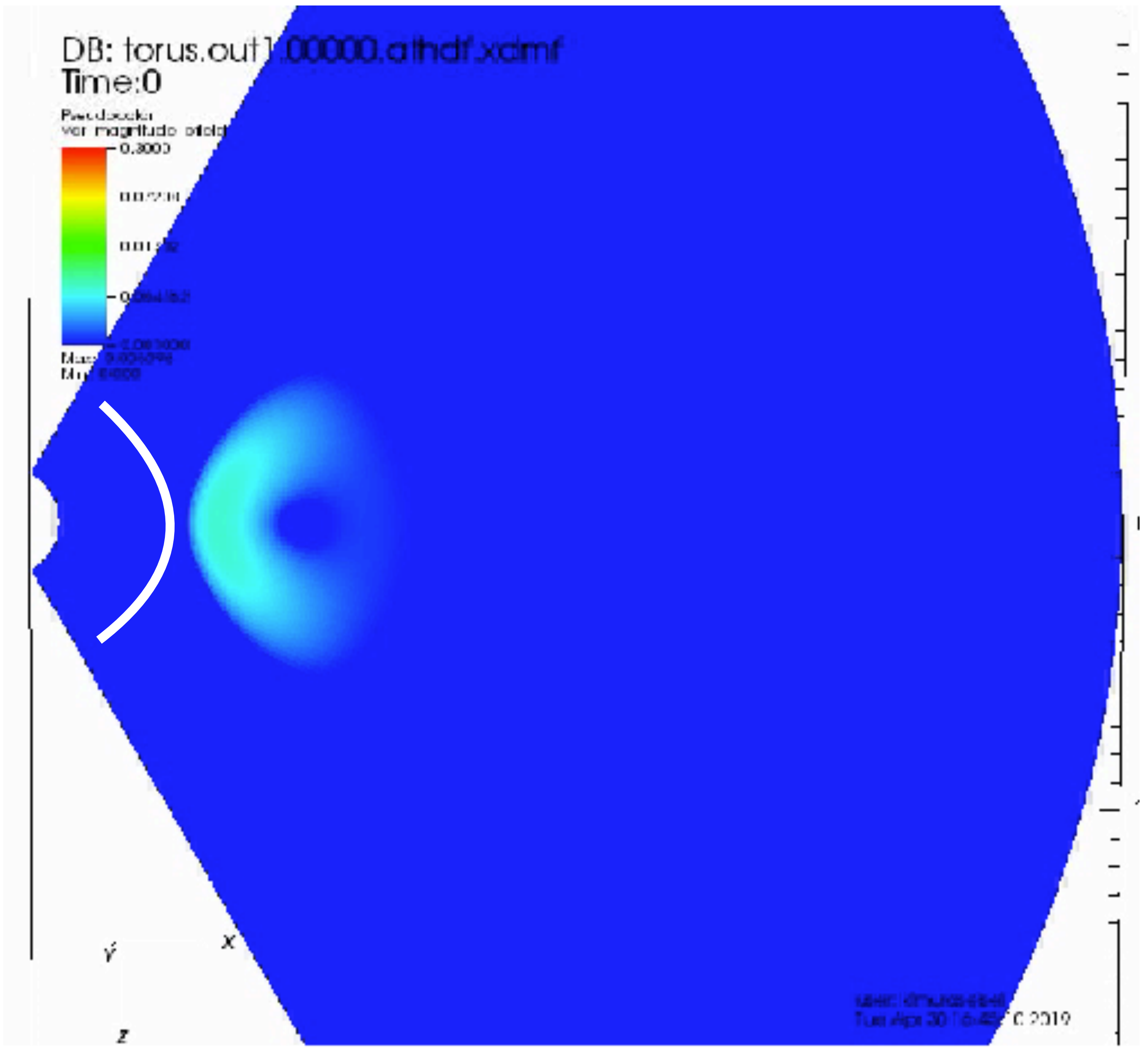
SSK et al. in prep

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

Density



Magnetic field



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

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

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

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

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

Solve equation of motion for 10^4 mono-energetic particles in MHD data and discuss evolution of the distribution function

MHD Data set

	Low dissipation (High-resolution / 3rd-order accuracy)	High dissipation (low-resolution / 2nd-order accuracy)
Snapshot (static EM field)	Model C (This work)	**Model D (SSK et al. 2019)**
Post process (moving EM field)	**Model A (This work)**	Model B (This work)

MHD Data set

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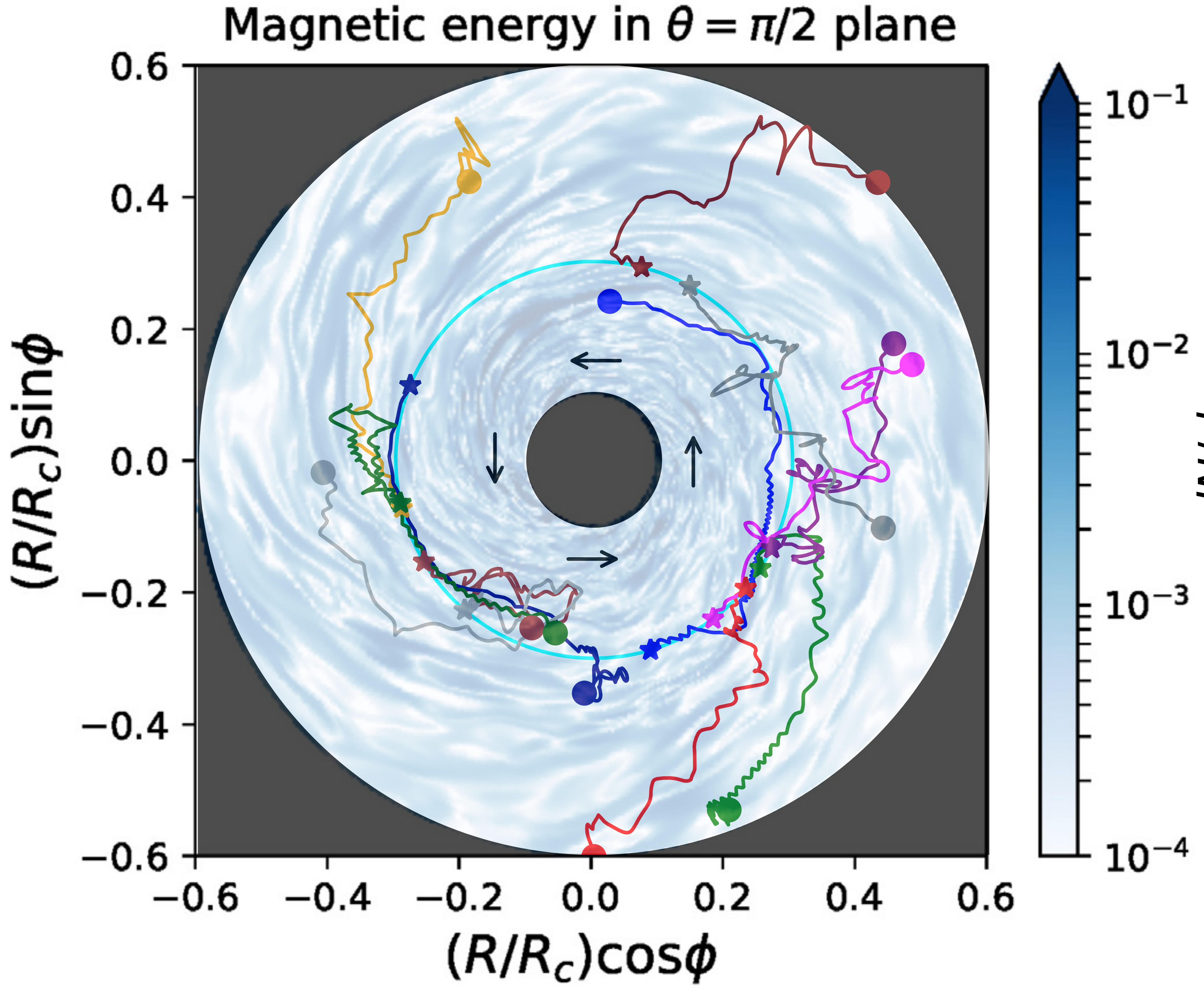
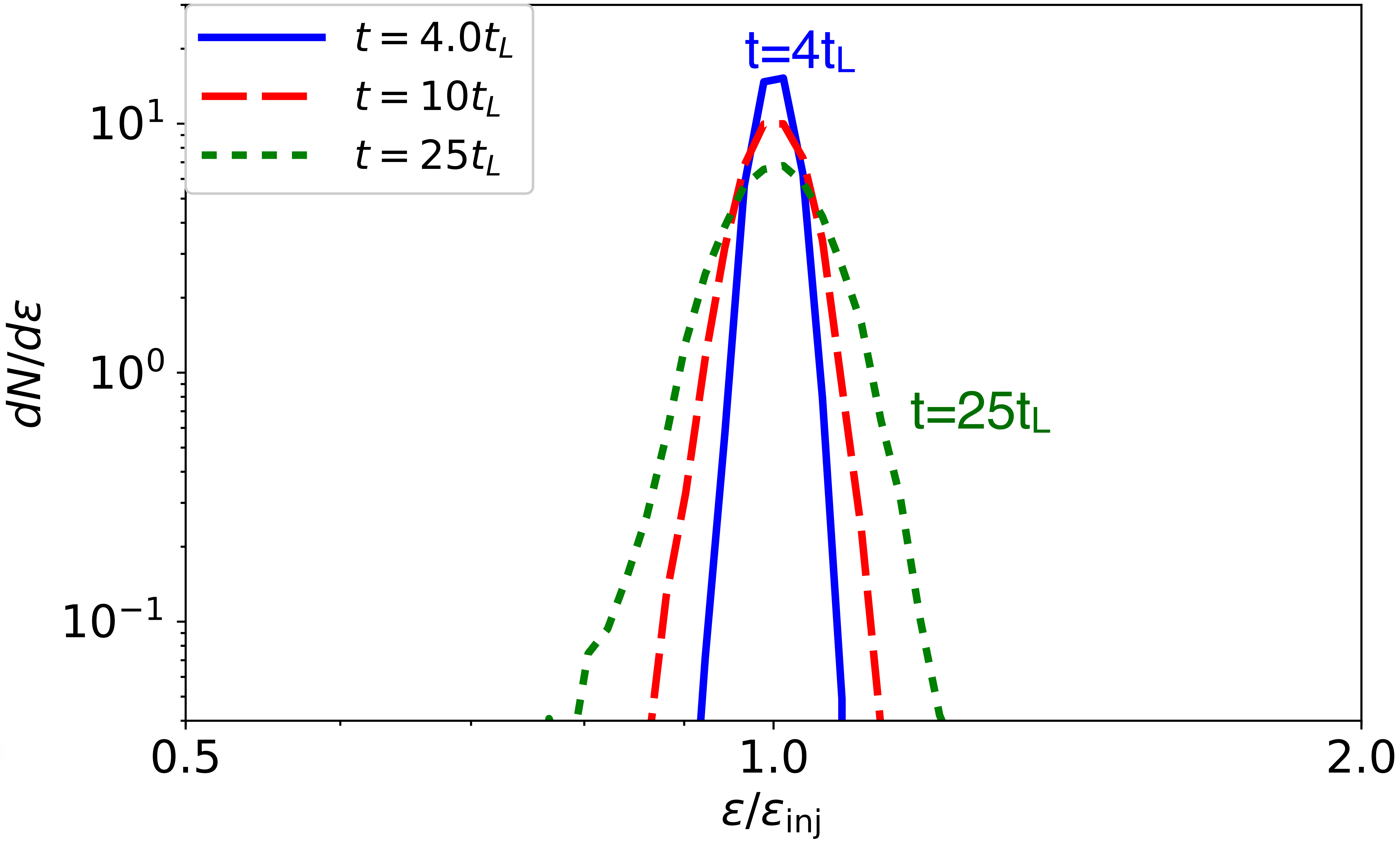
Diffusion in Energy Space





SSK et al. 2019 MNRAS

- Particles randomly change their motions by interaction with turbulence
- $B_\phi > B_r$ —> particles move ϕ direction

- Evaluate particle energies in fluid rest frame
- Evolution of Energy distribution function can be written by diffusion in energy space

