The Origin of Cosmic High-energy Neutrino Background

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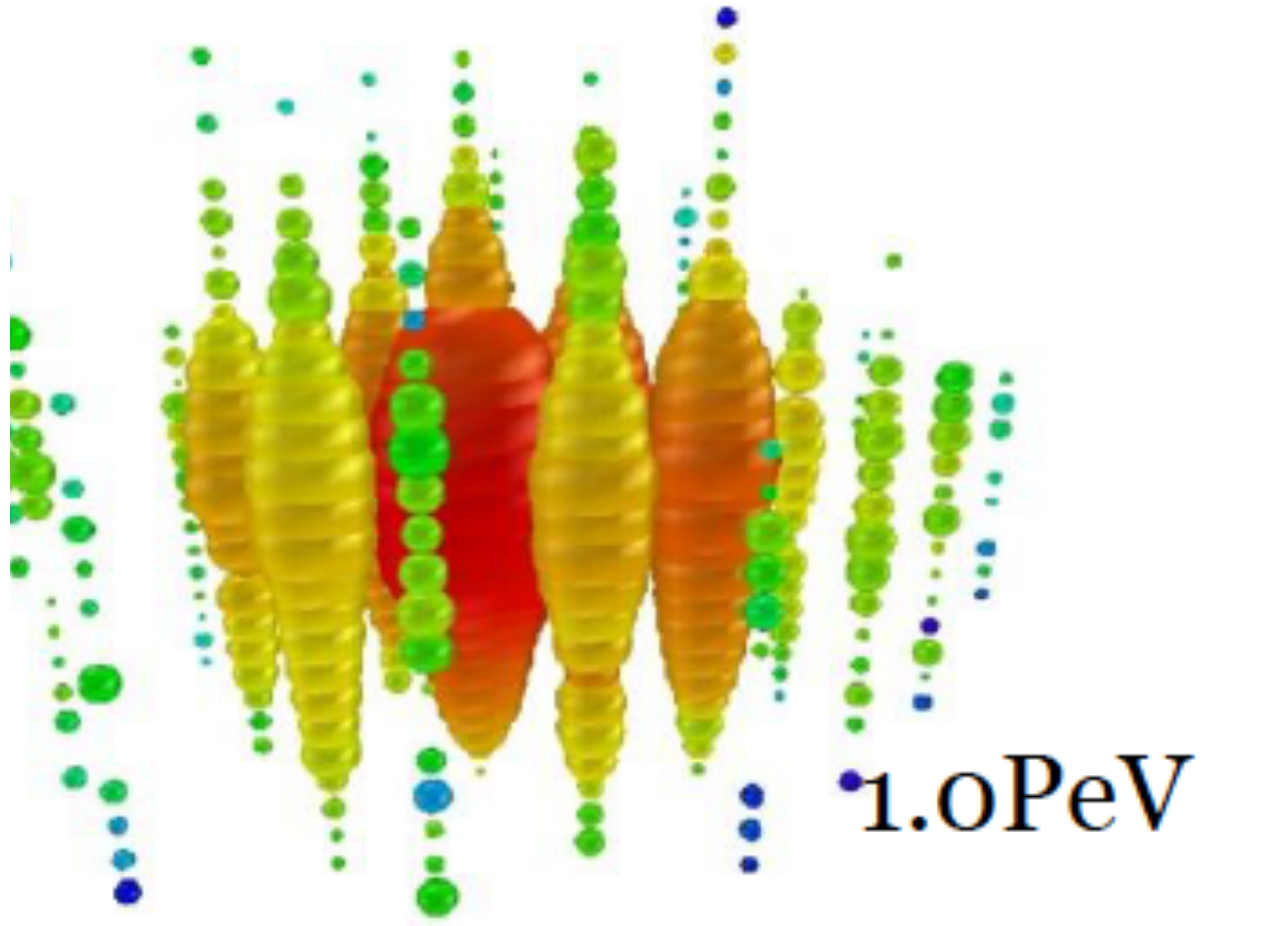
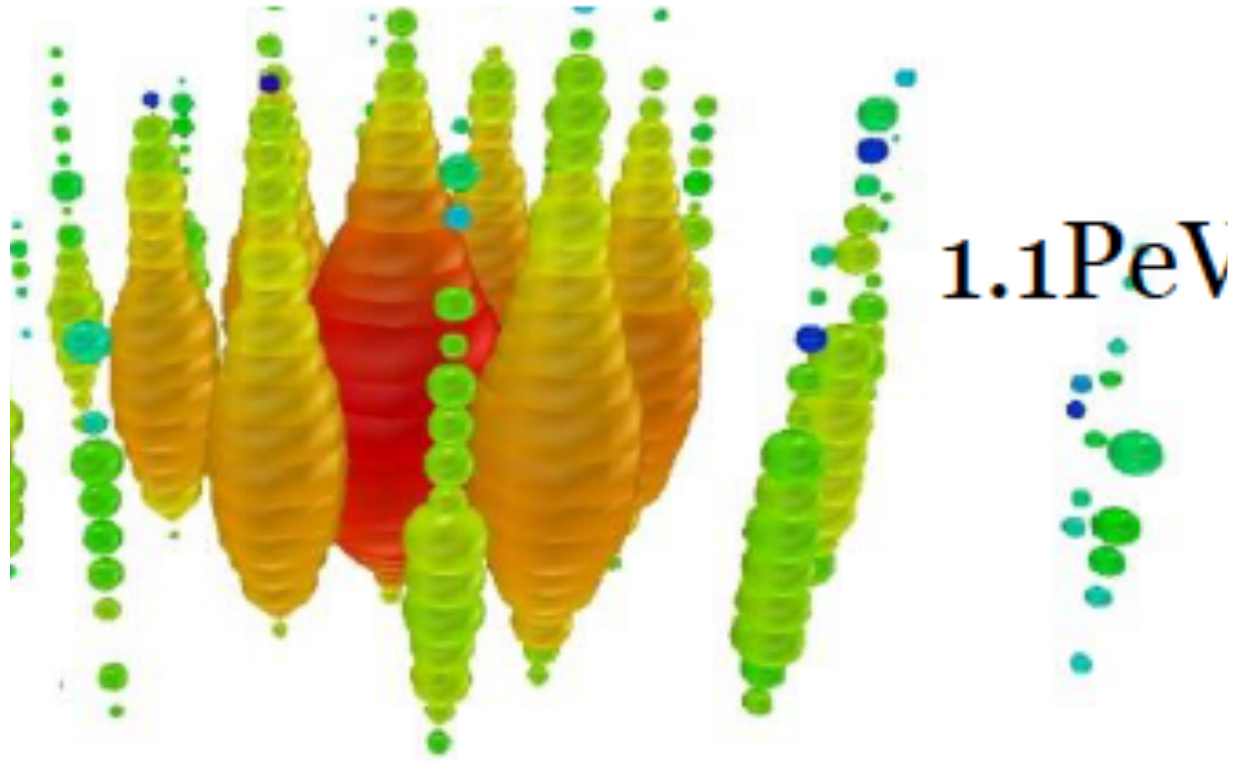
Contents