Diffusion Coefficient

- If evolution is written by

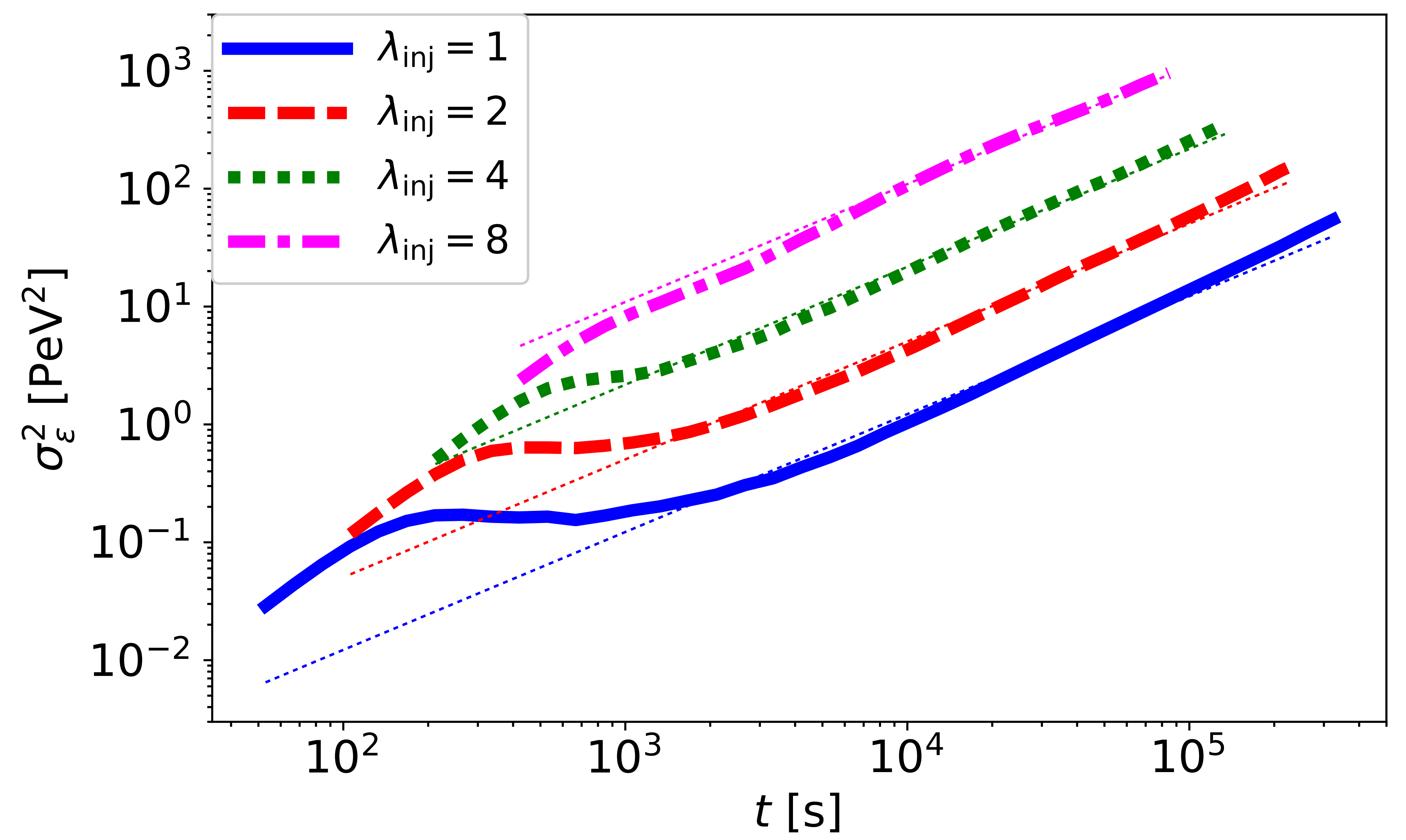
$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p}\right)$$

we can obtain the relation: $\sigma_\epsilon^2 \approx 2 D_{\epsilon_{\rm ini}} t\,.$

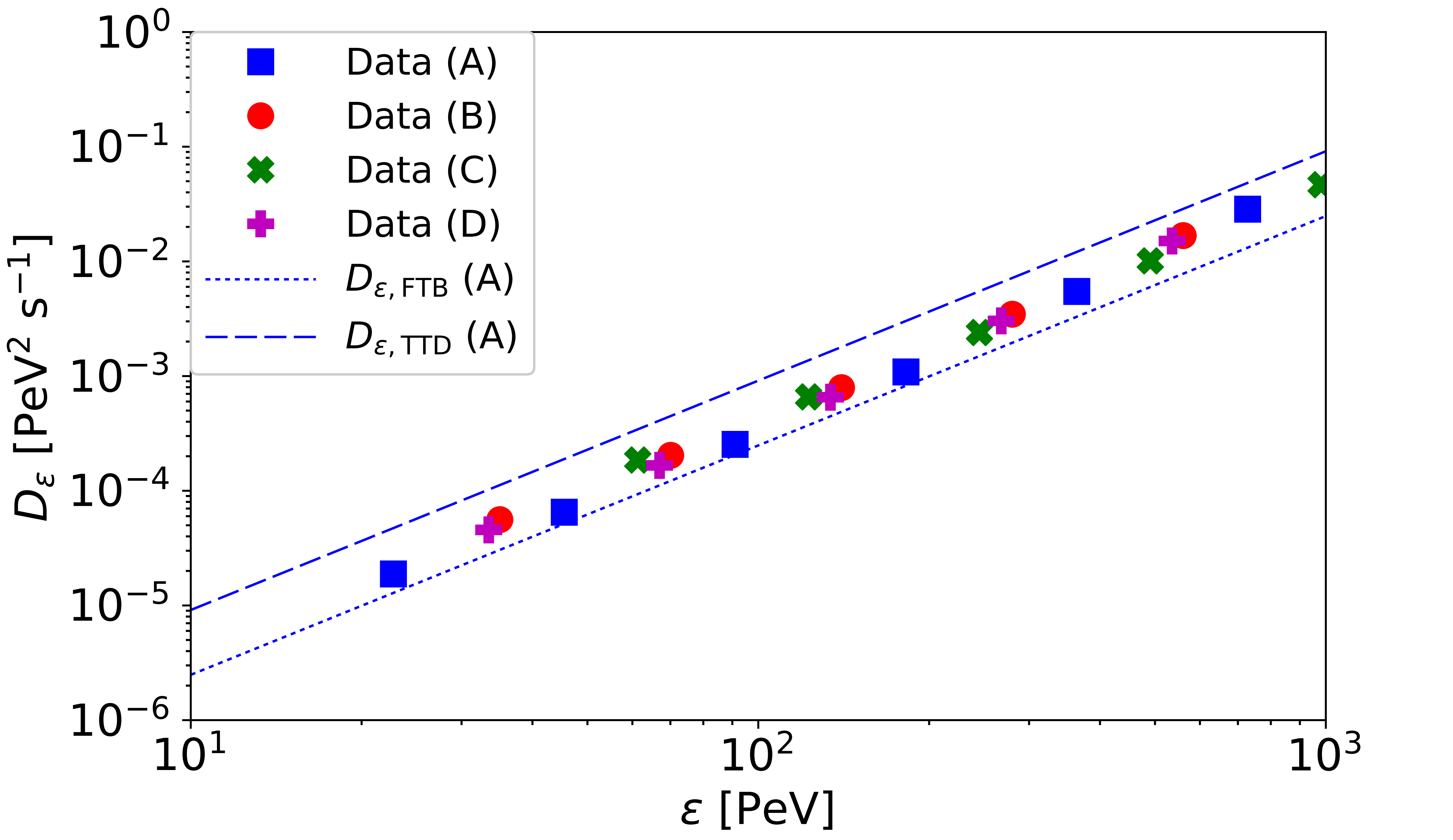
- From the power spectrum of MHD simulation, the largest eddy has most of the turbulent power
→ interaction timescale $t_{\rm int} \sim H/c$
& energy change rate $\Delta\epsilon \sim (V_{\rm turb}/c)^2\epsilon$
↓

$$D_{\epsilon,{\rm FTB}} \approx \frac{1}{3}\frac{\Delta\epsilon^2}{t_{\rm int}} \sim \frac{4\epsilon^2}{3}\frac{c}{L_{\rm tur}}\left(\frac{V_{R,{\rm tur}}}{c}\right)^2 \propto \epsilon^2 M^{-1}\chi^{-2}$$

All the CR particles interact with eddies of largest scales?



SSK et al. 2019 MNRAS



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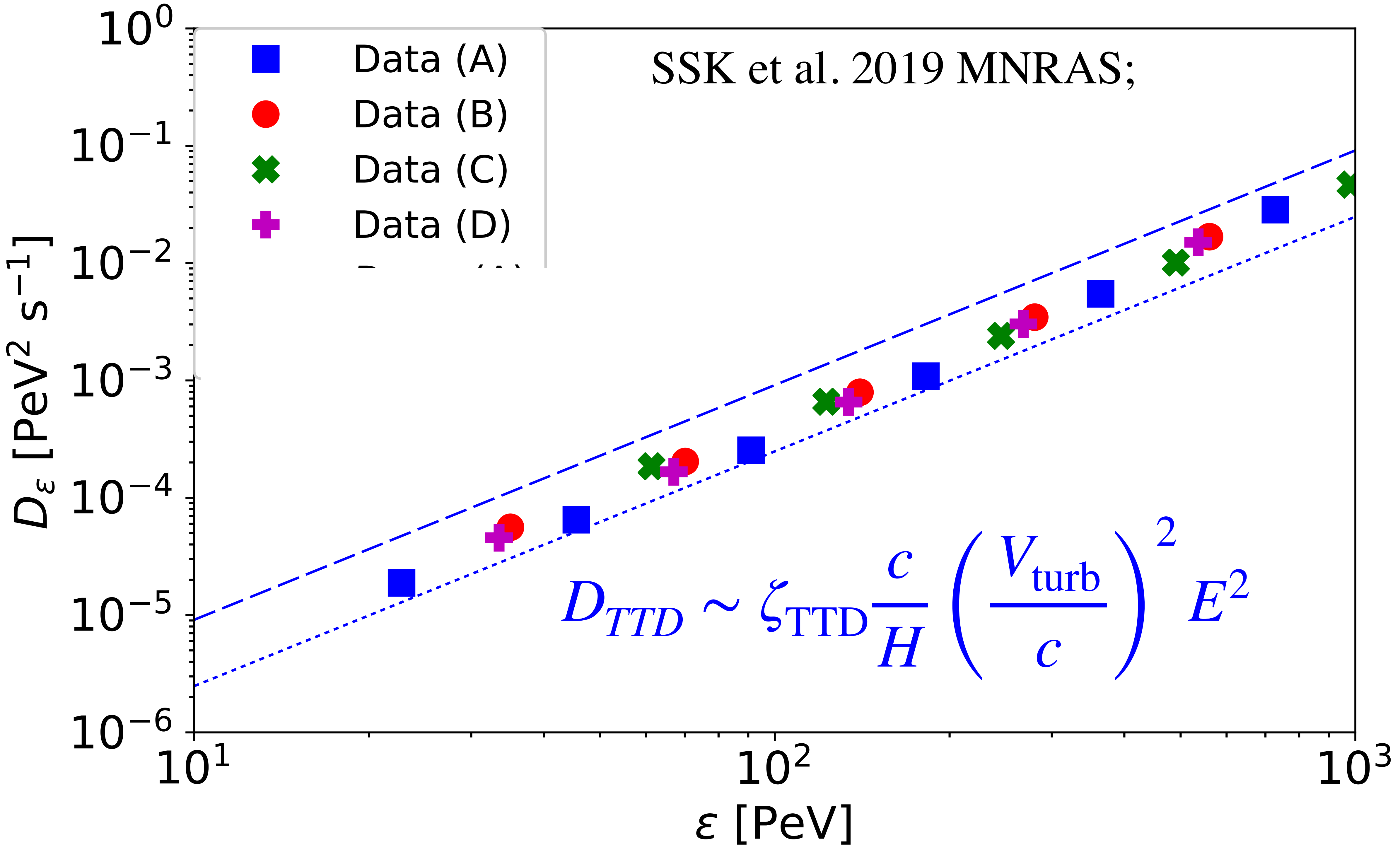
Diffusion Coefficients in E space

- Low-resolution runs (Model D)