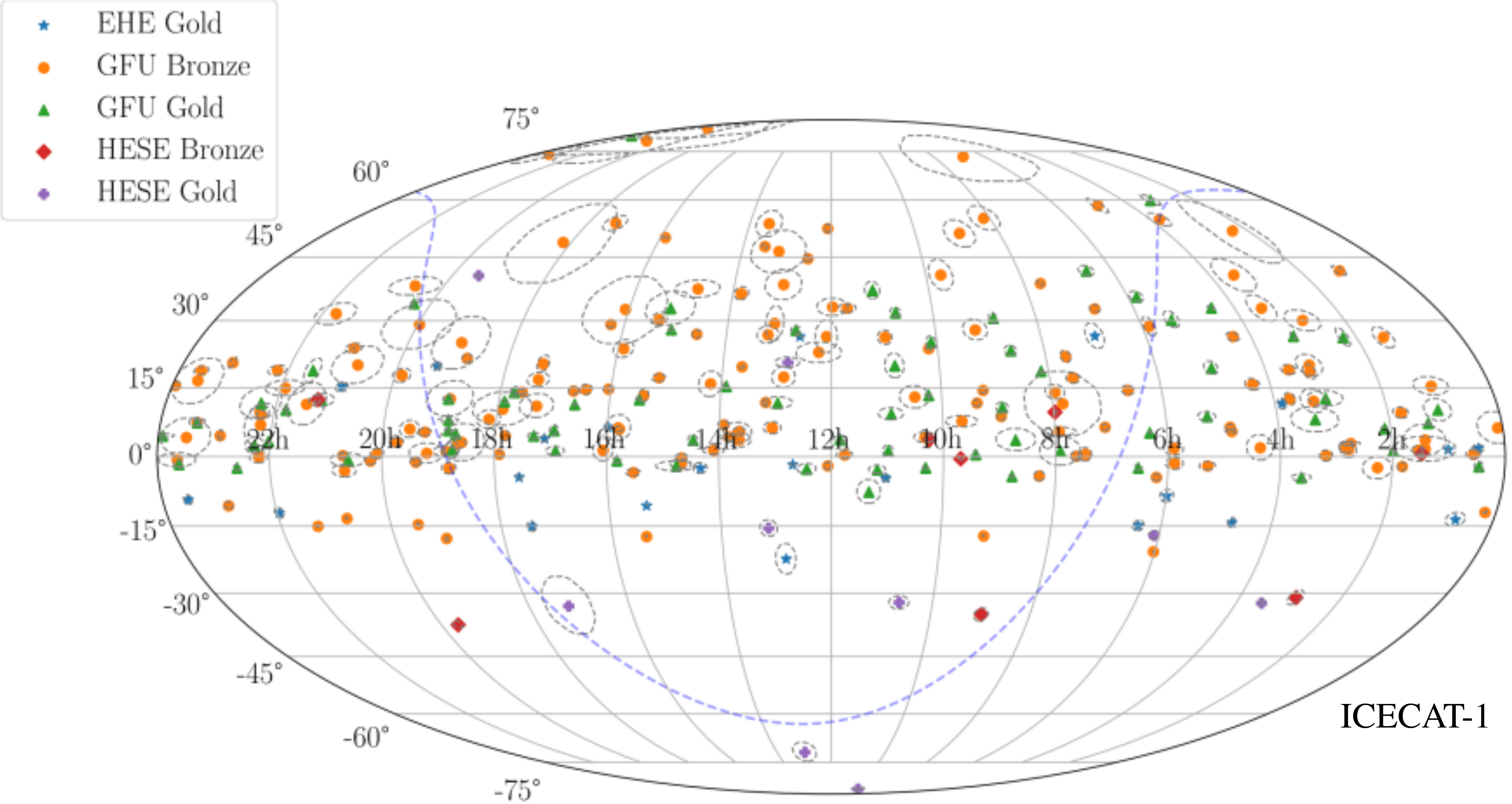
Detection of Cosmic Neutrinos



IceCube 2013 PRL

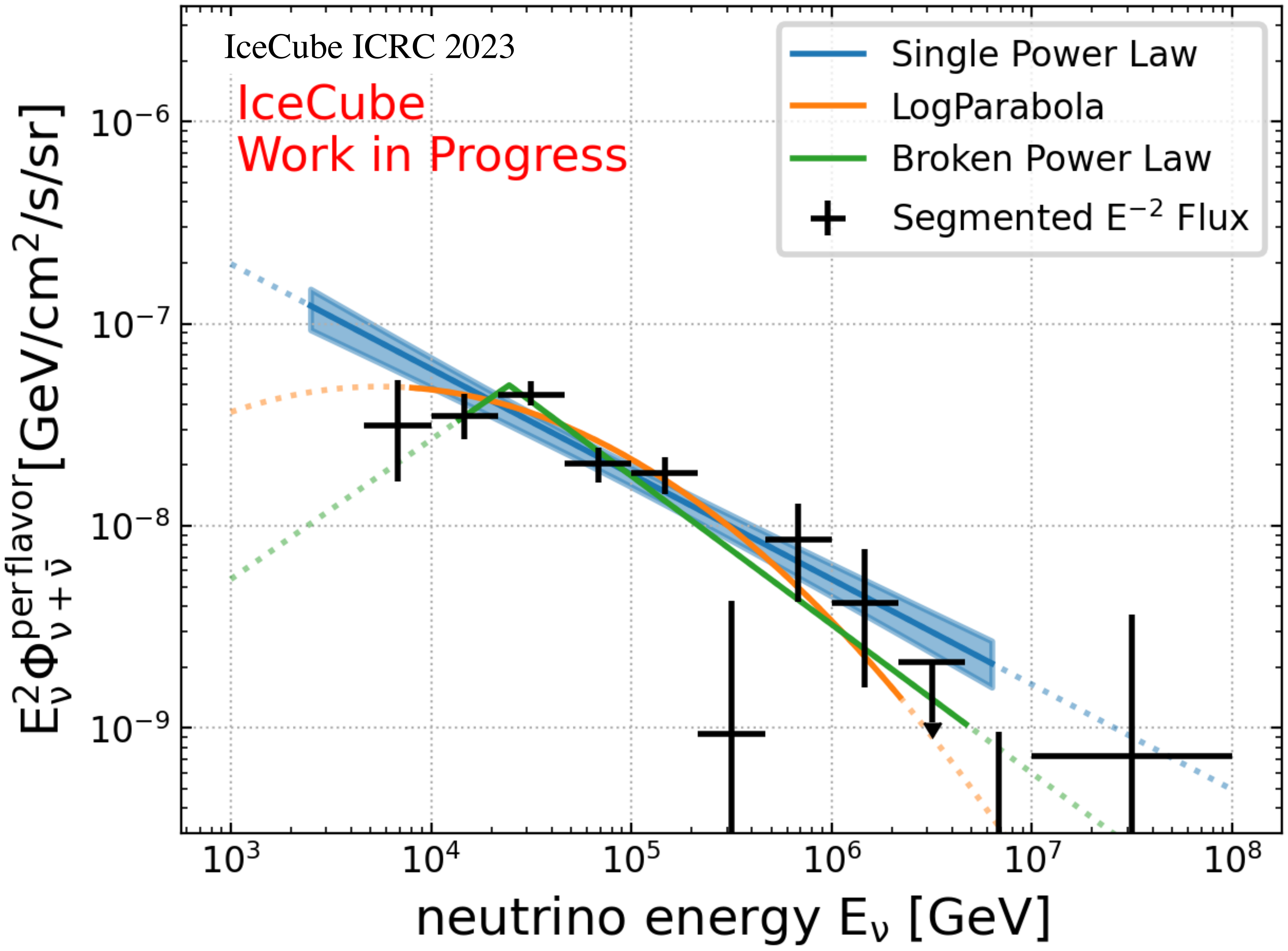


- IceCube reported detection of extraterrestrial neutrinos in 2013



- ~ 300 Cosmic neutrino candidates
- Isotropic distribution
  —> Cosmic high-energy neutrino background

Cosmic HE Neutrino Background Spectrum

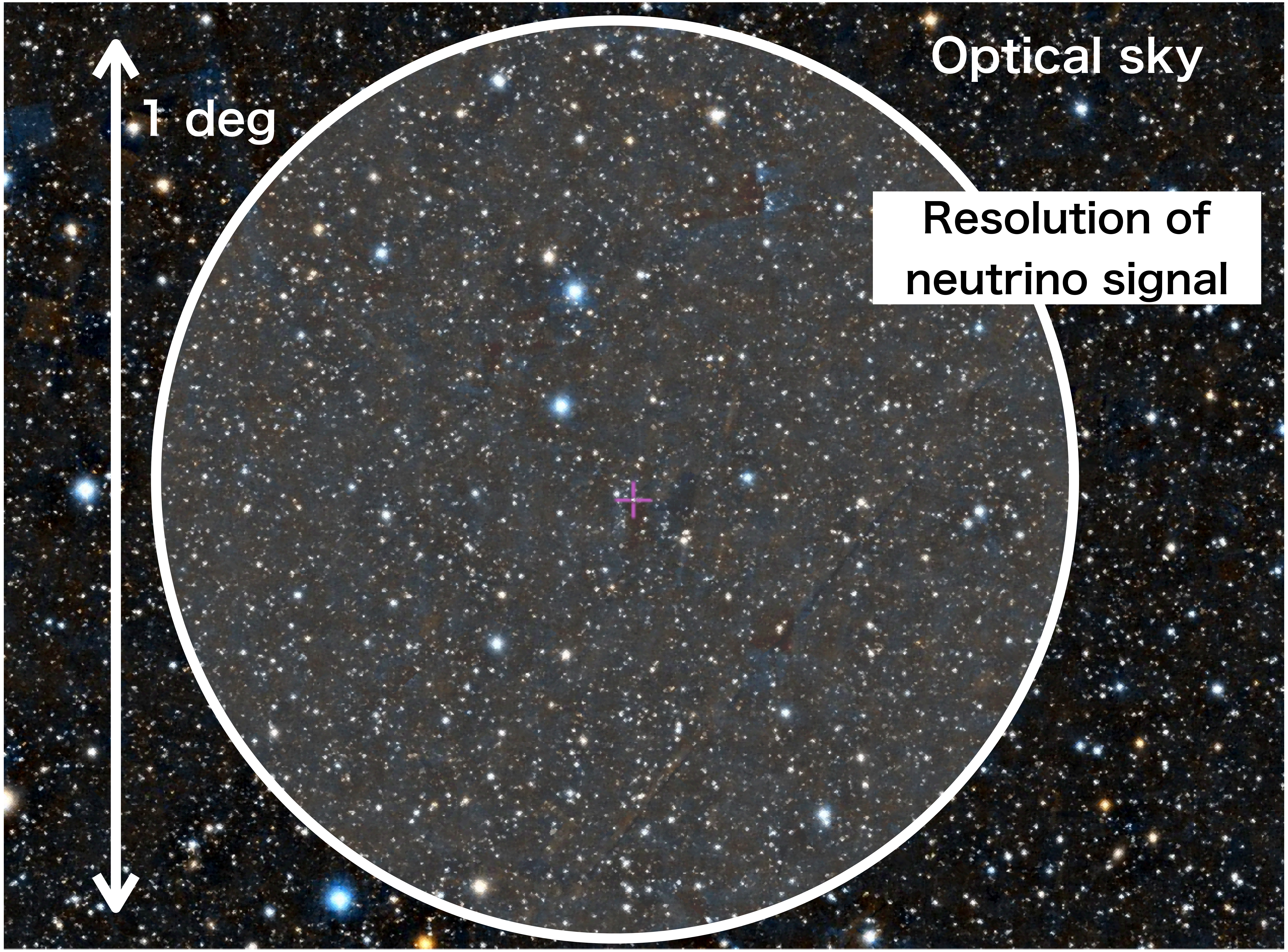


- Energy range: TeV-PeV
- Consistent with single power-law
- **Soft spectrum**

$$\frac{dN}{dE} \propto E^{-2.5}$$

Origin of cosmic ν bkgd is a new big mystery

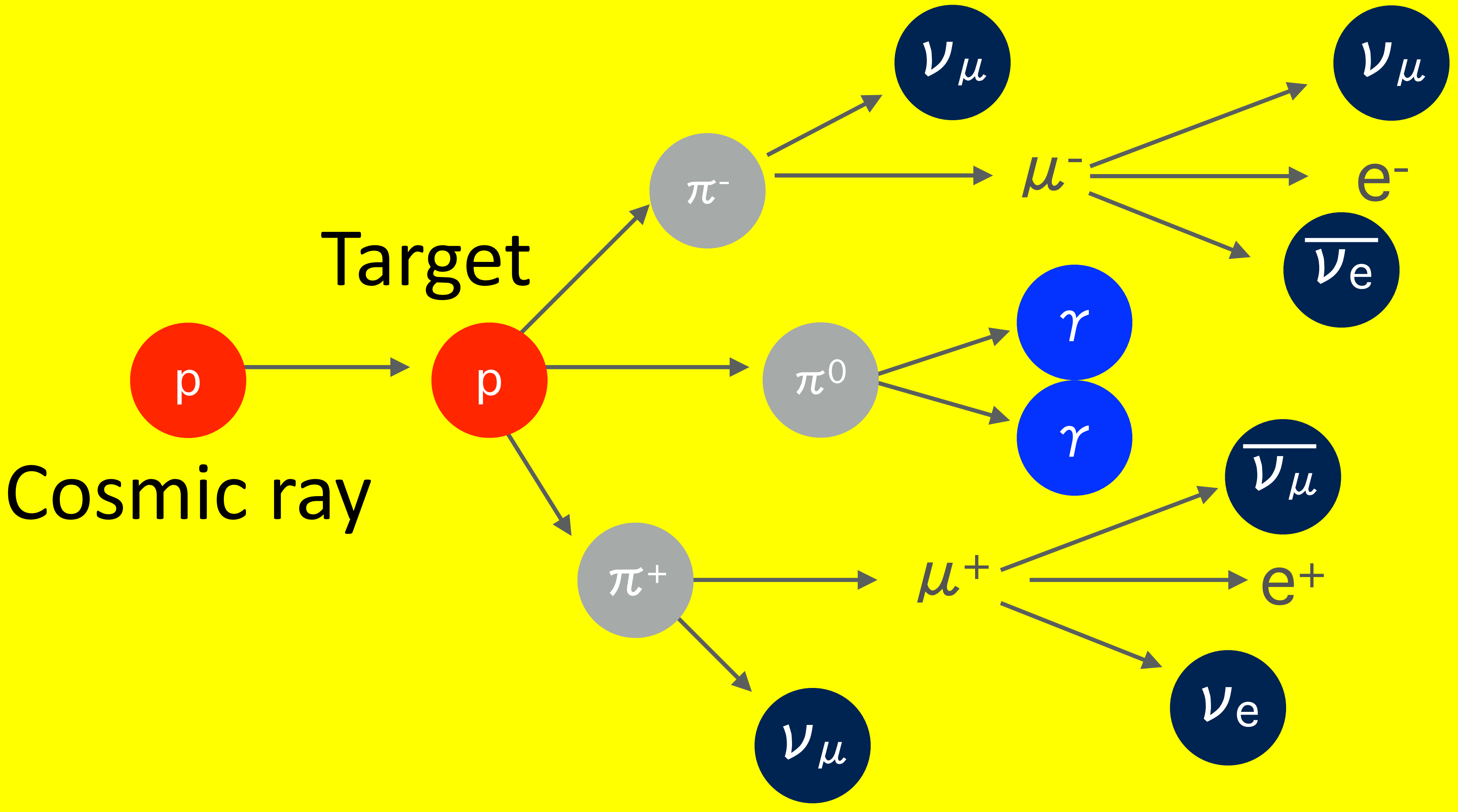
Difficulty for Neutrino Source Identification



- Optical telescopes
  ~ 1 sec (Subaru)
- Neutrino signals
  ~ 3600 sec (IceCube)
- Too many optical objects within error region
- Pick up source candidates
  —> Theoretical prediction

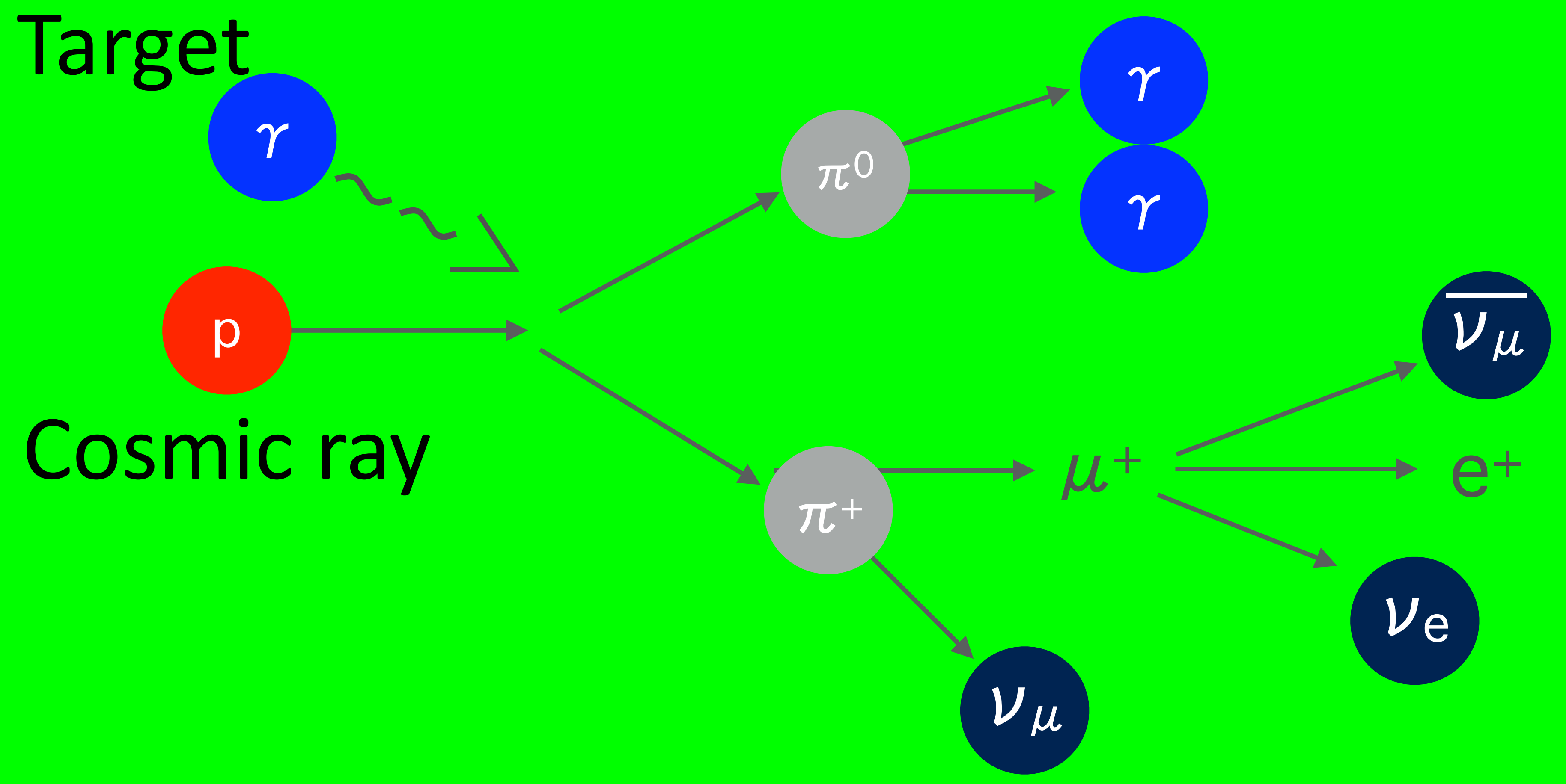
High-energy neutrino production

- pp inelastic collision



- p+p → p+p+π
- π^±→ 3ν+e
- π⁰→2γ

- Photomeson production (pγ)