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

Diffusion Coefficients in E space

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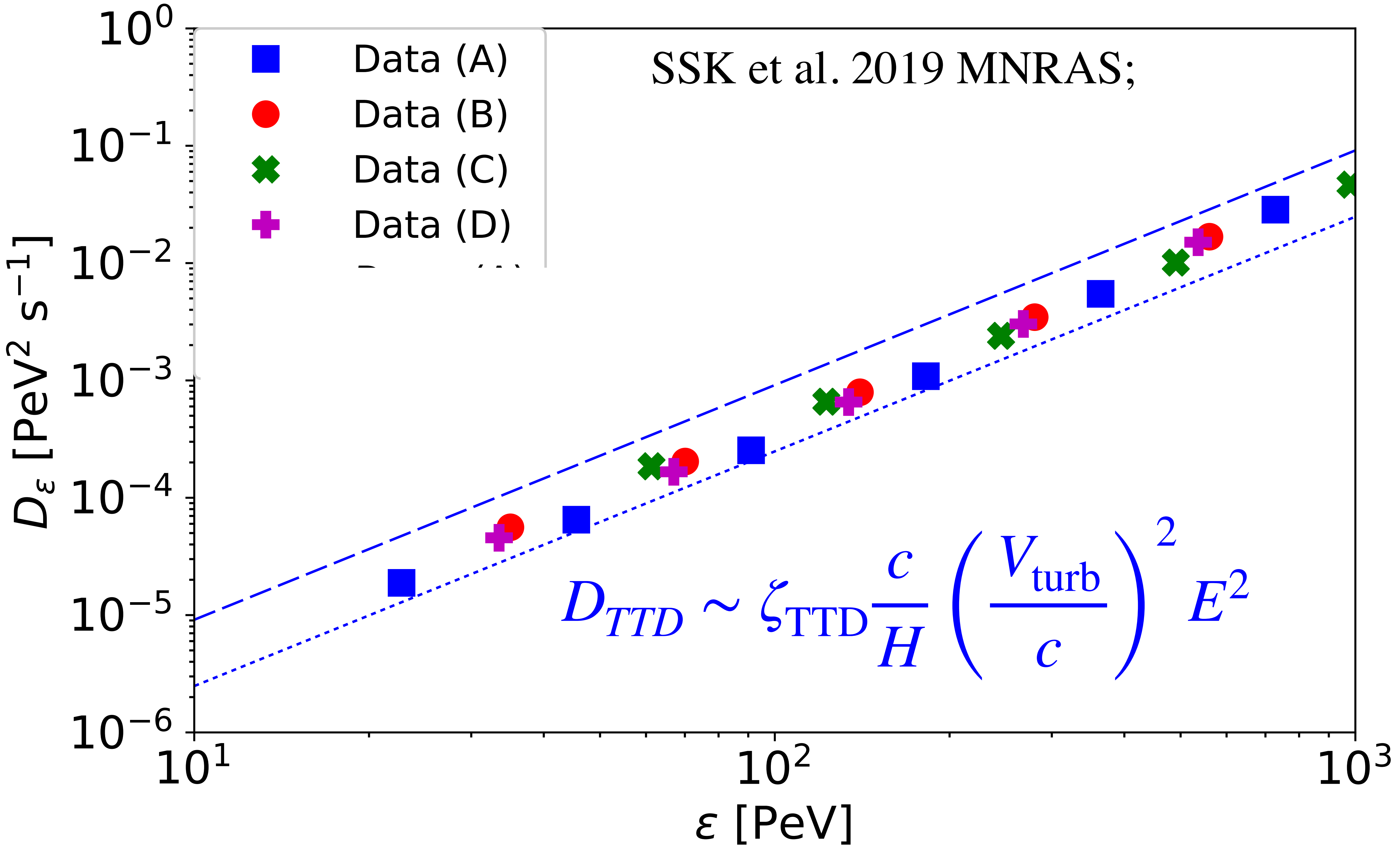
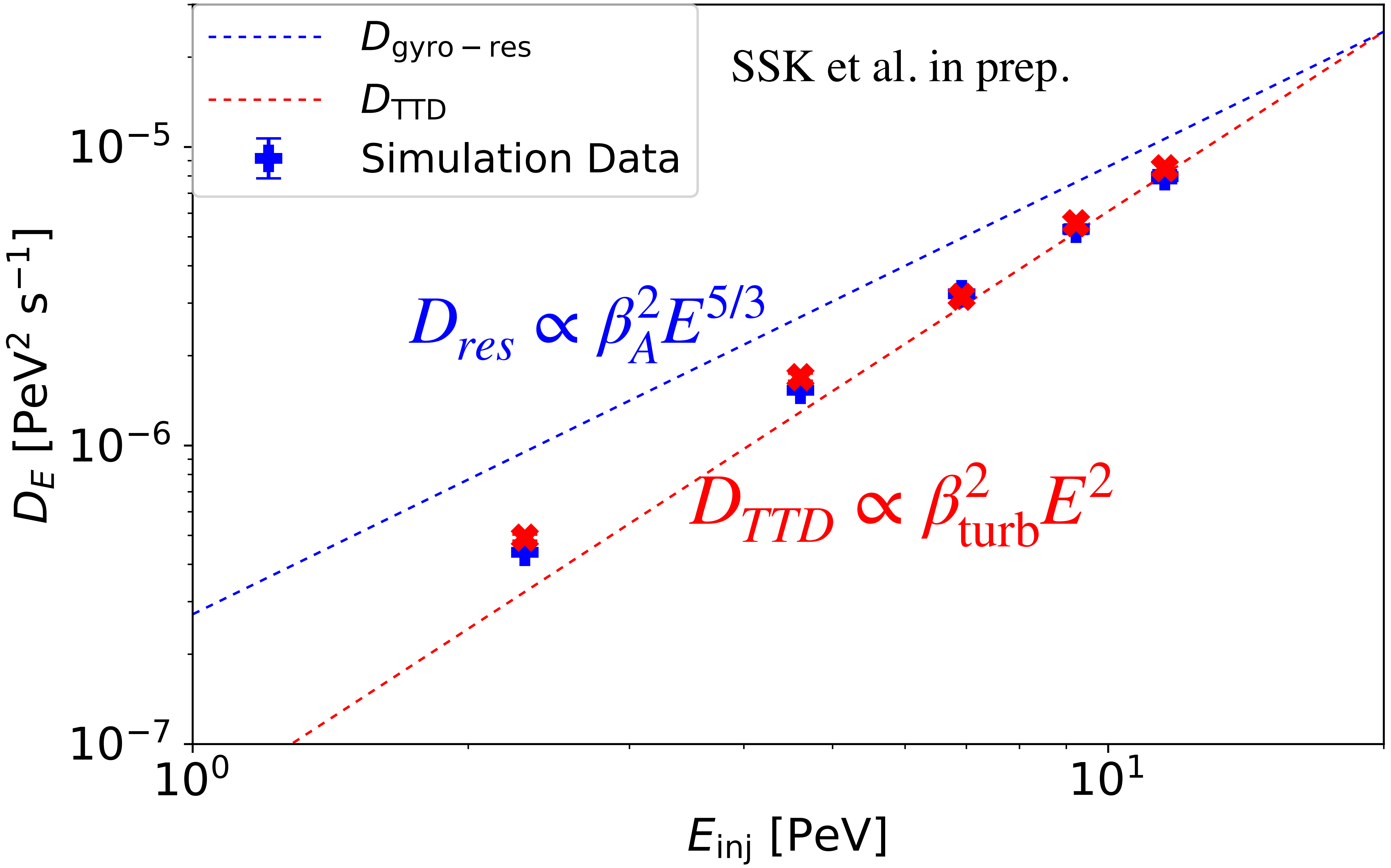


- All the particles interact with the largest eddies
- Roughly consistent with analytic estimates

- High-resolution runs (Model A)

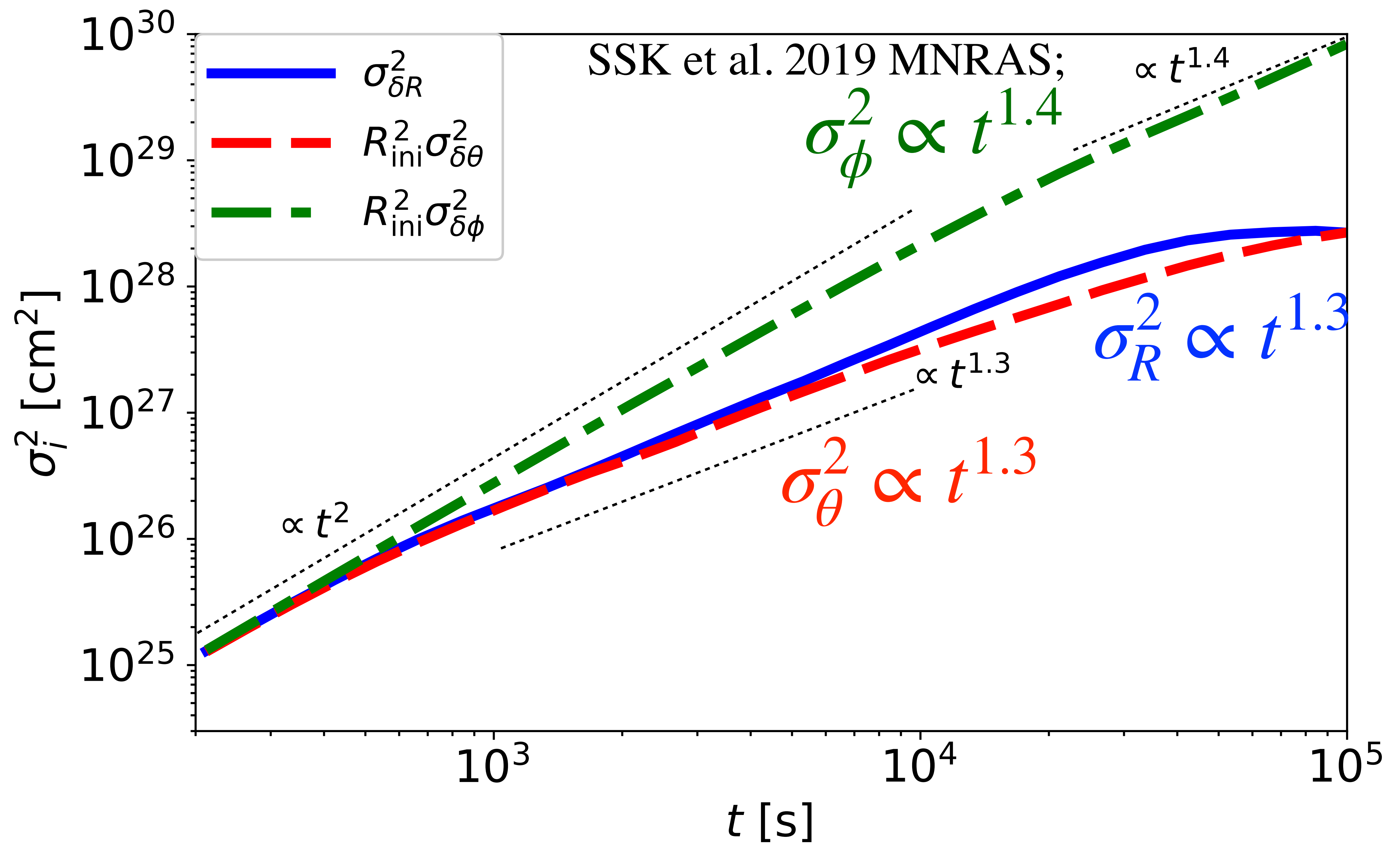


- $D_E \propto E^{1.7}$ —> Gyro-resonance?
- Small scale turbulence is important!

D_E depends on resolution

Diffusion in configuration space

- Low–resolution runs (Model D)

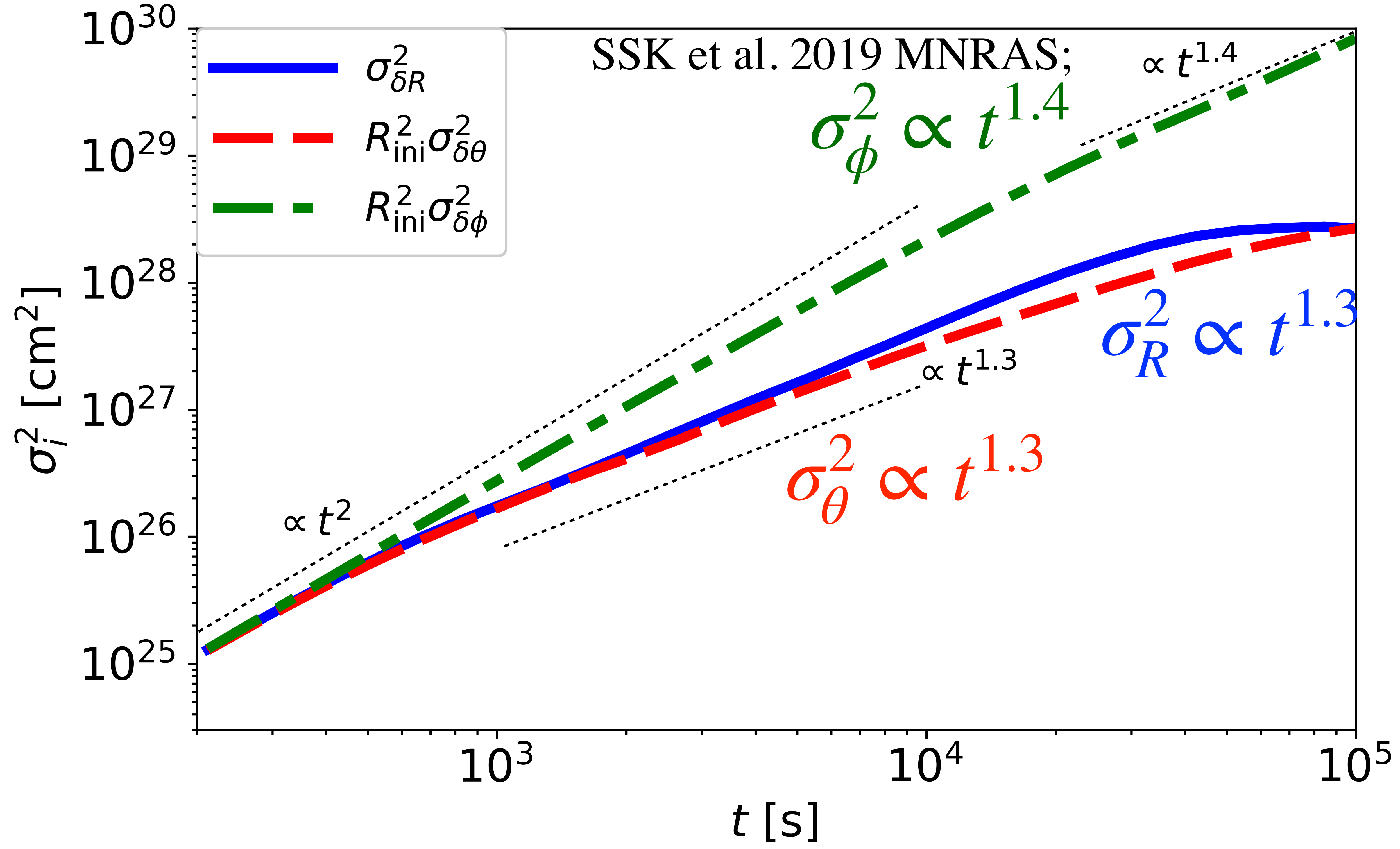


- Super-diffusion in all the directions

High-resolution runs results in diffusion in configuration space!

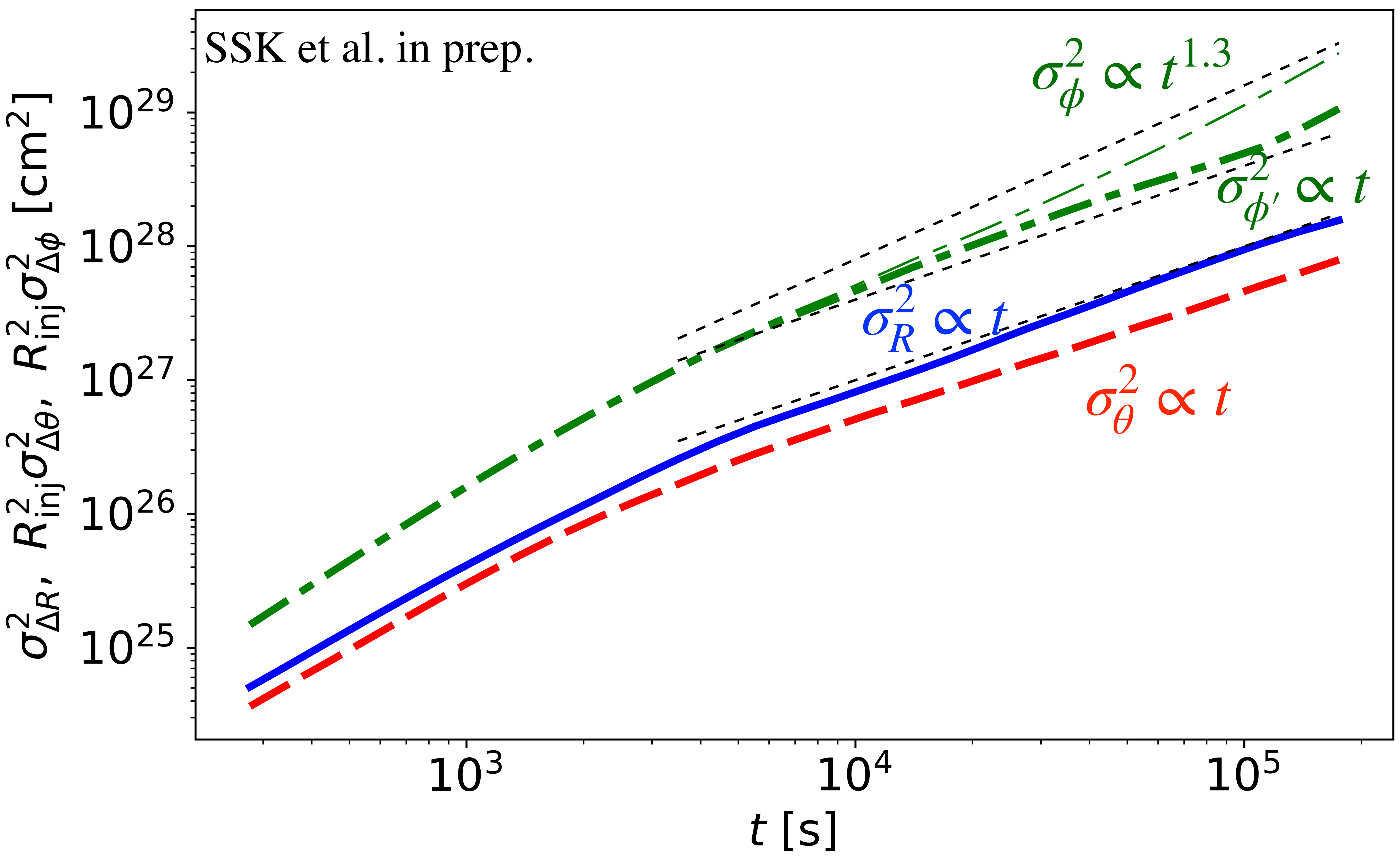
Diffusion in configuration space

- Low-resolution runs (Model D)



- Super-diffusion in all the directions

- High-resolution runs (Model A)

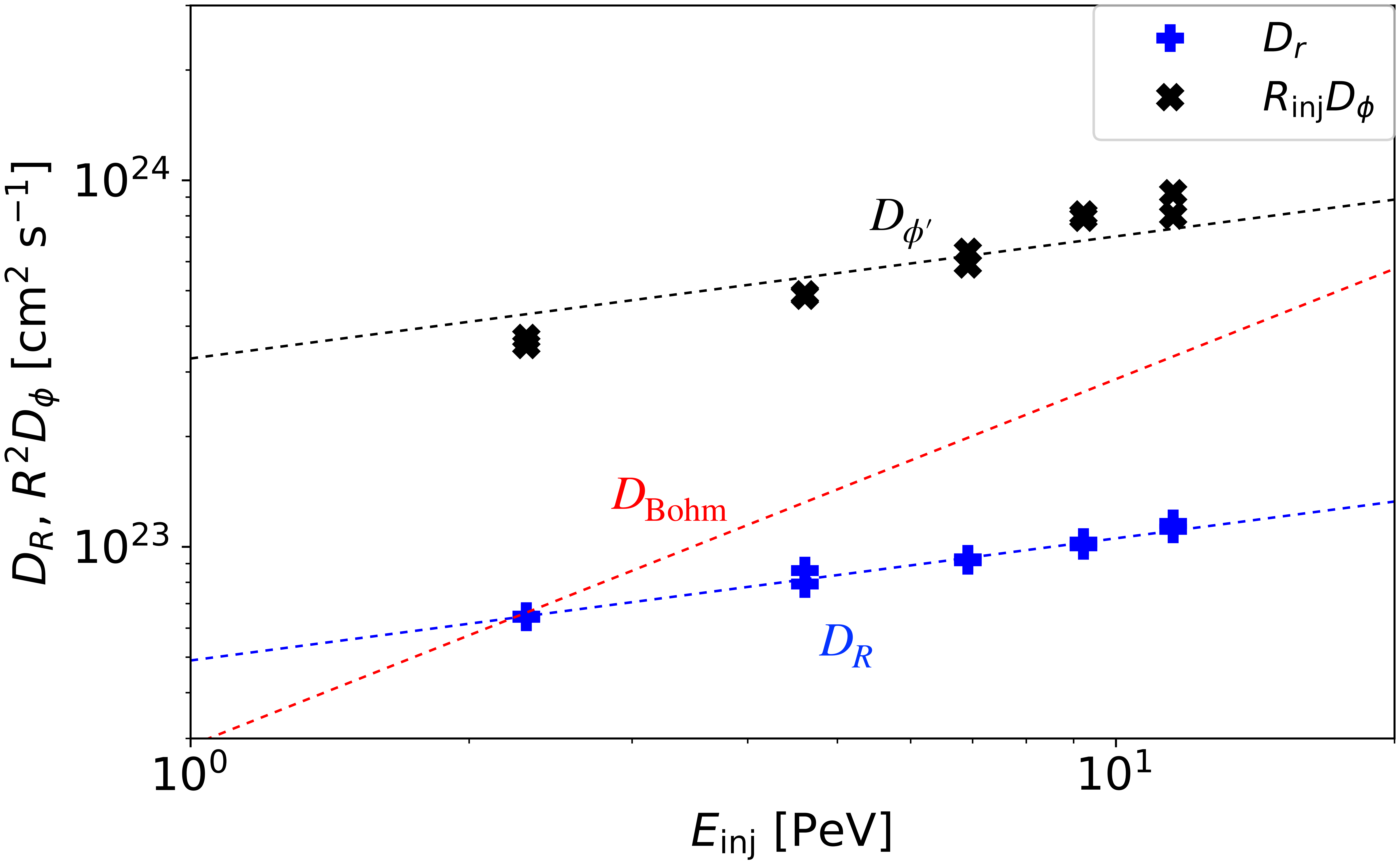


- Diffusion in all the directions
  $(\phi' = \phi - \Omega_K t)$

High-resolution runs results in diffusion in configuration space!

Diffusion coefficients in R space

- $D_R \propto E^{0.3}$
- consistent with gyro-resonance
- Inconsistent with Bohm/TTD
- We observe Bohm diff.
  in local shearing box sim.
  —> global effect?
- $R^2 D_{\phi'} / D_R \approx B_\phi / B_R$
  —> **diffusion along B-field**

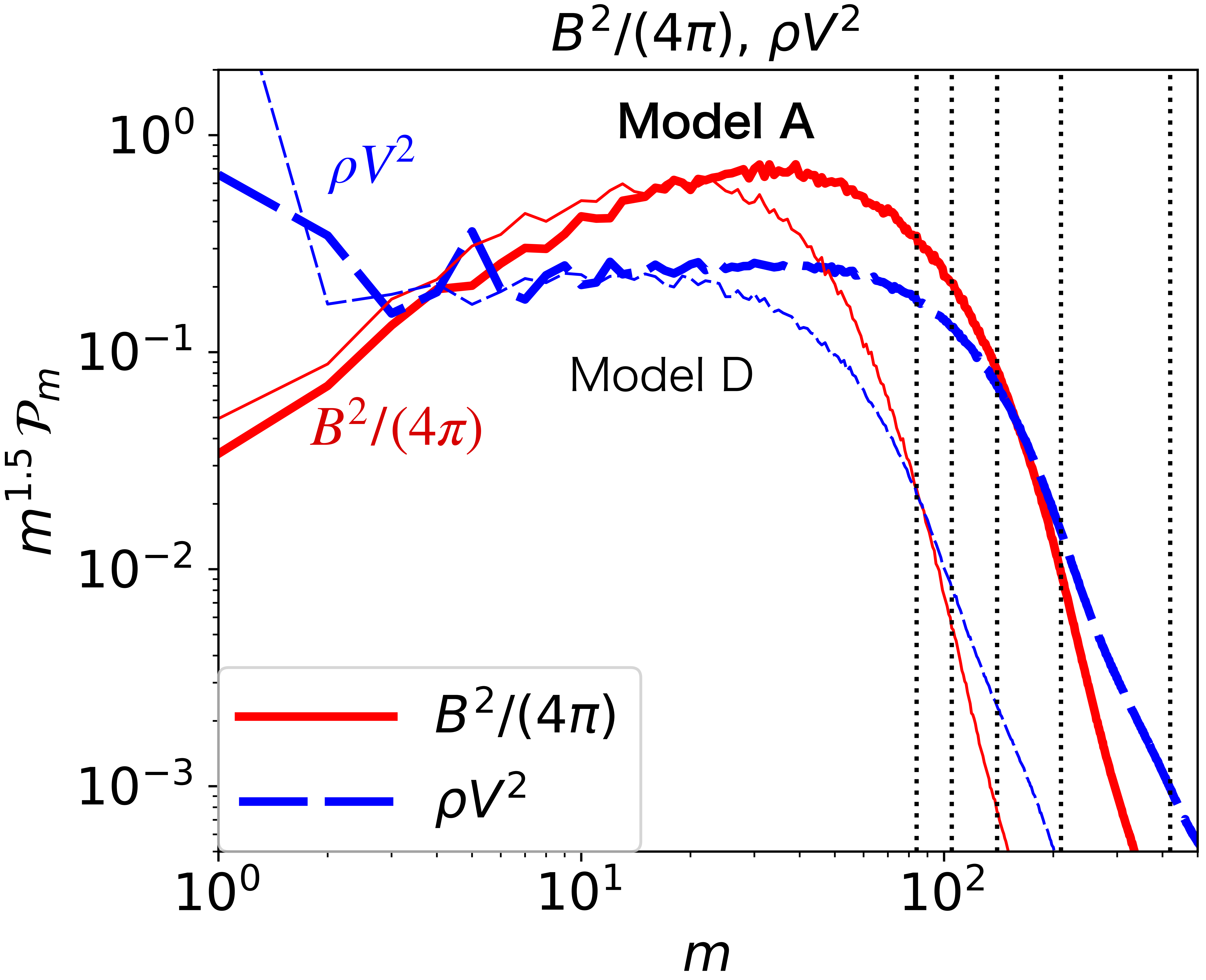


Power Spectrum

$$X_m = \frac{1}{\sqrt{2\pi}} \int X \exp(-im\phi) \mathrm{d}\phi,$$

$$\mathcal{P}_m = \frac{\int |X_m|^2 R \mathrm{d}R \mathrm{d}\theta}{\int R \mathrm{d}R \mathrm{d}\theta},$$

- Model A has powers in smaller scales, but **we have insufficient resolution**
- These simulations would not capture gyro-resonance properly



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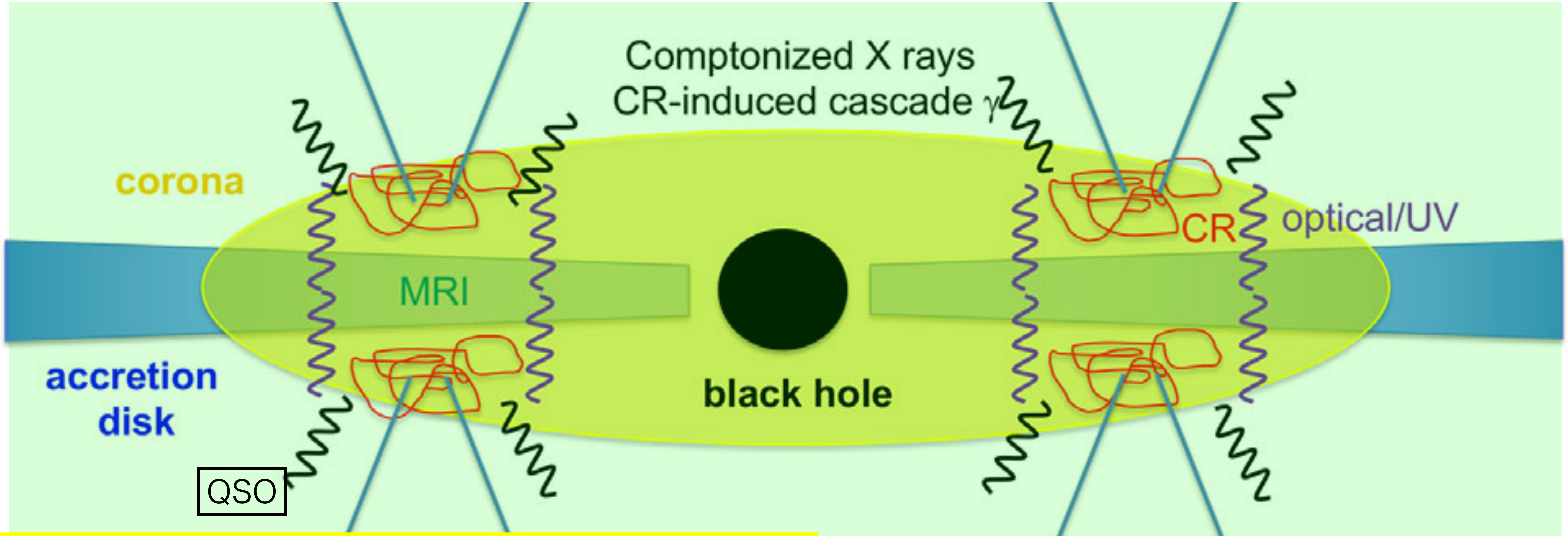
AGN Corona Model