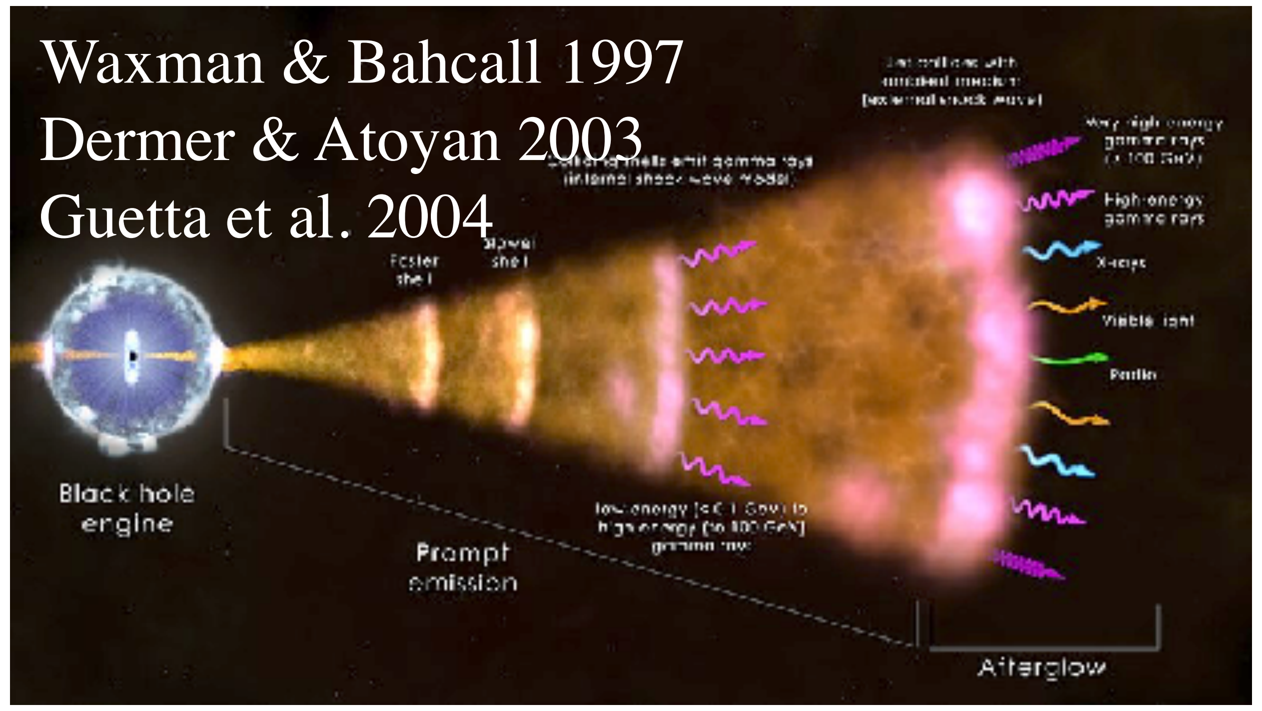
- p+γ → p+π
- π^±→ 3ν+e
- π⁰→2γ

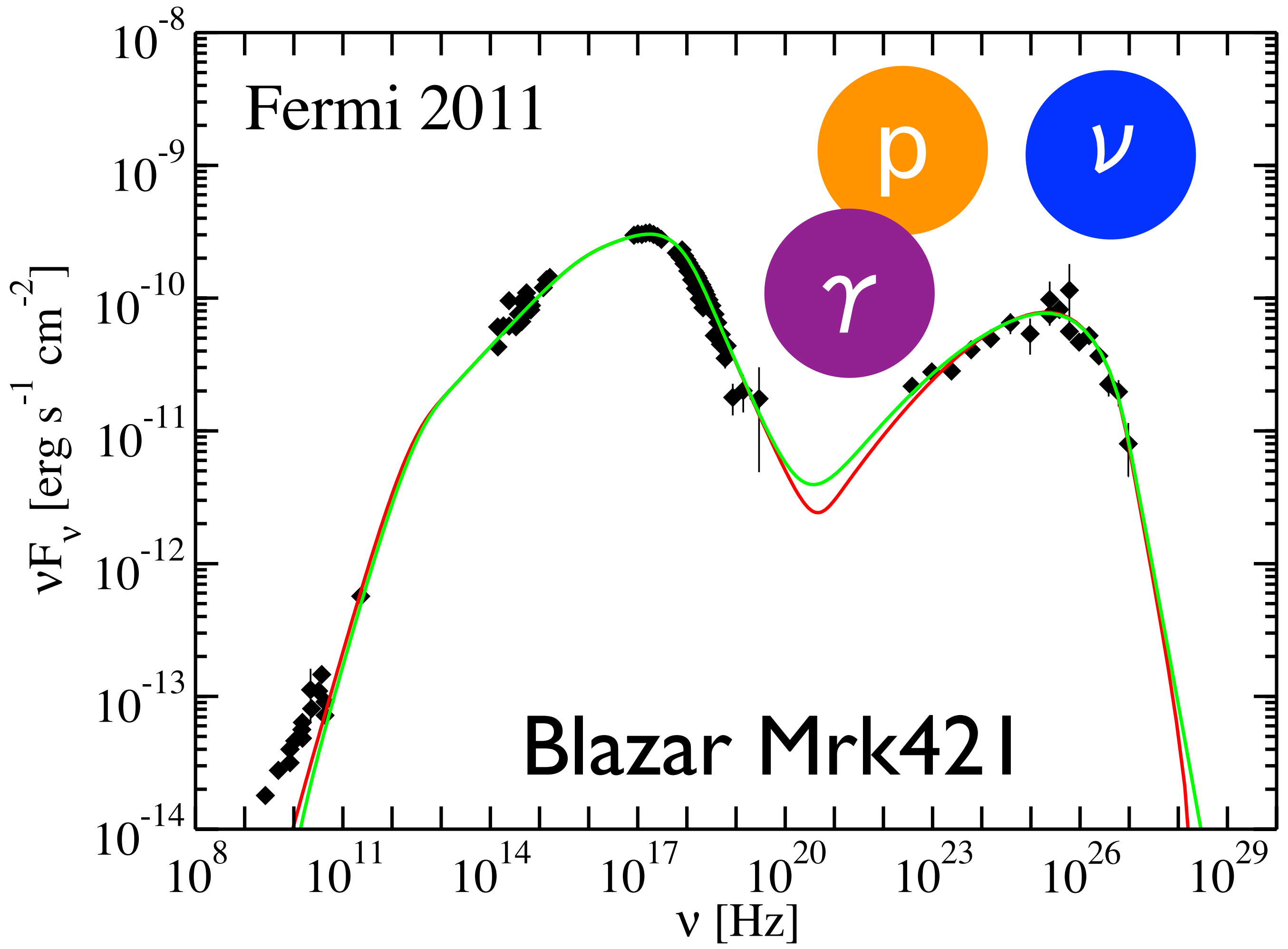
Interaction between CRs & photons/nuclei → Neutrino production

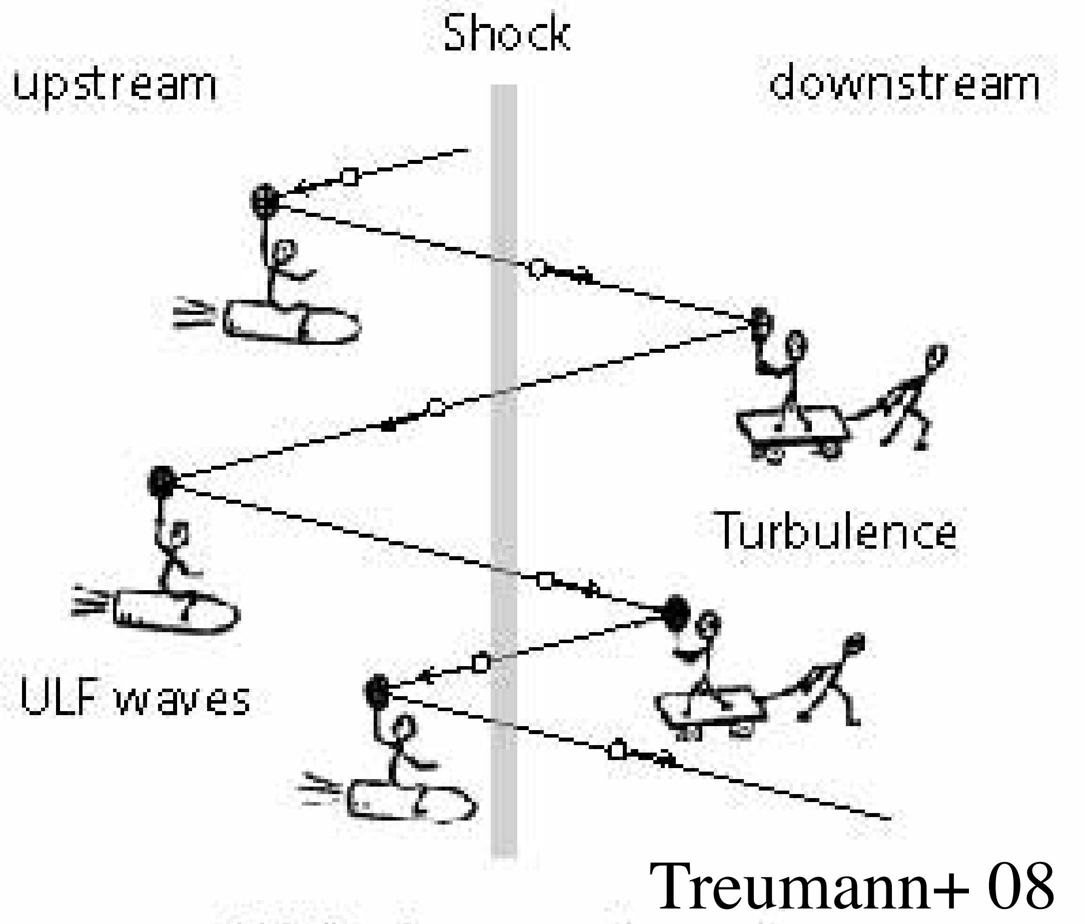
Gamma-rays inevitably accompanied with neutrinos