Murase, SSK, Meszaros 2020



- Equations for cosmic-ray protons

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

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

- Equations for electromagnetic cascades

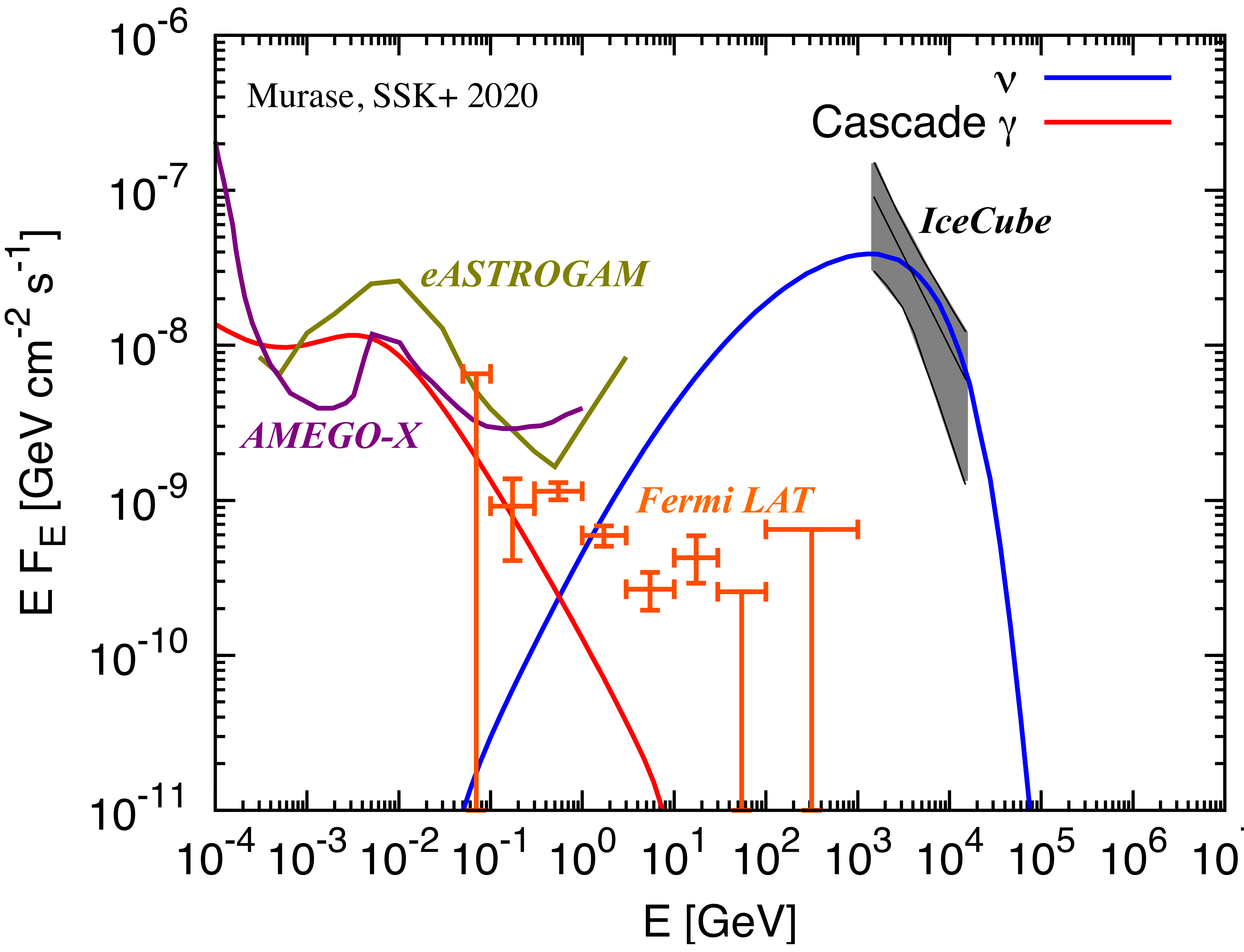
$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\rm esc}} + \dot{n}^{(\rm IC)}_{\varepsilon_\gamma} + \dot{n}^{(\rm ff)}_{\varepsilon_\gamma} + \dot{n}^{(\rm syn)}_{\varepsilon_\gamma} + \dot{n}^{\rm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

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

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**

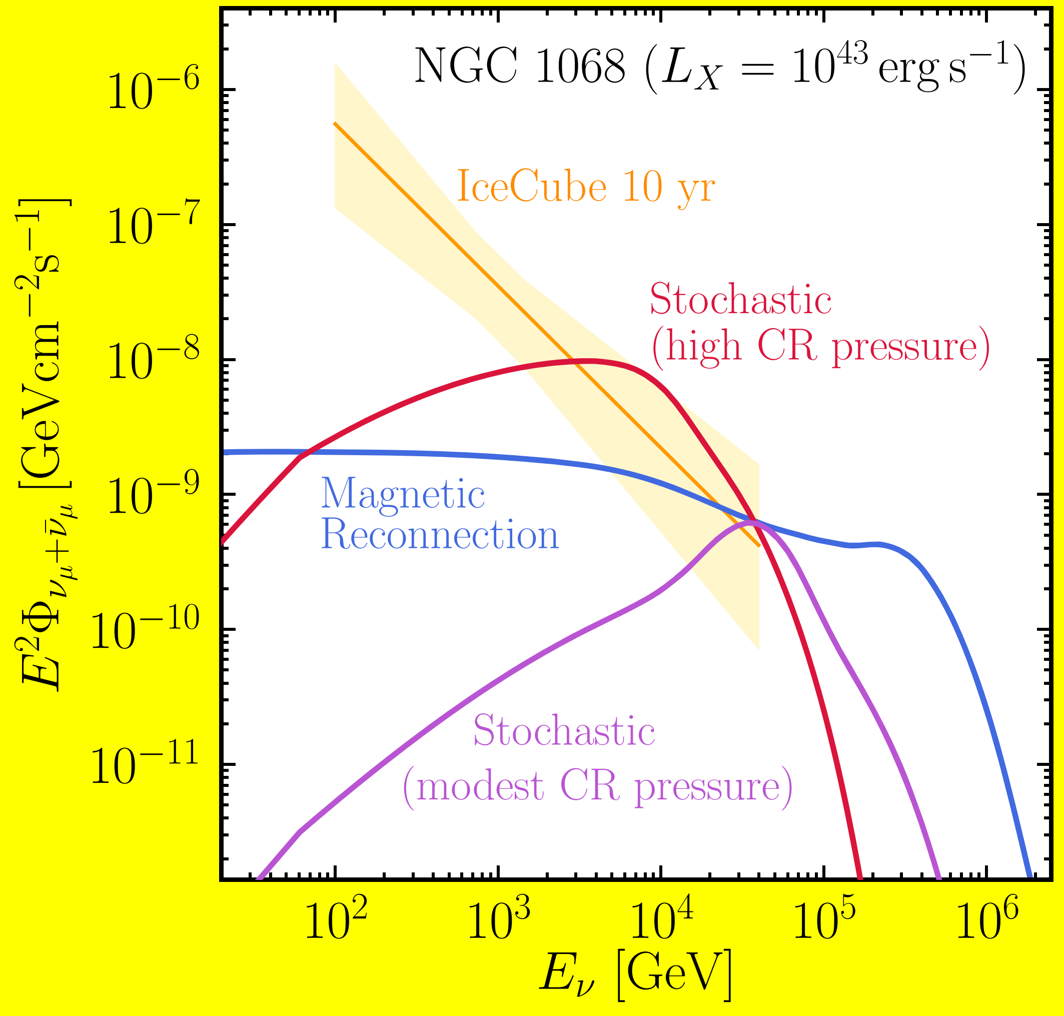


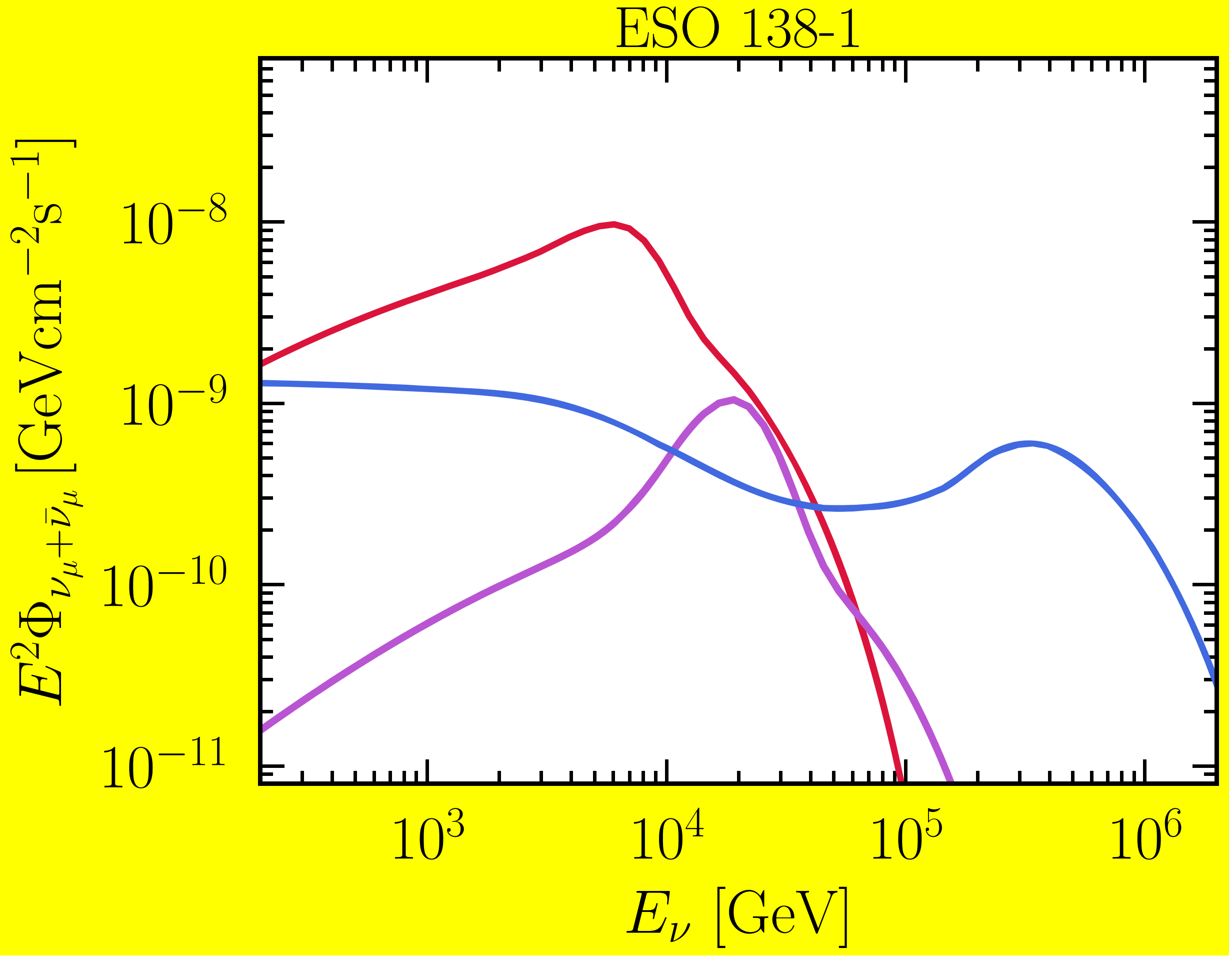
Nearby Seyfert galaxies

Kheirandish, Murase, SSK 2021

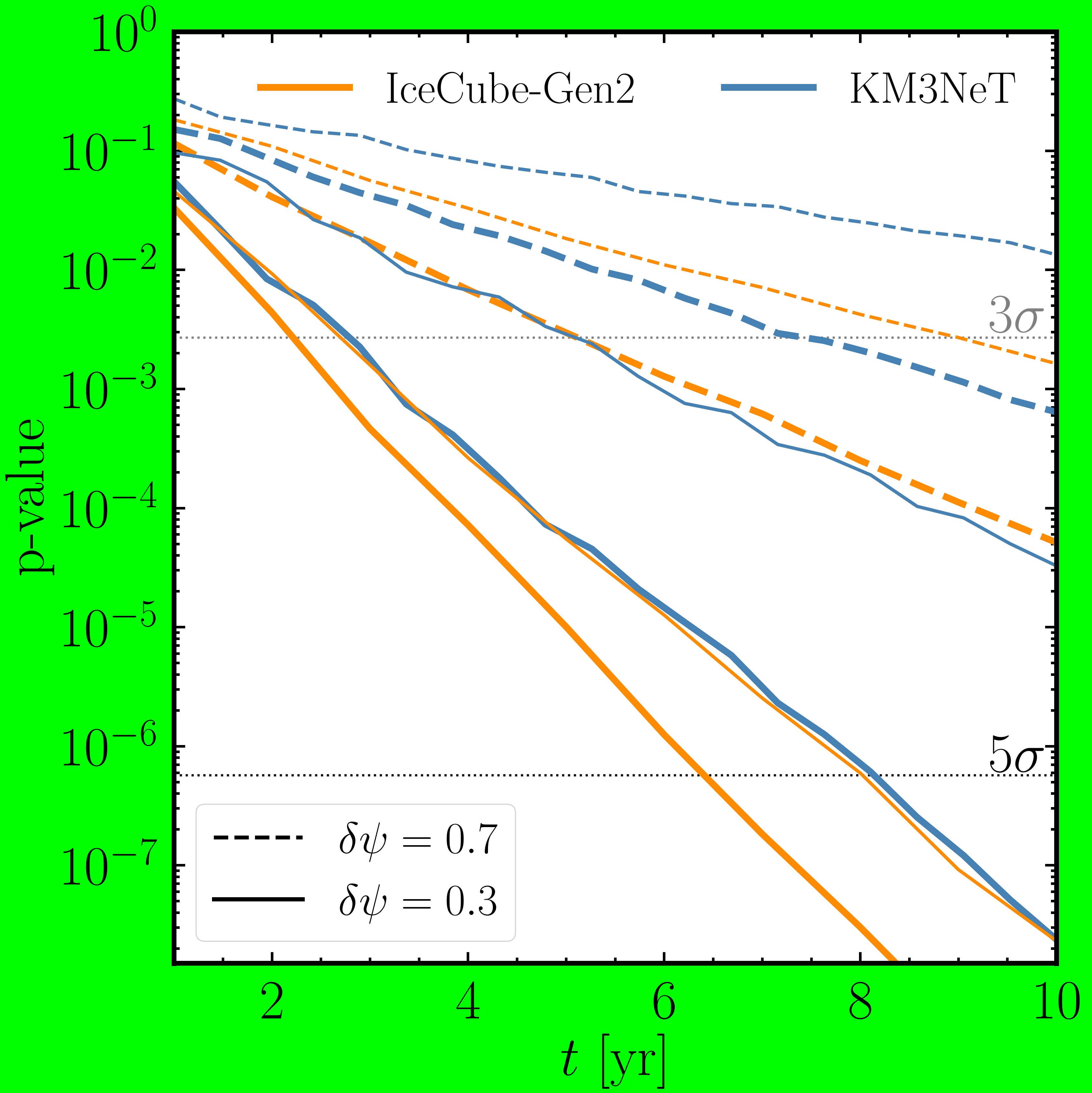
- Our model predicts $L_\nu \propto L_X$
  —> list up bright ν-source candidates

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





- Stacking nearby Seyferts

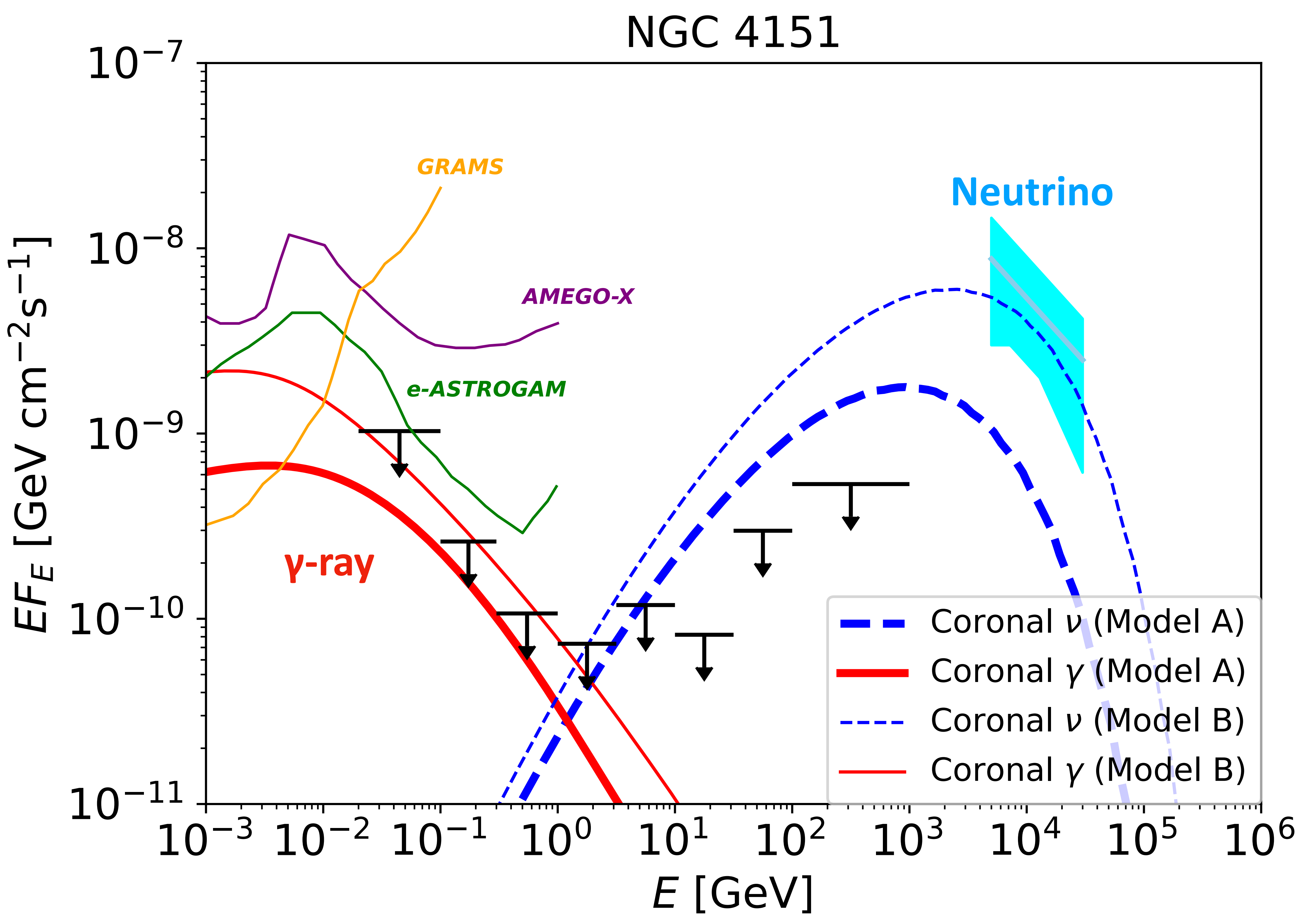


- Future detectors should detect ν from AGN
  —> **testable by future neutrino experiments**

ν & γ from Nearby Seyfert Galaxies

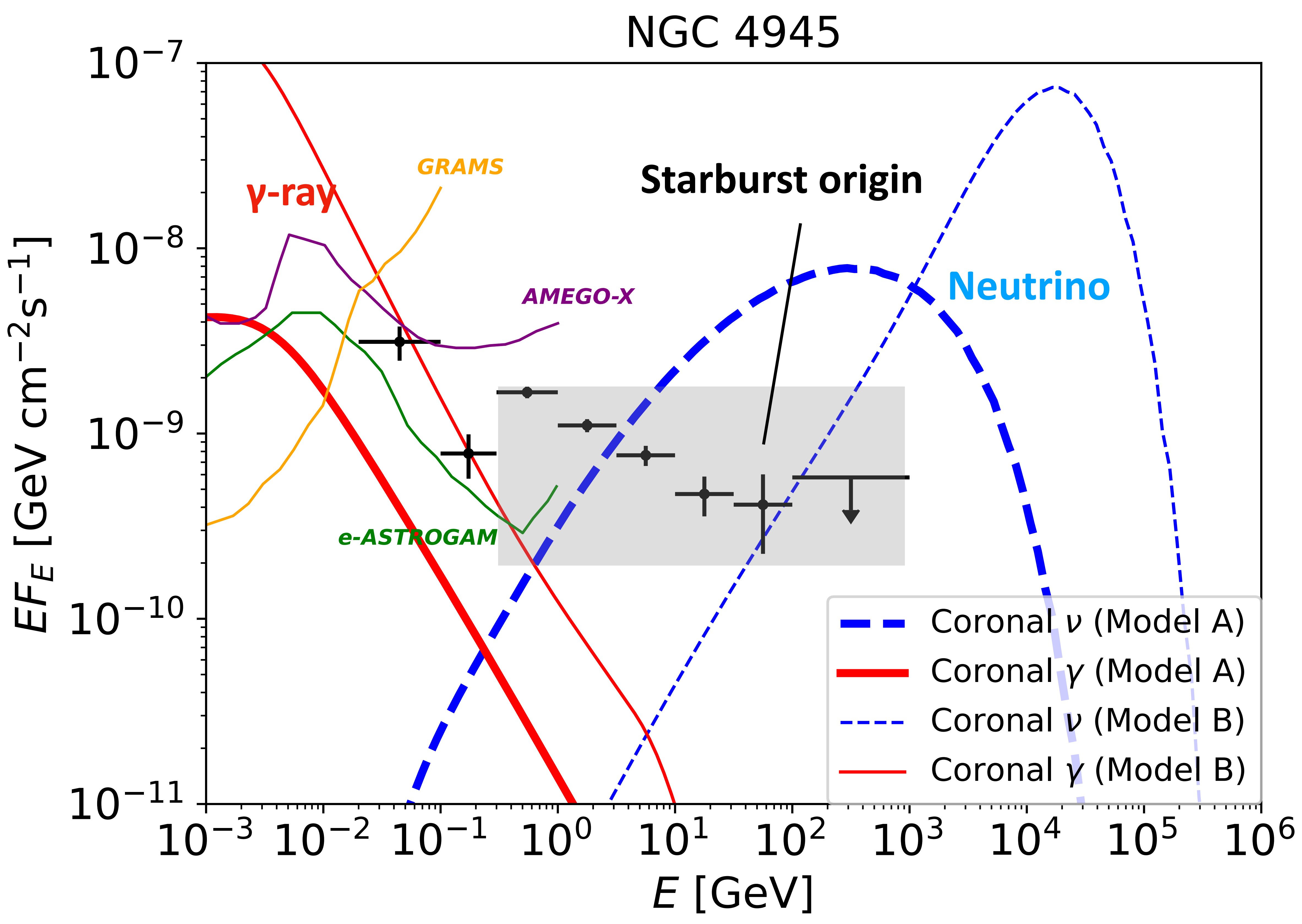
Murase, Karwin, SSK et al. 2024

- NGC 4151: Neutrino source candidate ($\sim 3\sigma$)