Source Candidates

- **Cosmic-ray accelerator** pγ
  - Gamma-ray Bursts
  - Blazars

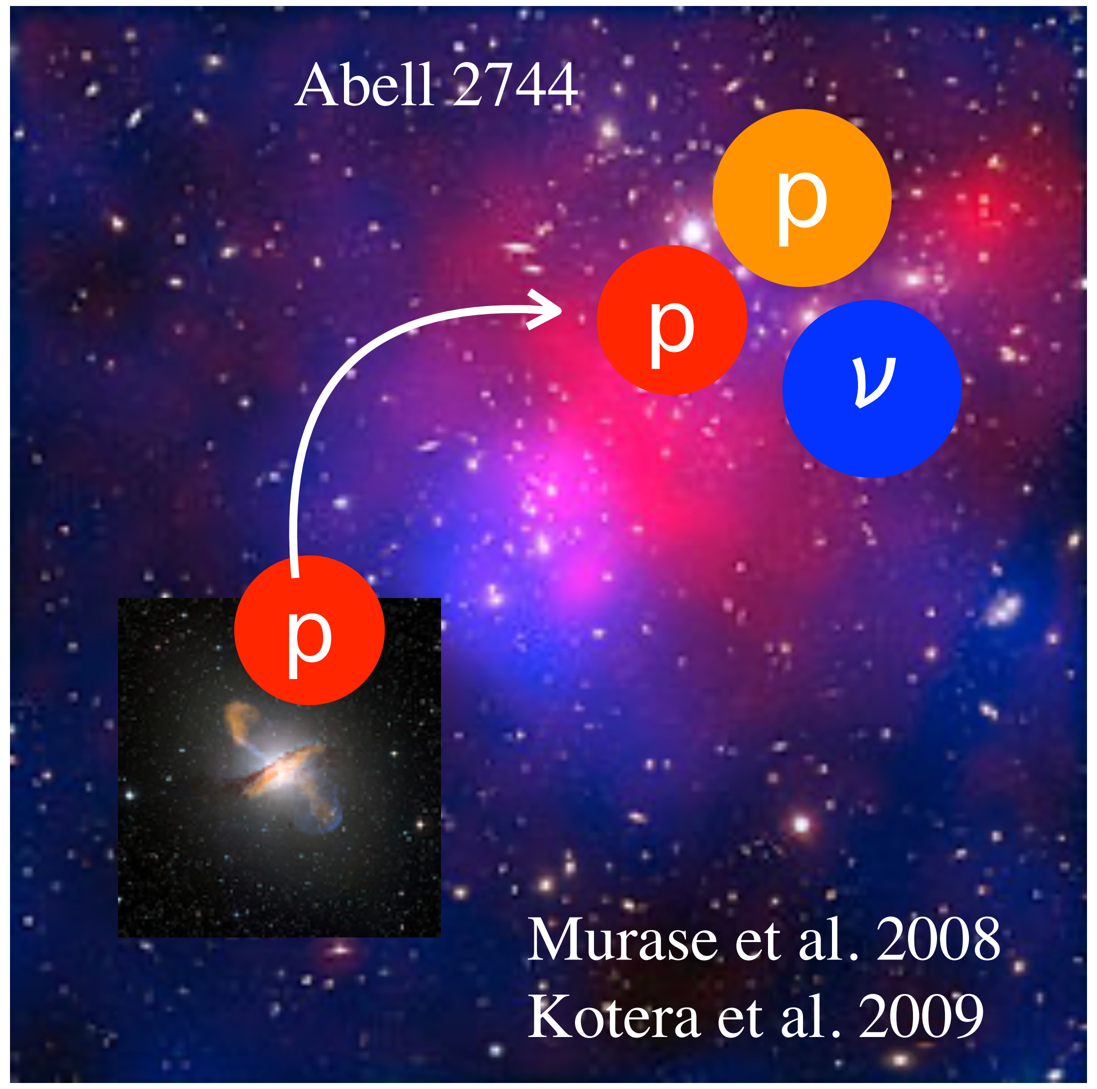


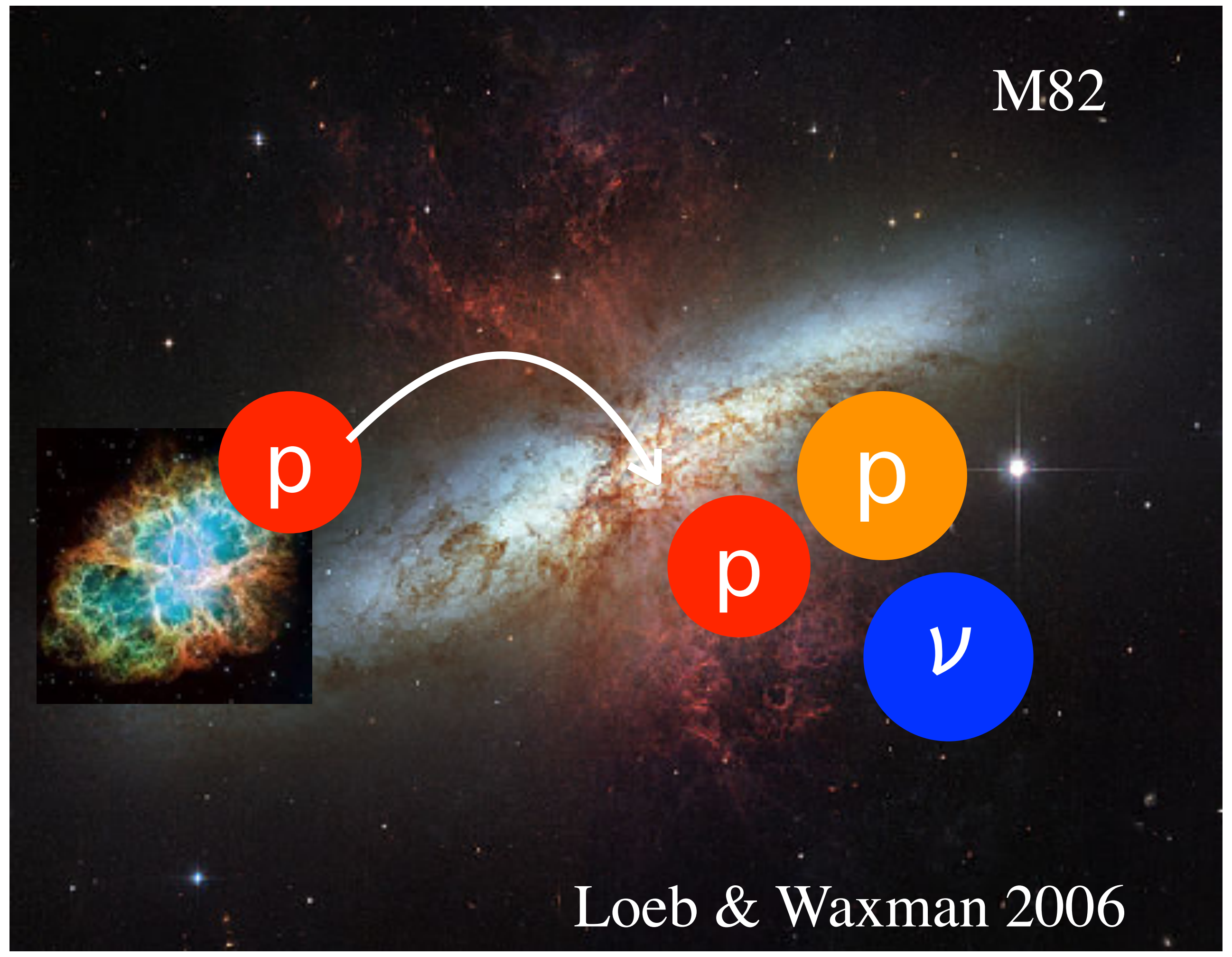




Diffusive acceleration

- **Cosmic-ray Reservoir** pp
  - Galaxy Clusters
  - Starburst Galaxies

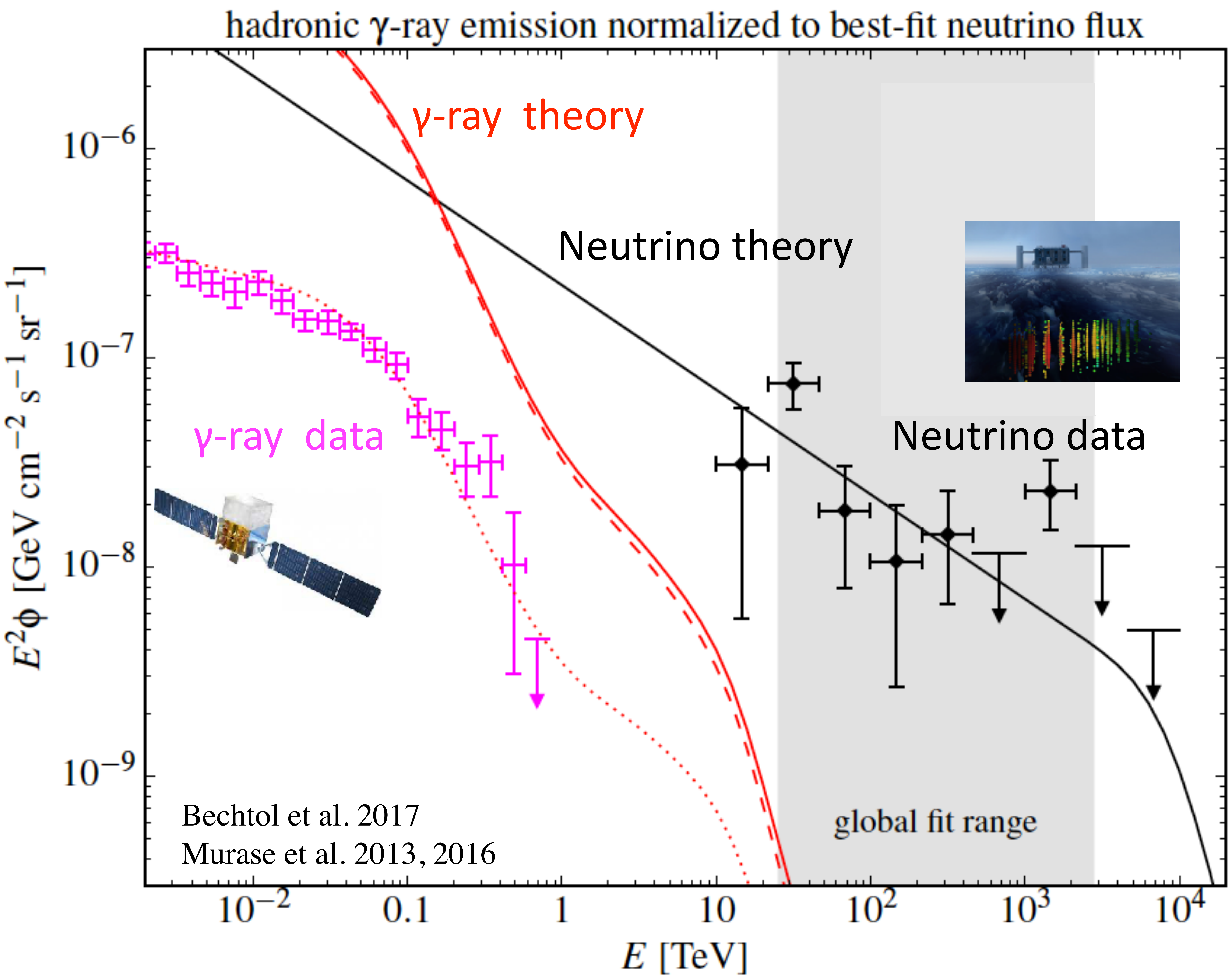




CR accelerators inside reservoir
→ CR trapped in reservoirs
→ Neutrino production by pp

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



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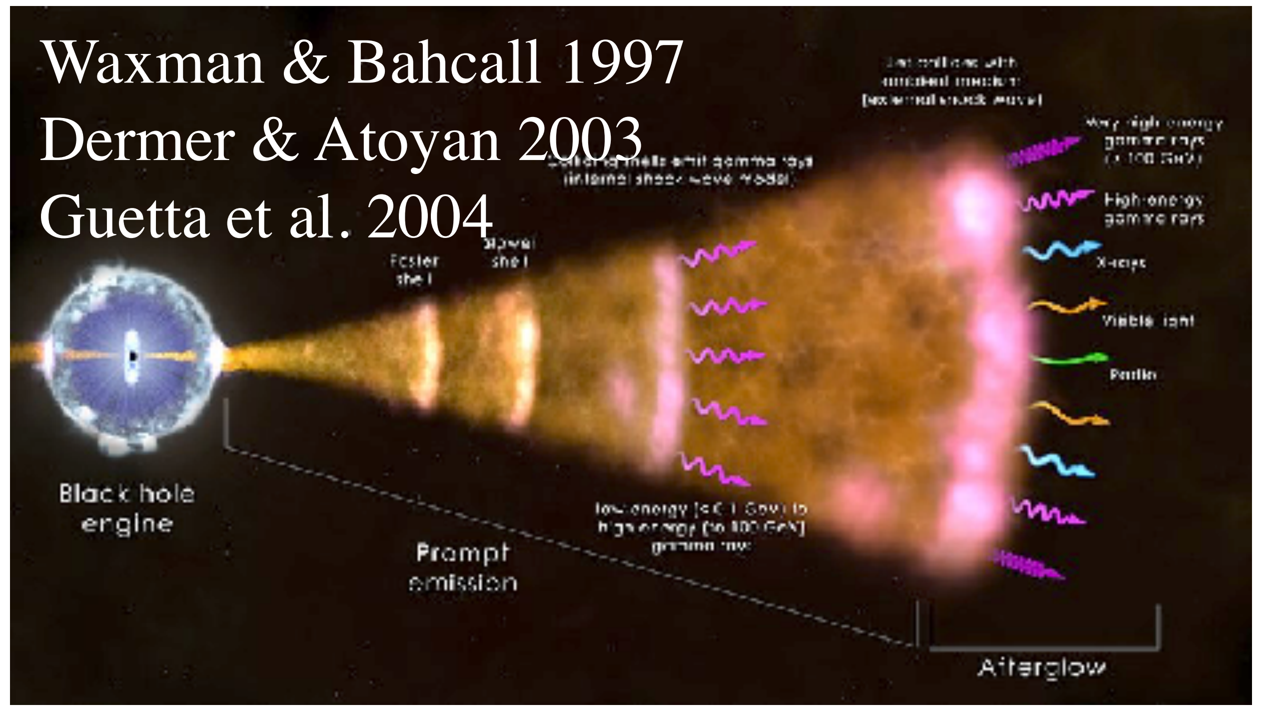

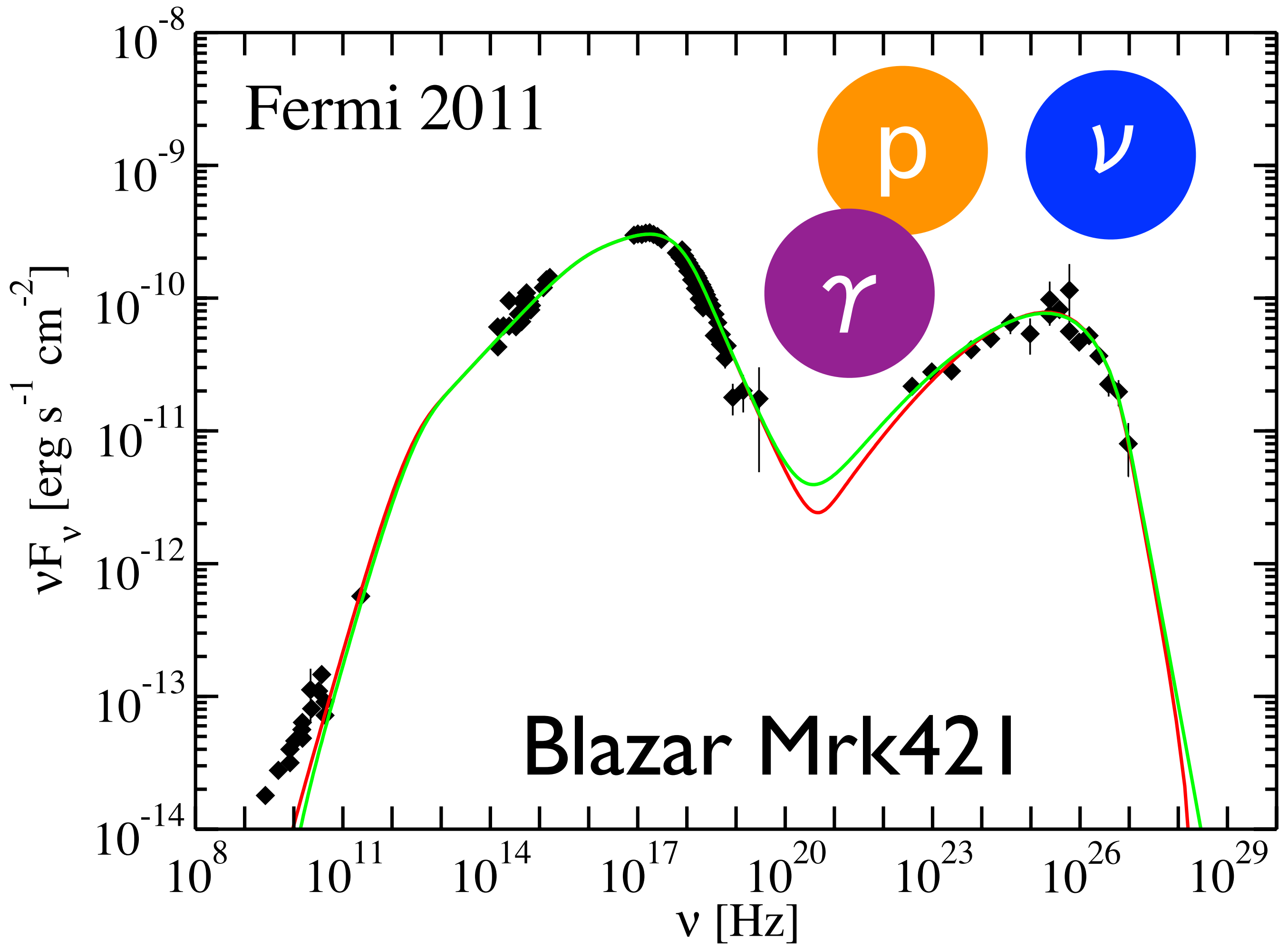

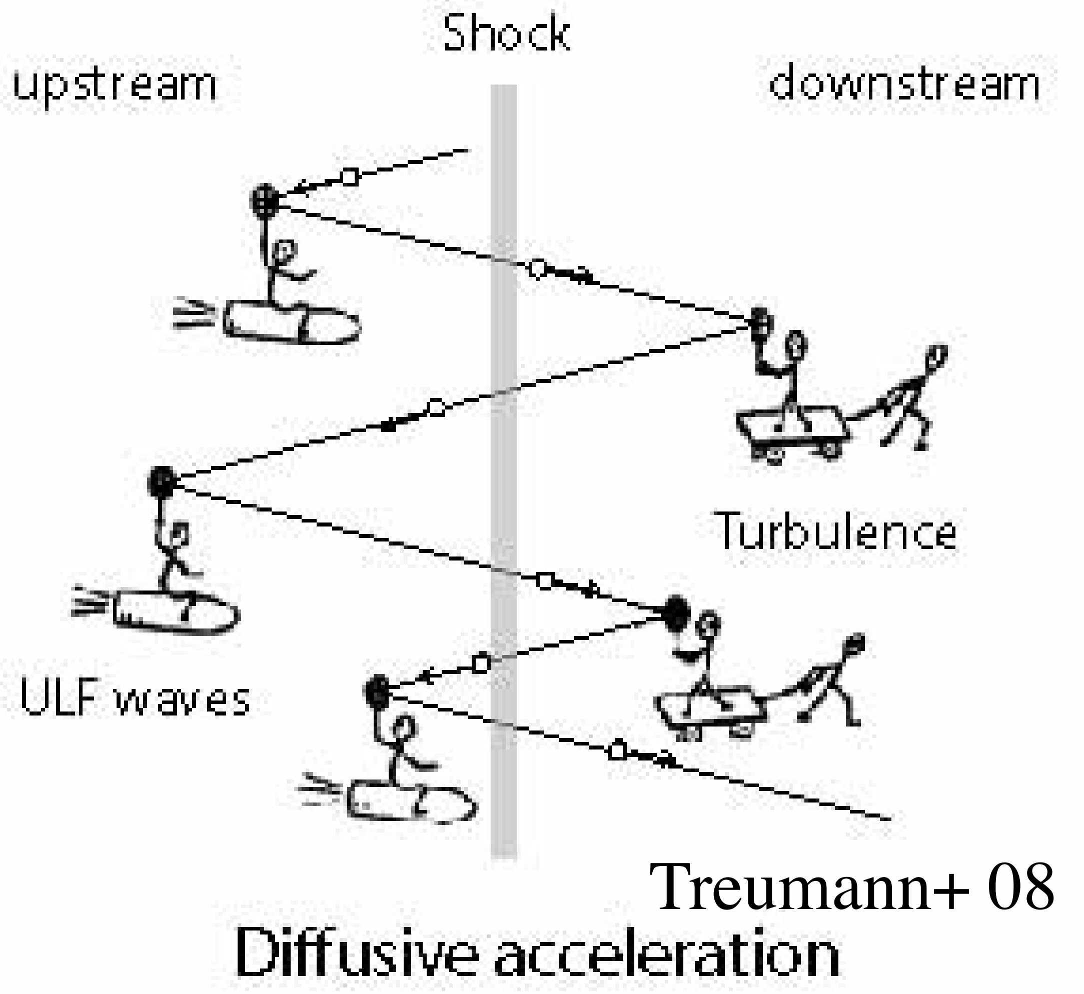

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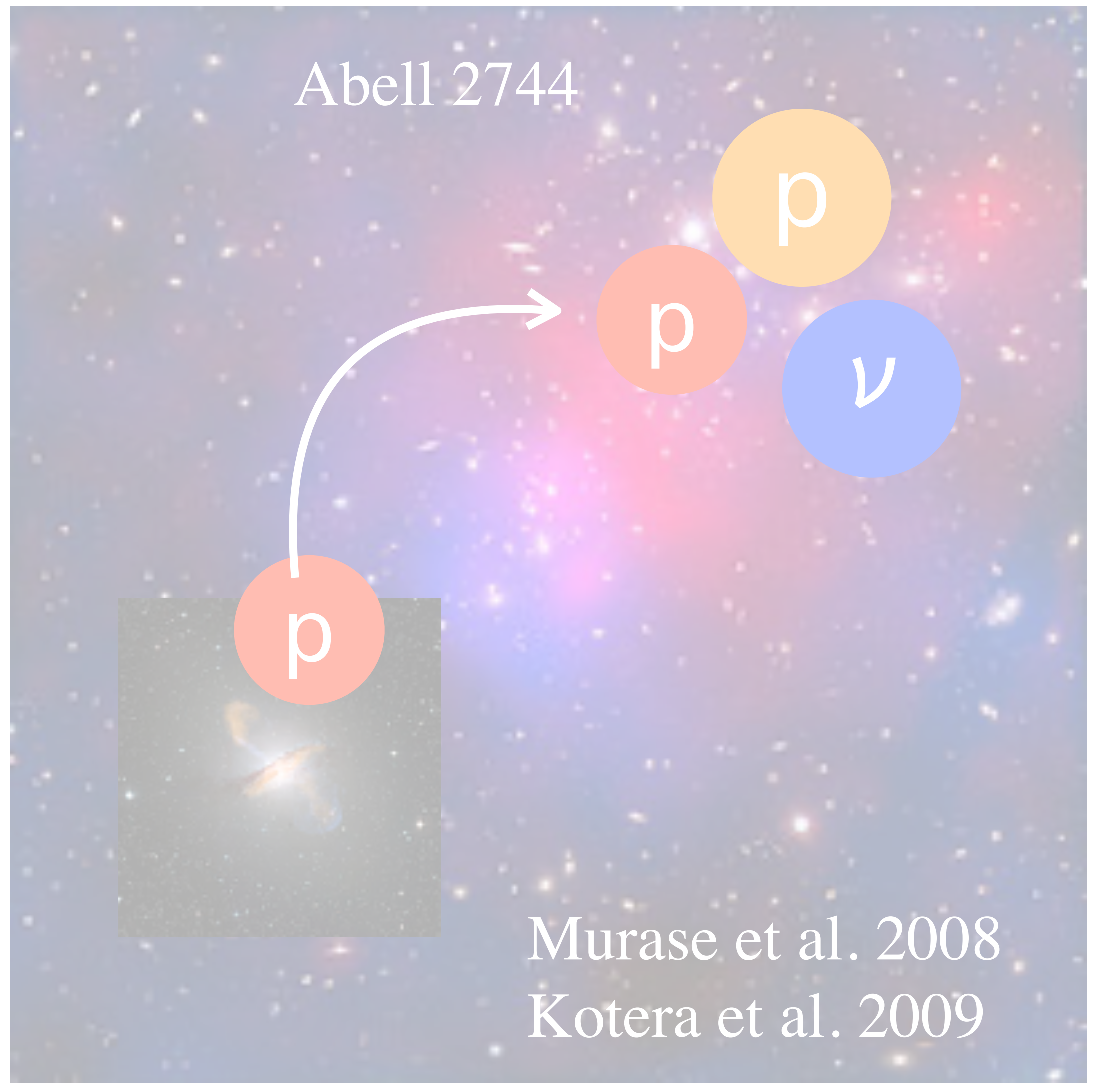
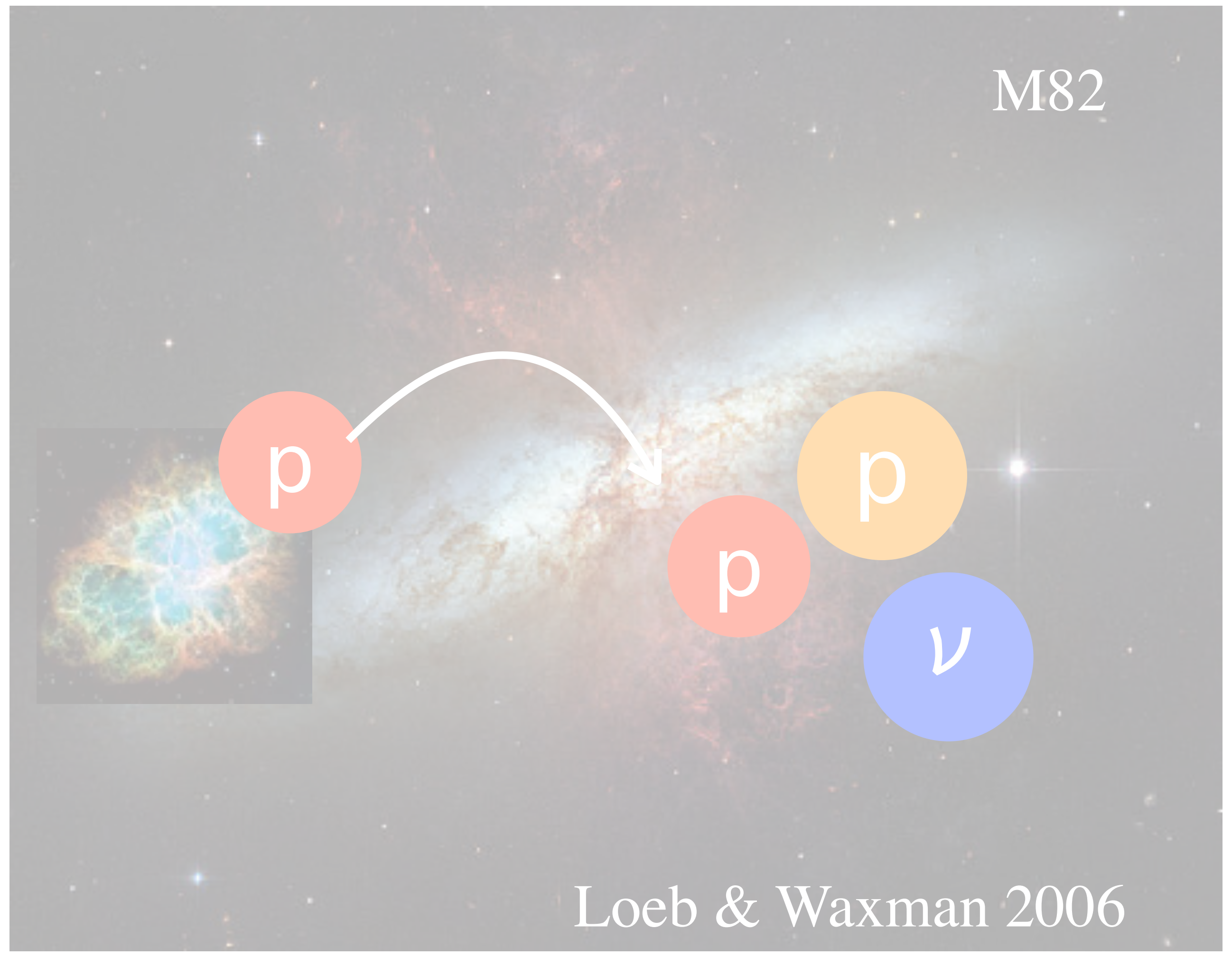