- Our model can reproduce the tentative ν data without overshooting γ data

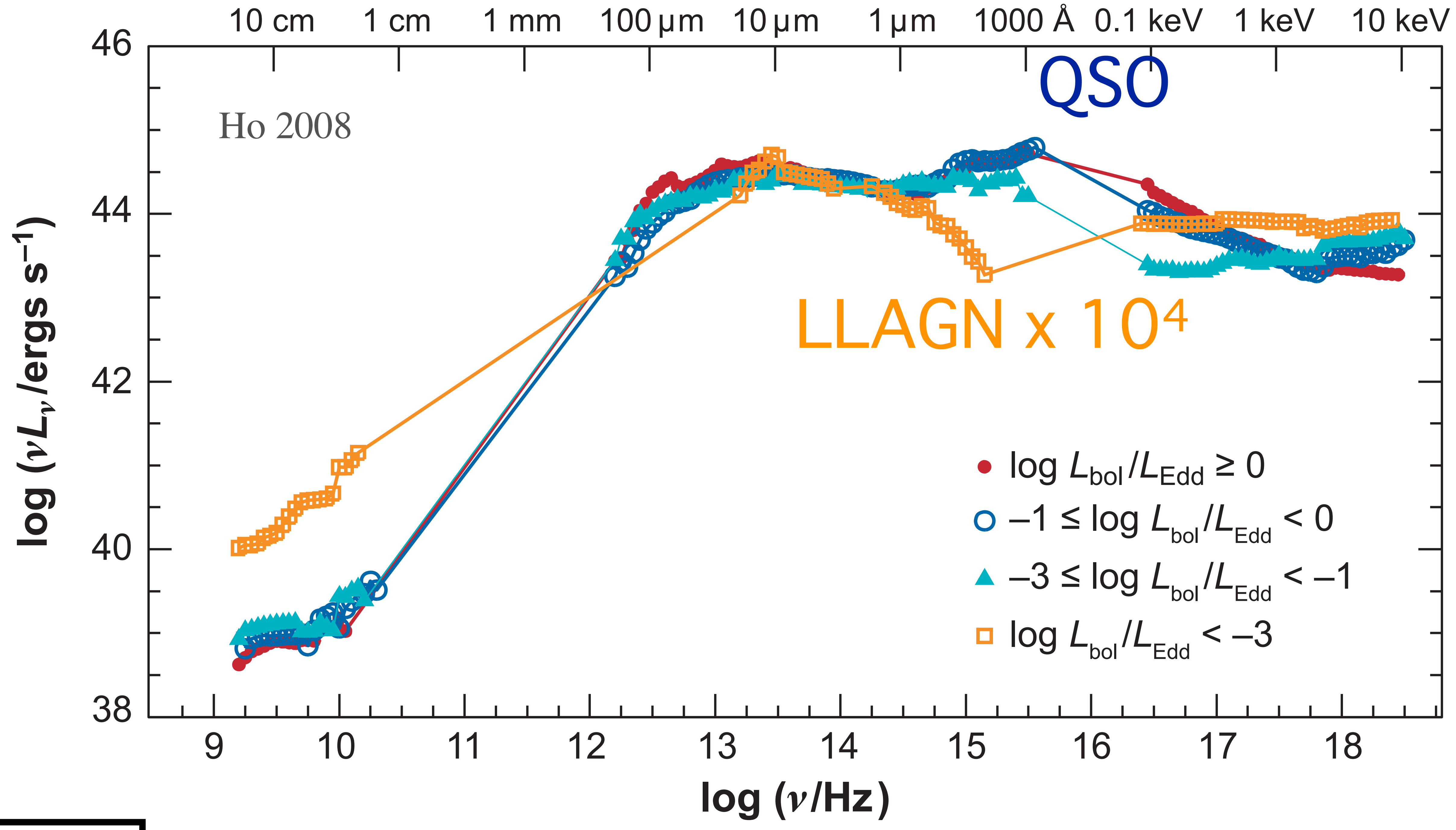
- NGC 4945: γ-ray emitting AGN

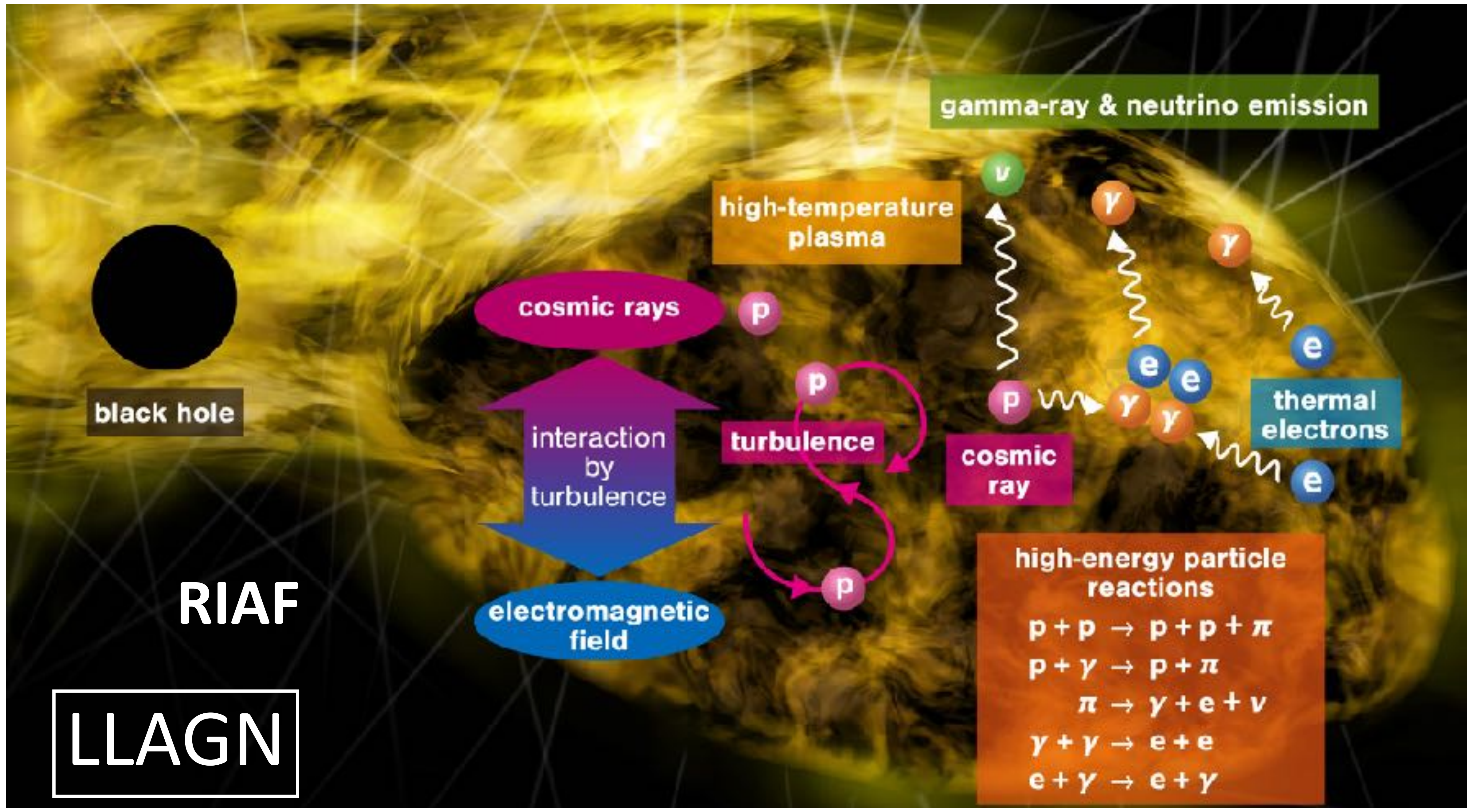


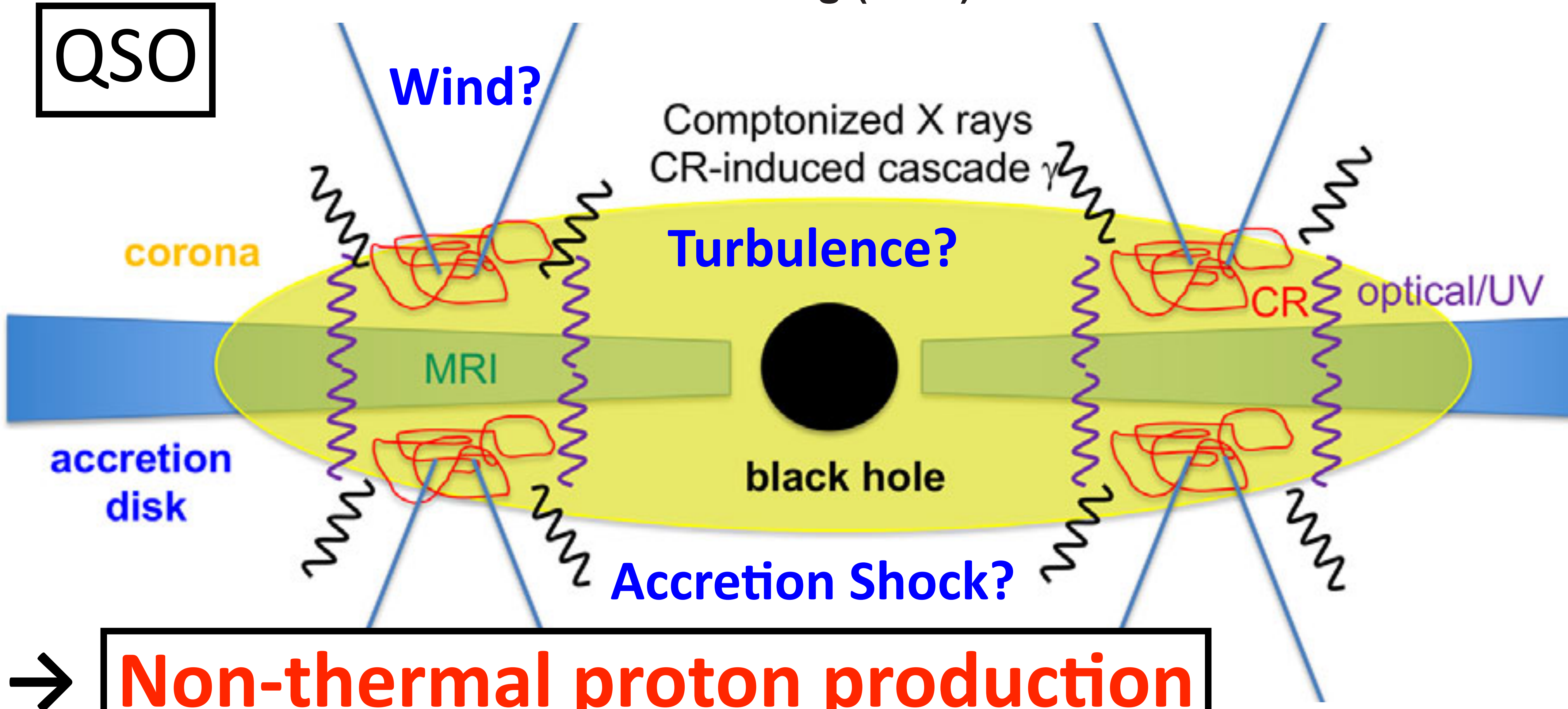
- Our coronal model can explain γ-ray data for $E < 0.3$GeV

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)