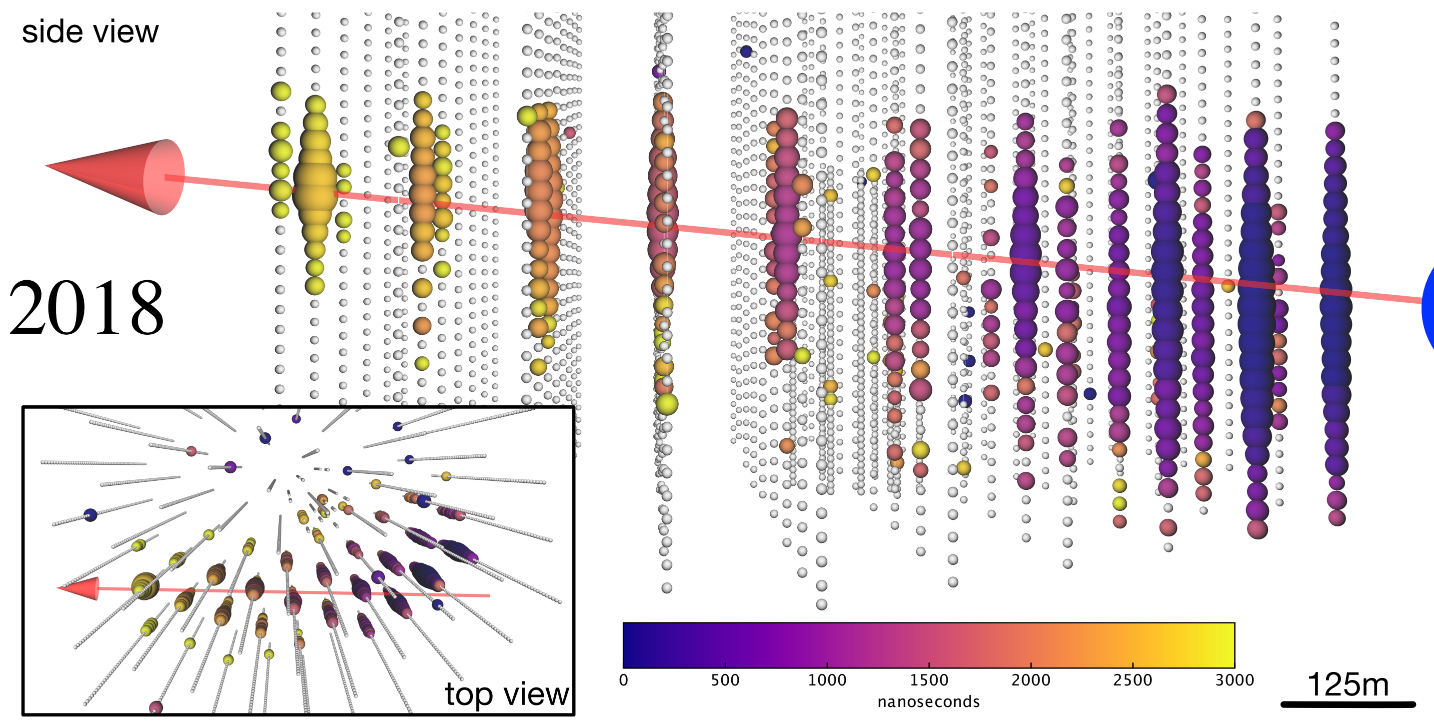
CR accelerators inside reservoir
→ CR trapped in reservoirs
→ Neutrino production by pp

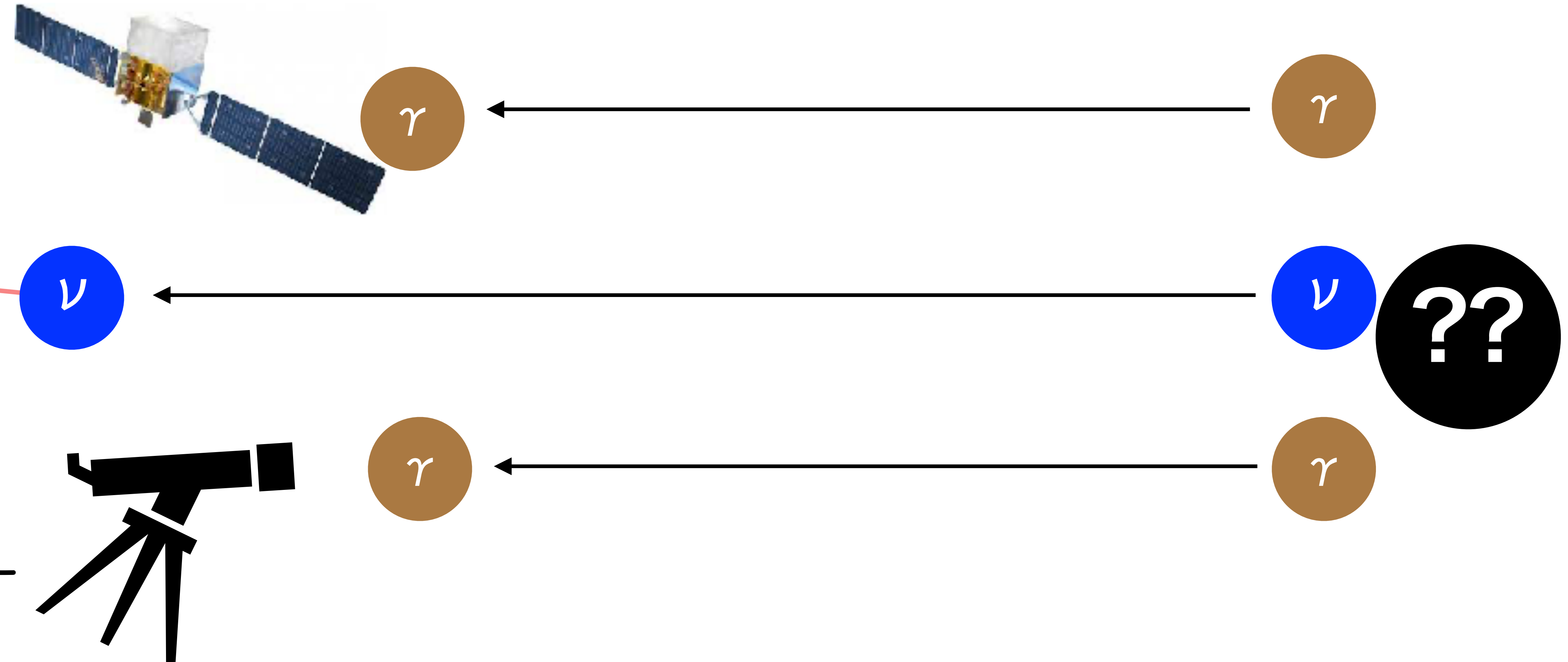
How to find neutrino sources

- Catalog search ($\gamma \rightarrow \nu$)
  - Matching neutrino data with EM source catalog
    → Neutrino source identification
  - Applicable to any kind of sources
  - Cannot control catalog quality

- Follow-up program ($\nu \rightarrow \gamma$)
  - EM follow-up observation to cosmic neutrino signal
    → Neutrino source identification
  - Applicable only to transients
  - Deeper observation possible

IceCube 2018





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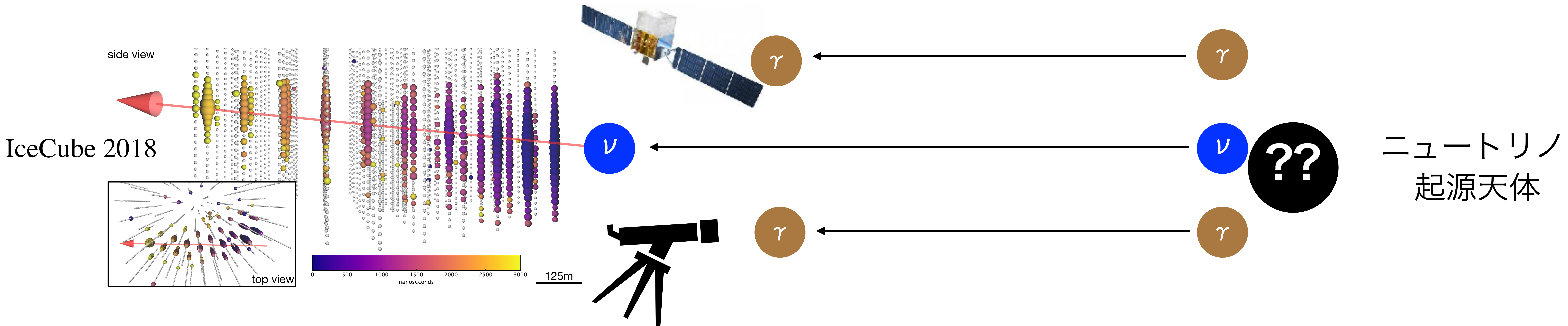
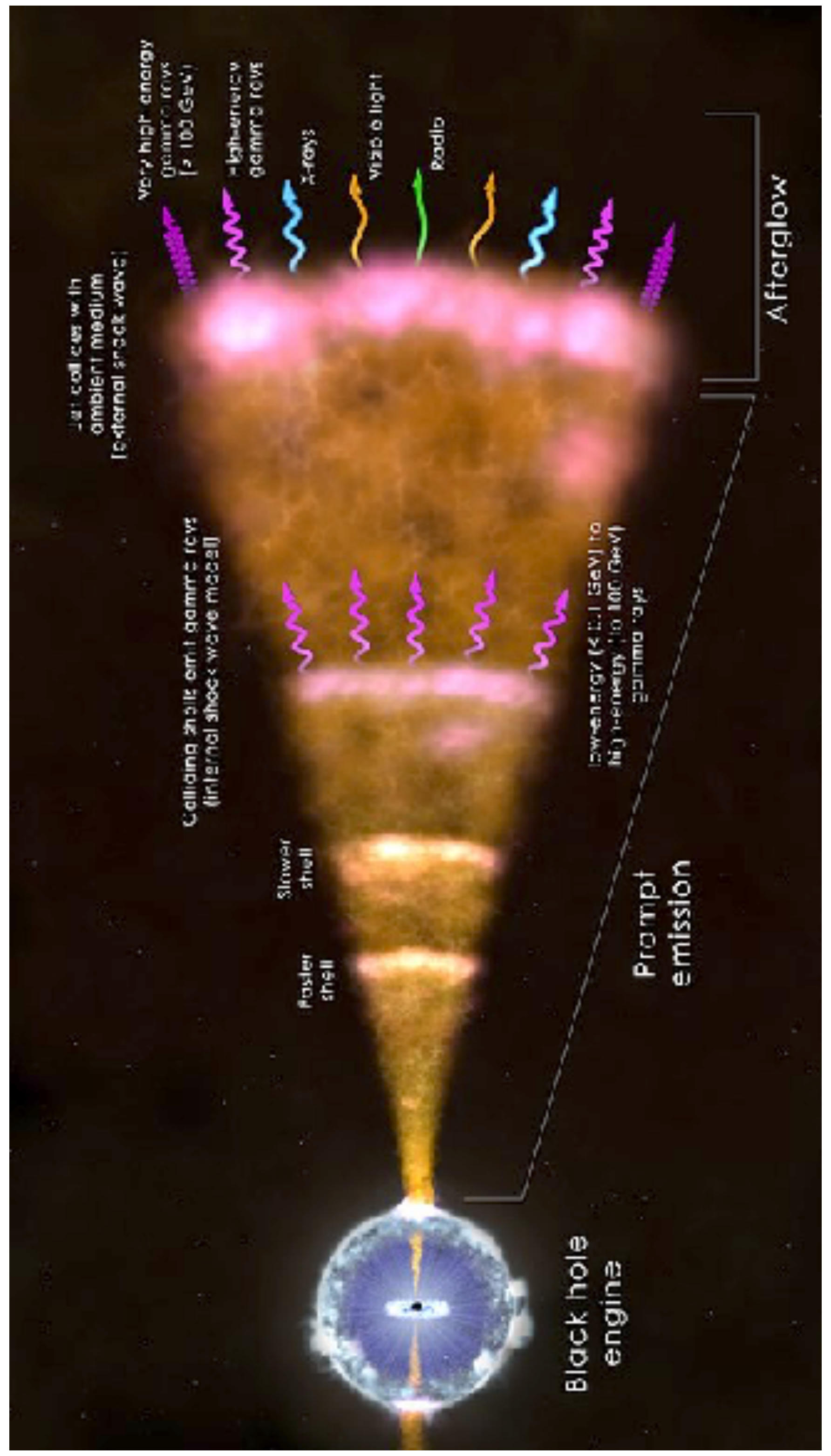
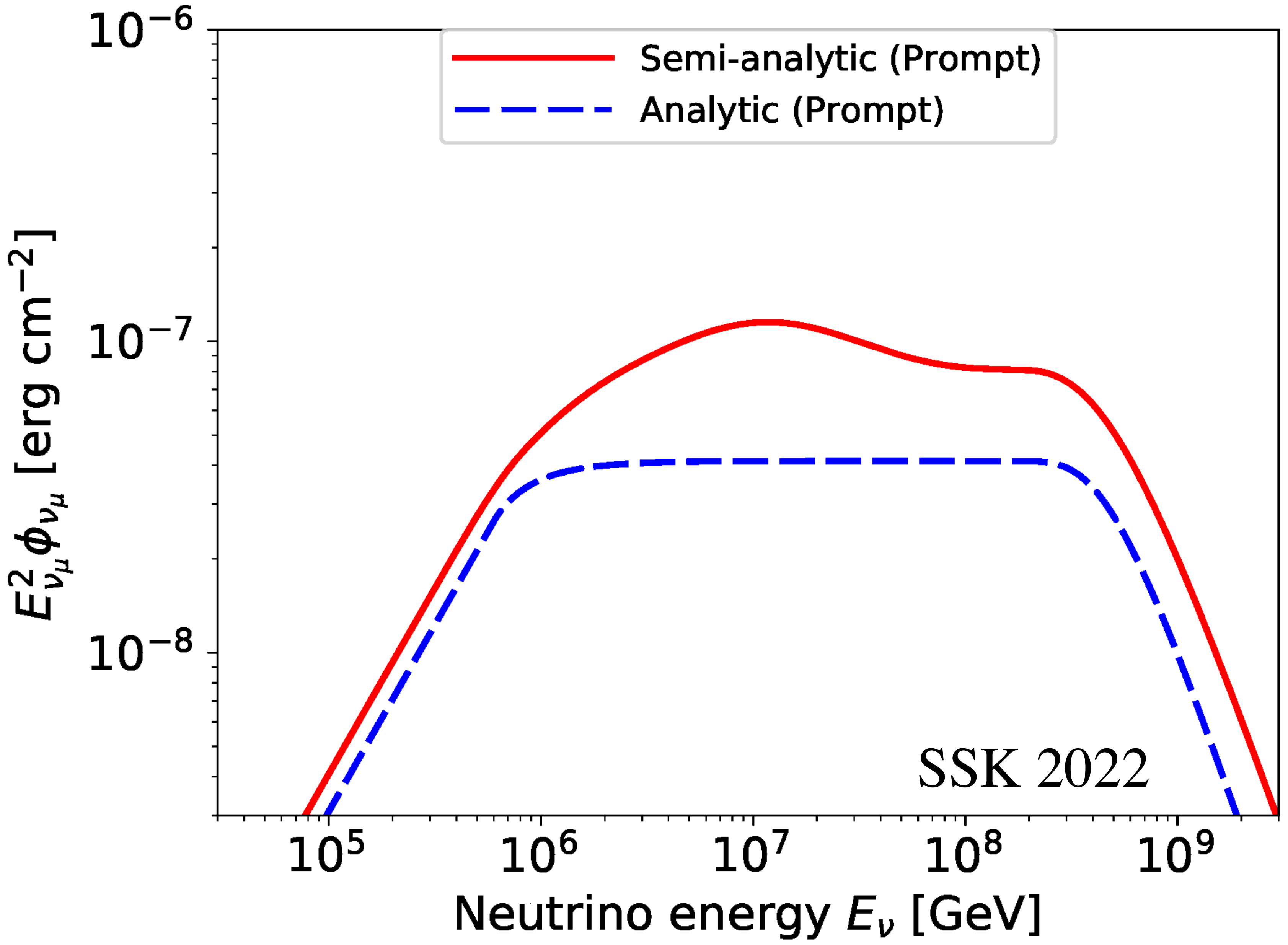
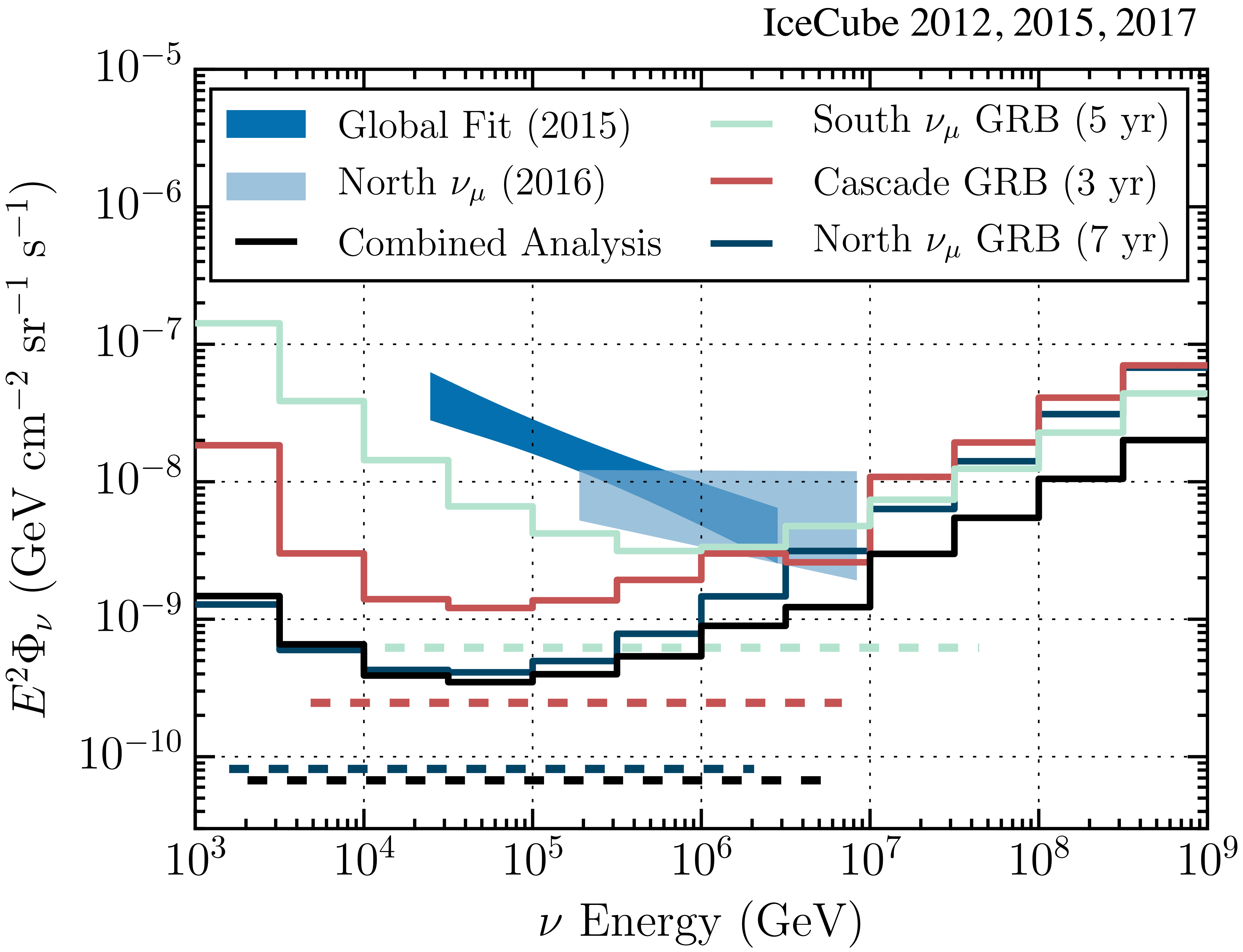


Stacking Analysis (GRBs)







- Stacking analysis of >1000 GRBs
  → No associated neutrinos
  → **Less than 1 % of cosmic neutrino background**

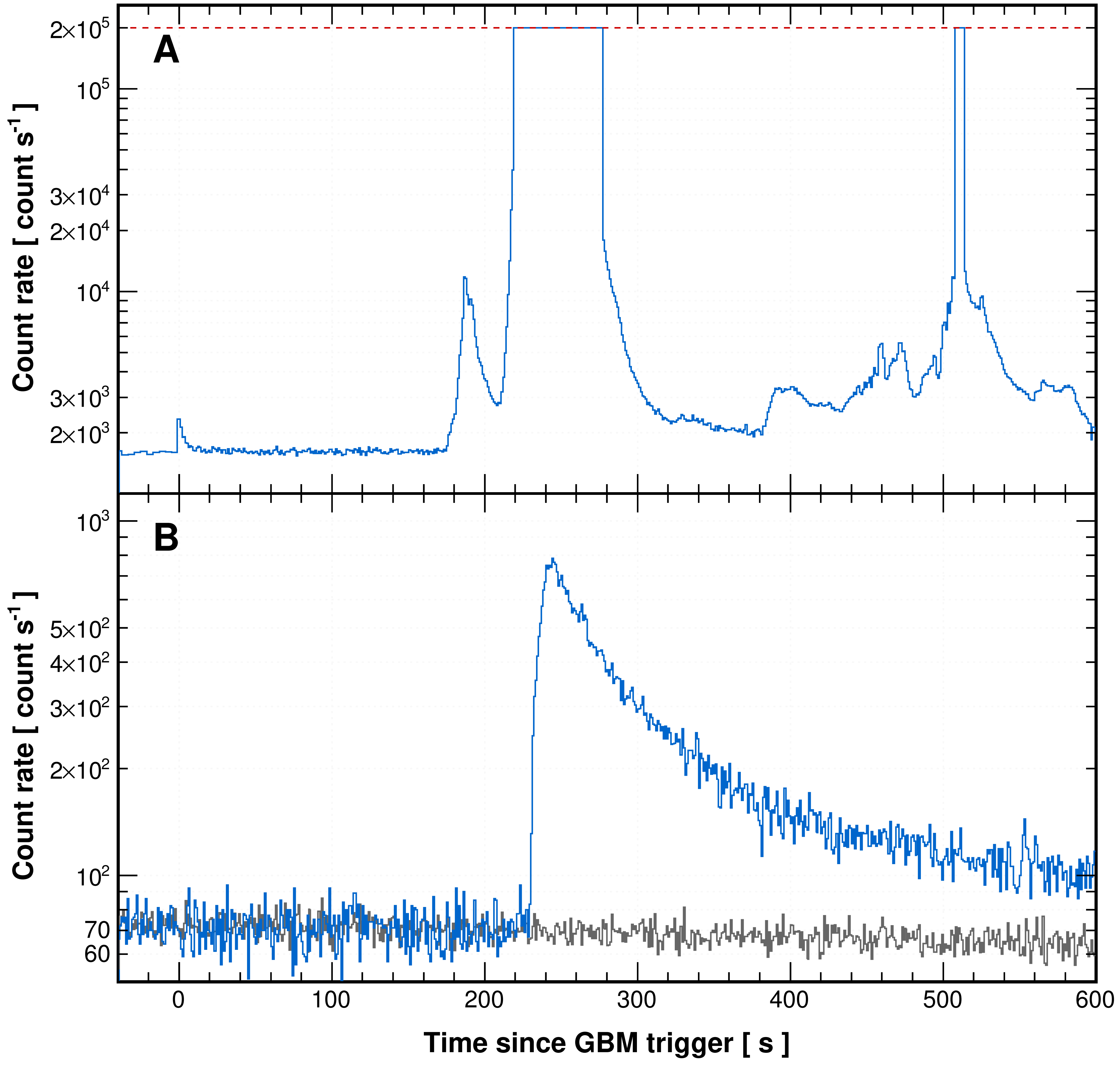
- Only the prompt phase is constrained
- Delayed emission may be still possible