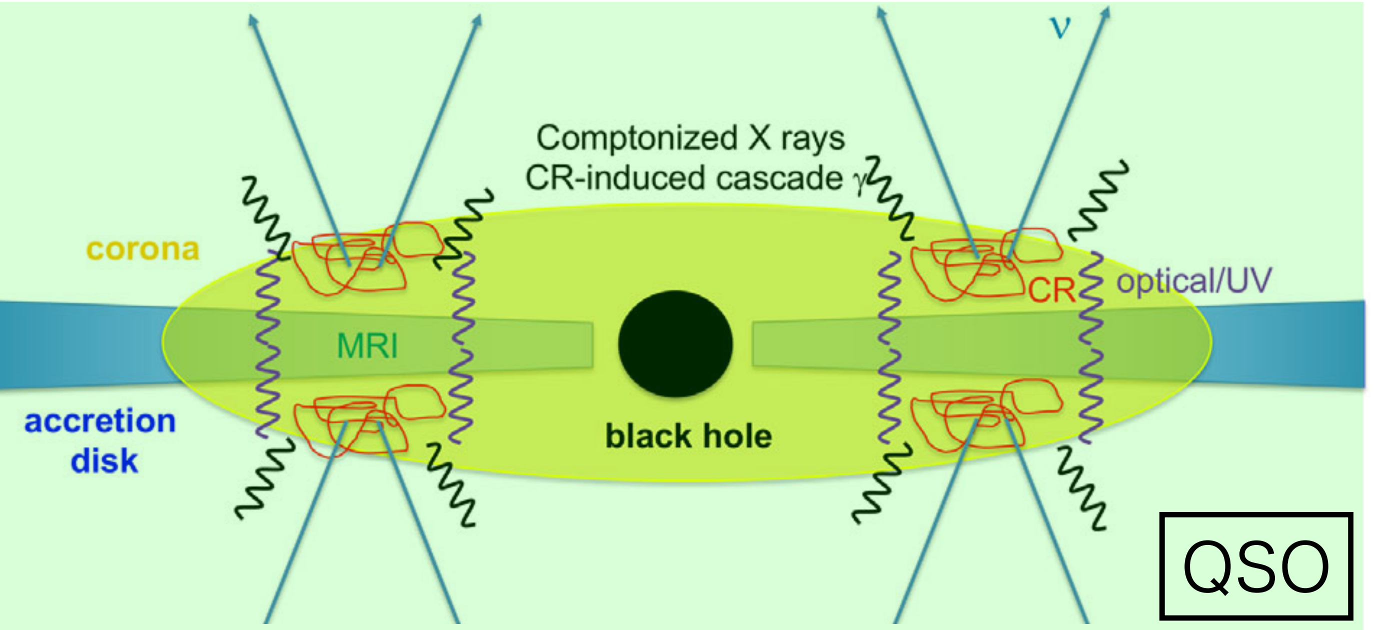




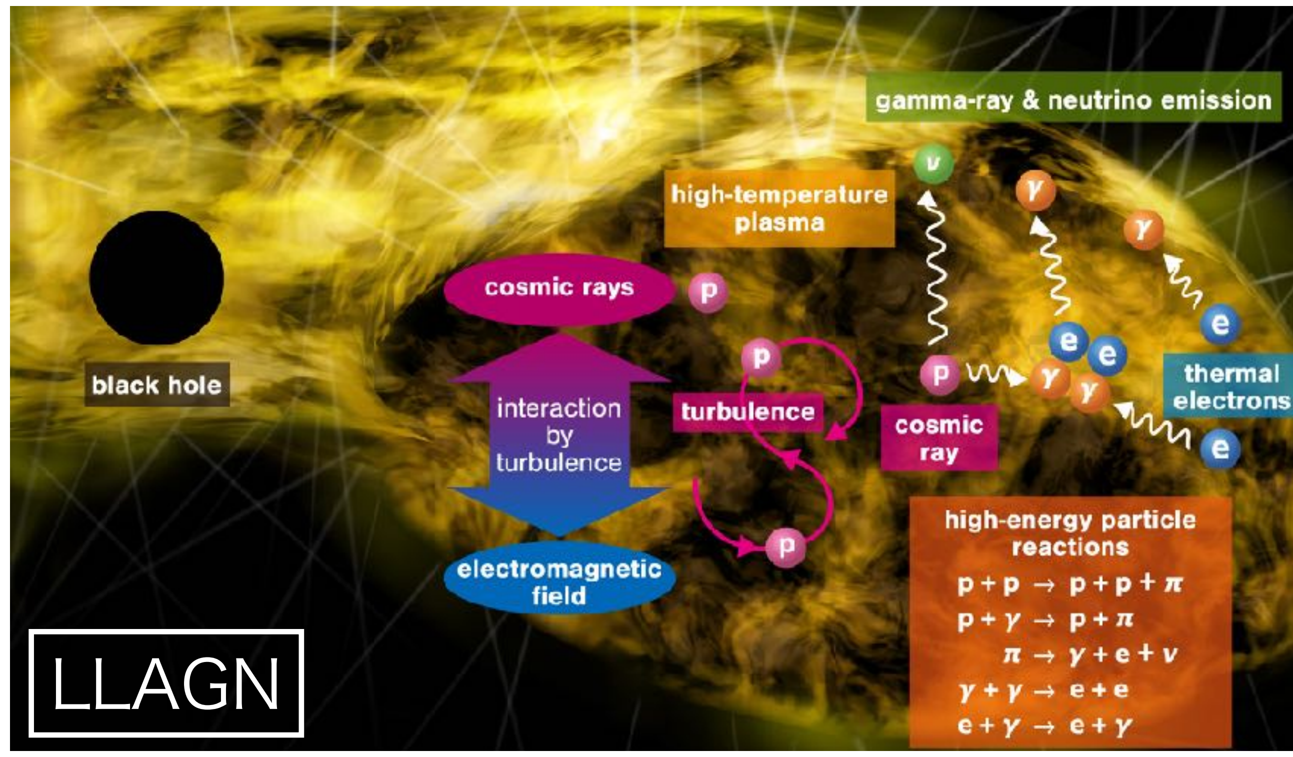


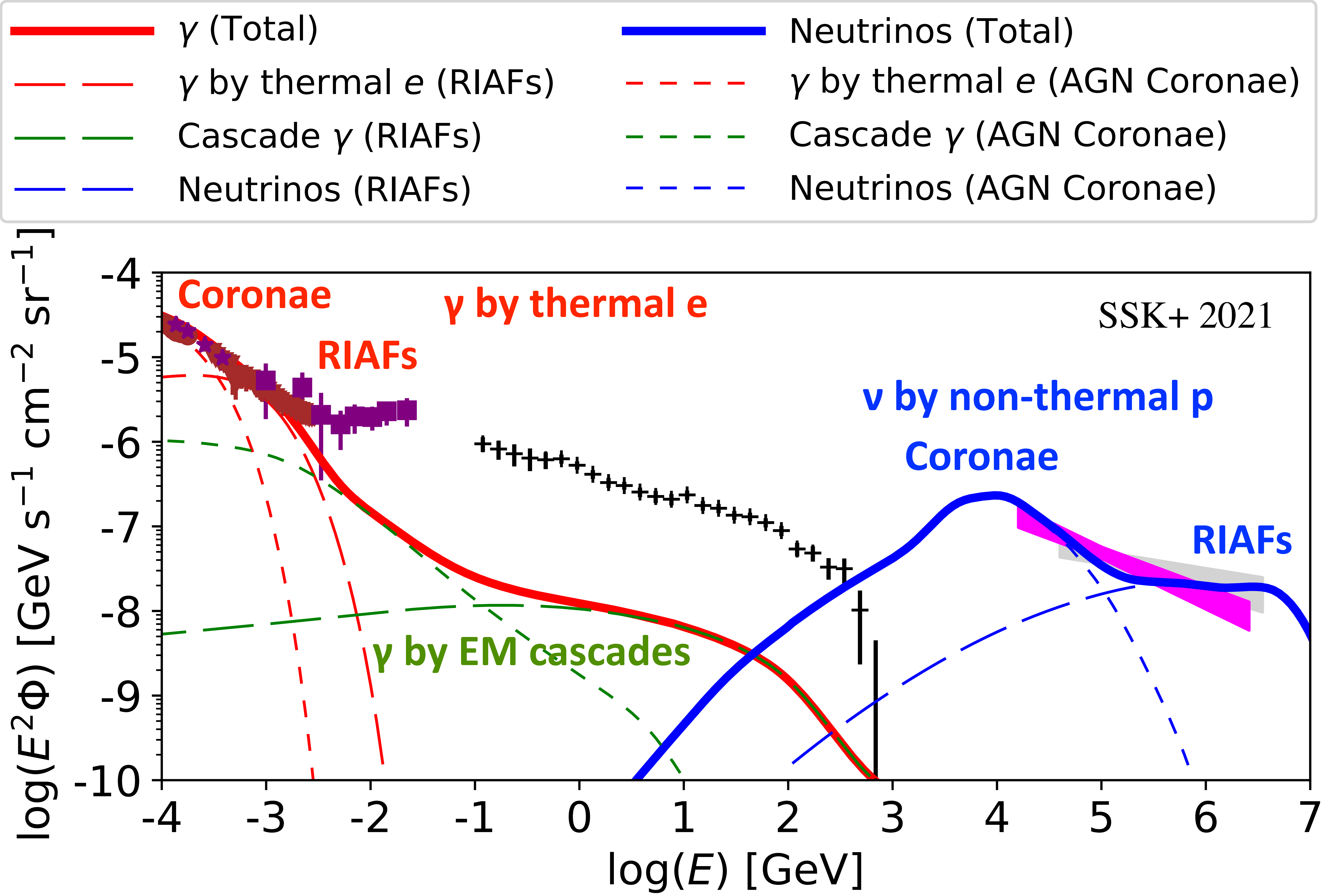
Protons in coronae & RIAFs are collisionless → Non-thermal proton production

Cosmic High-energy Background from RQ AGNs



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

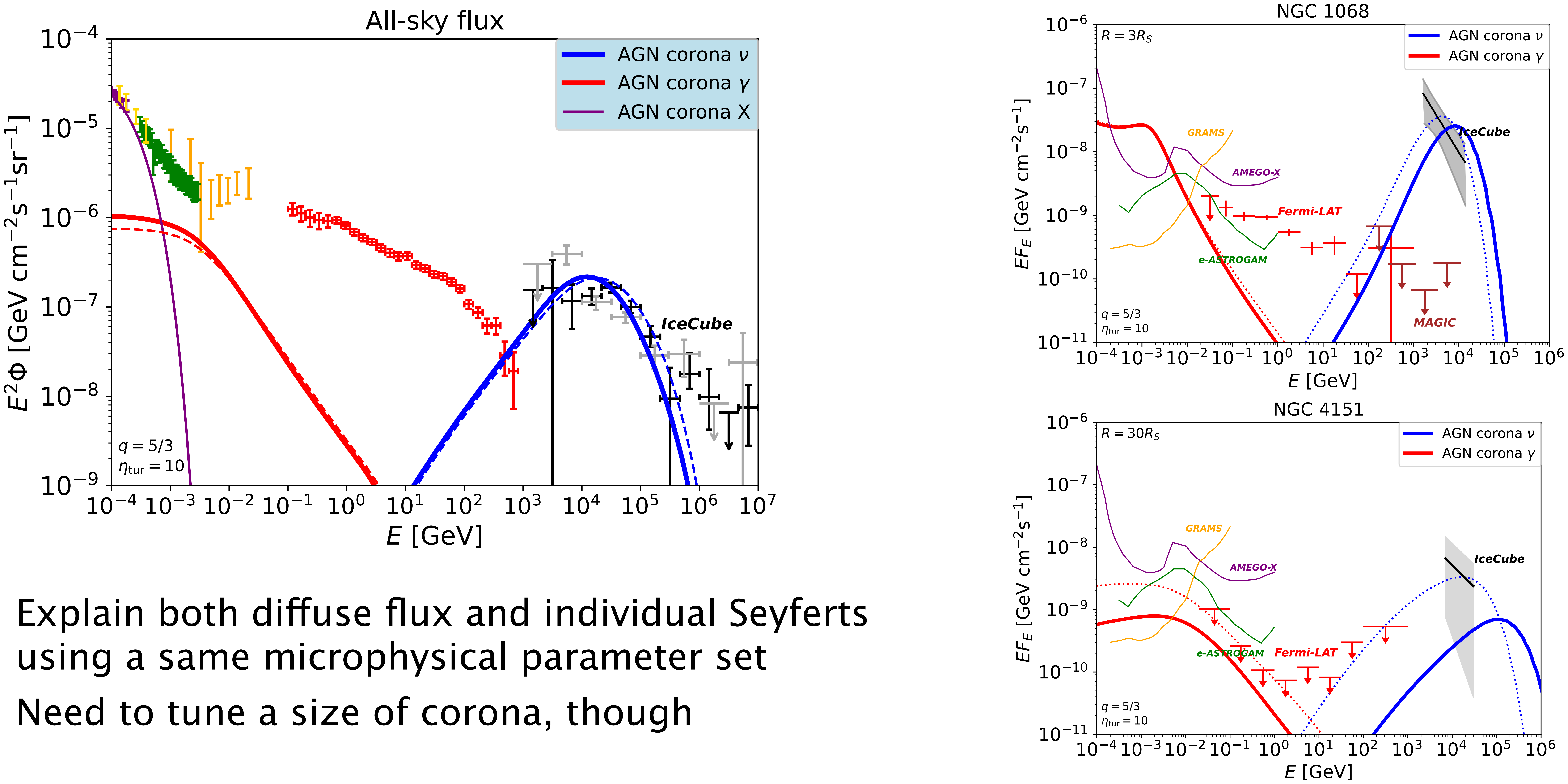




- QSO: X-ray & 10 TeV neutrinos
- LLAGN: MeV γ & PeV neutrinos
- Copious photons
  → efficient γγ —> e+e-
  → strong GeV γ attenuation
  → GeV flux below the Fermi data
- **AGN cores can account for keV-MeV γ & TeV-PeV ν background**

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

Diffuse flux VS individual Seyferts



- Explain both diffuse flux and individual Seyferts using a same microphysical parameter set
- Need to tune a size of corona, though

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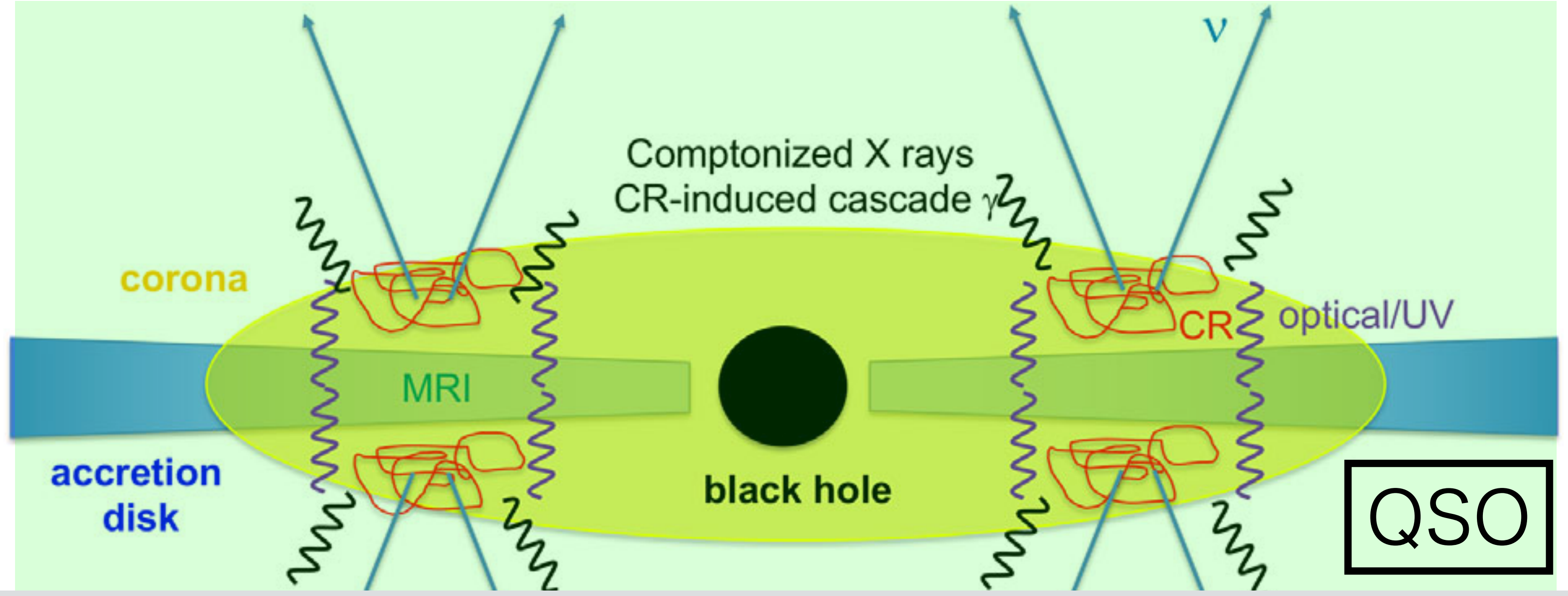
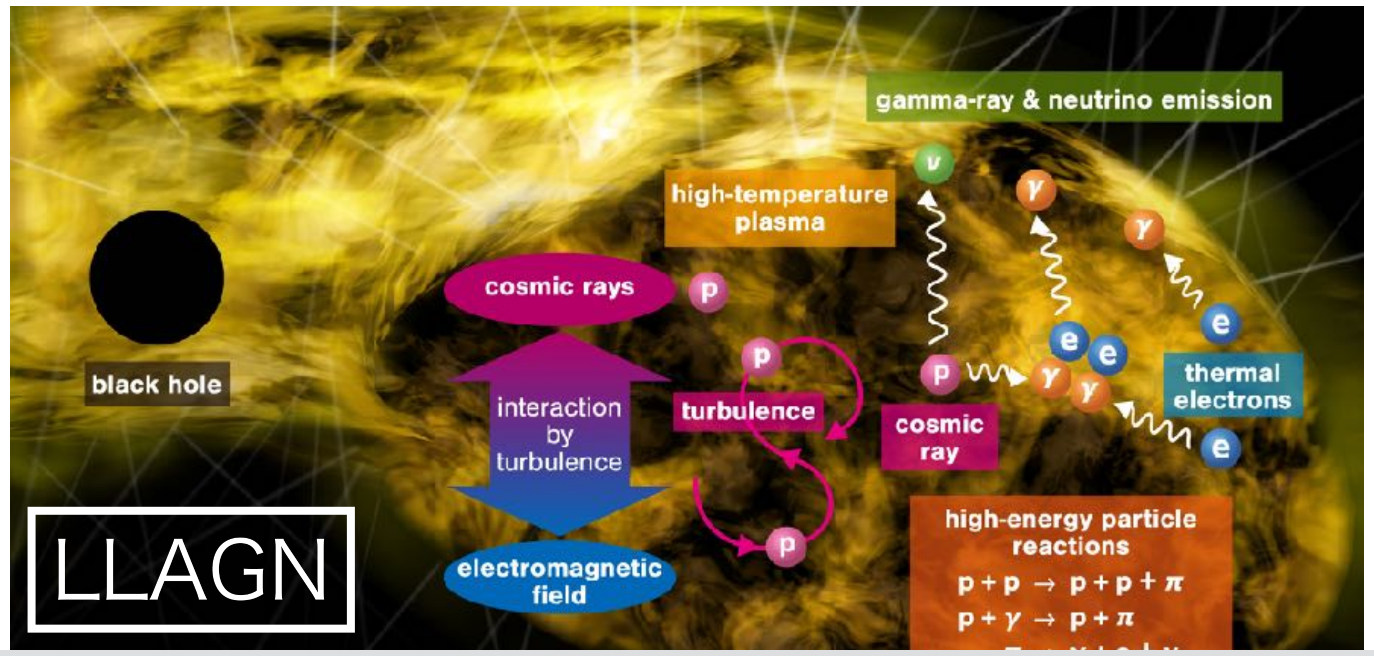
- Introduction to neutrino astrophysics
- CR acceleration in AGN accretion flows
- Neutrino emission modeling
- Summary

Summary





- IceCube reported evidence of neutrino signal from Seyfert galaxies
- **Production sites of these high-energy neutrinos are under debates**
- We consider stochastic acceleration in accretion flows including coronae
- MHD + test-particle simulations confirm that stochastic acceleration occurs in accretion flows, which is described well by the diffusion equation in energy space
- 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)