Murase et al. 2006 PRL; SSK et al. 2017 ApJ;
but see IceCube 2022 for limit on delayed emission

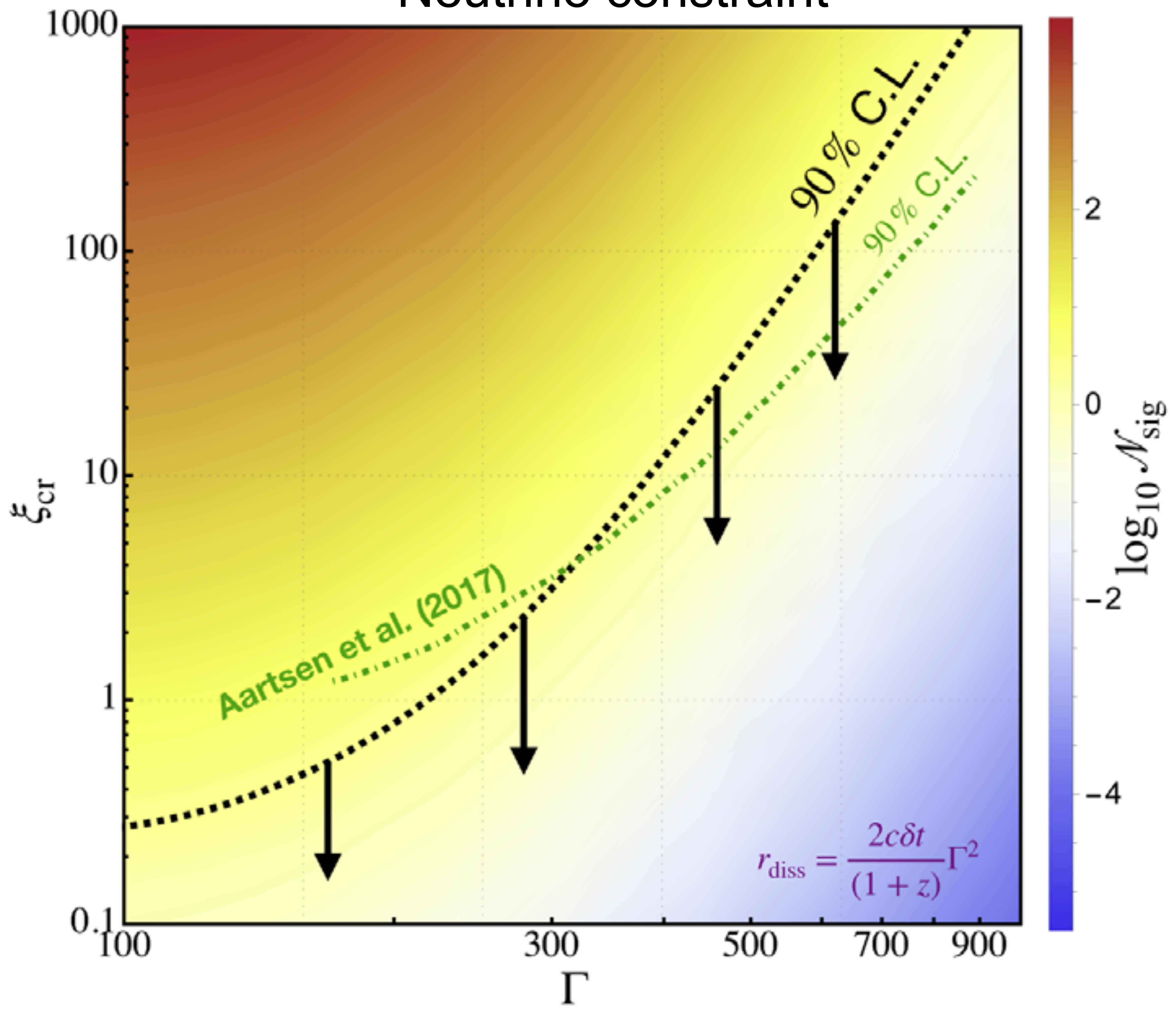
GRB221009A

Murase+, SSK+ 2022

Photon lightcurve

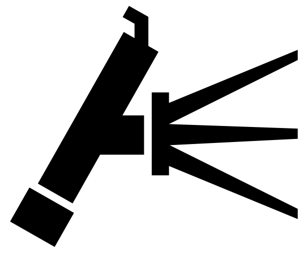


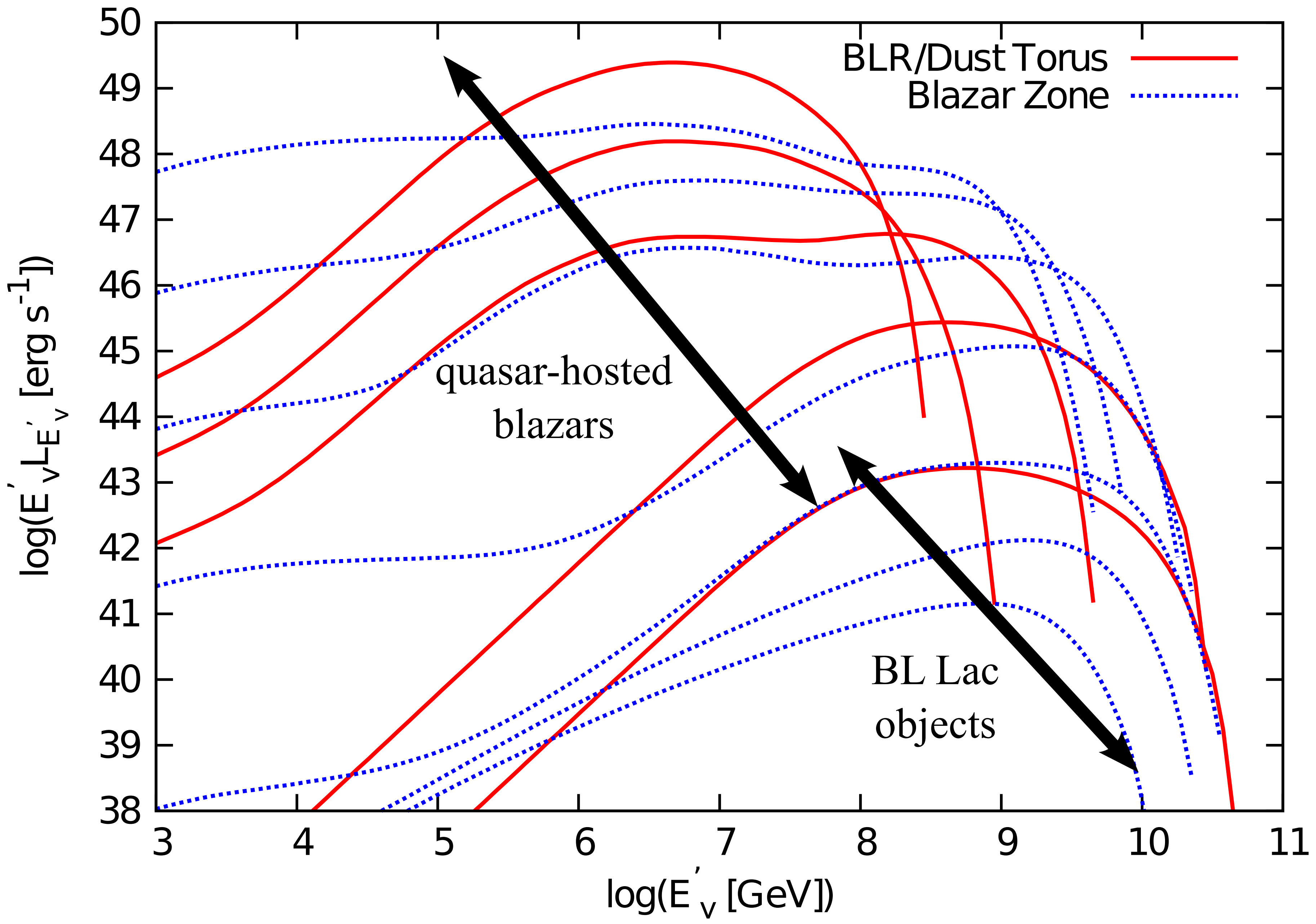
Neutrino constraint



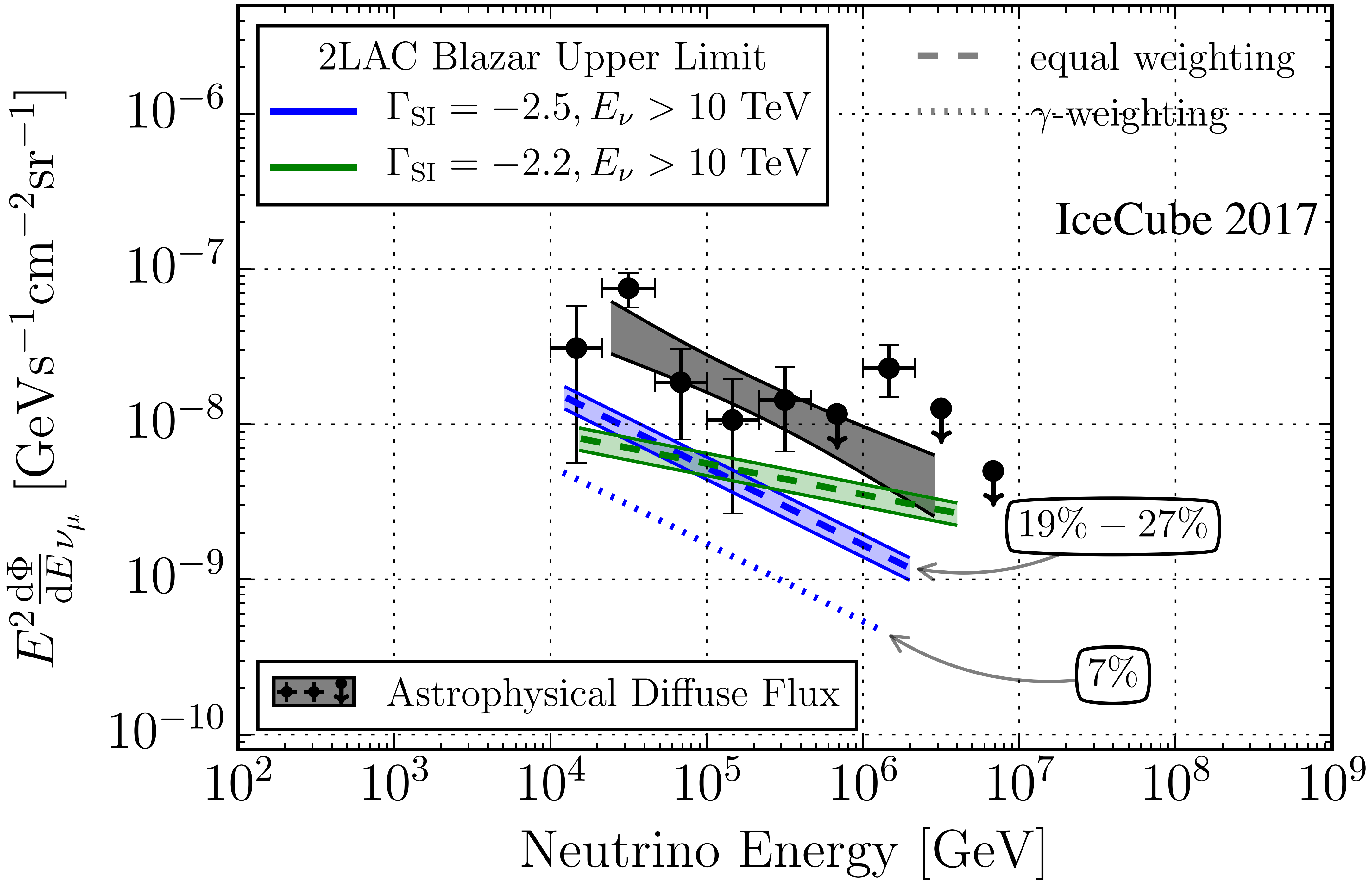
- Single event puts a limit comparable to ~1000 GRBs

Stacking Analysis (Blazars)





Murase et al. 2014



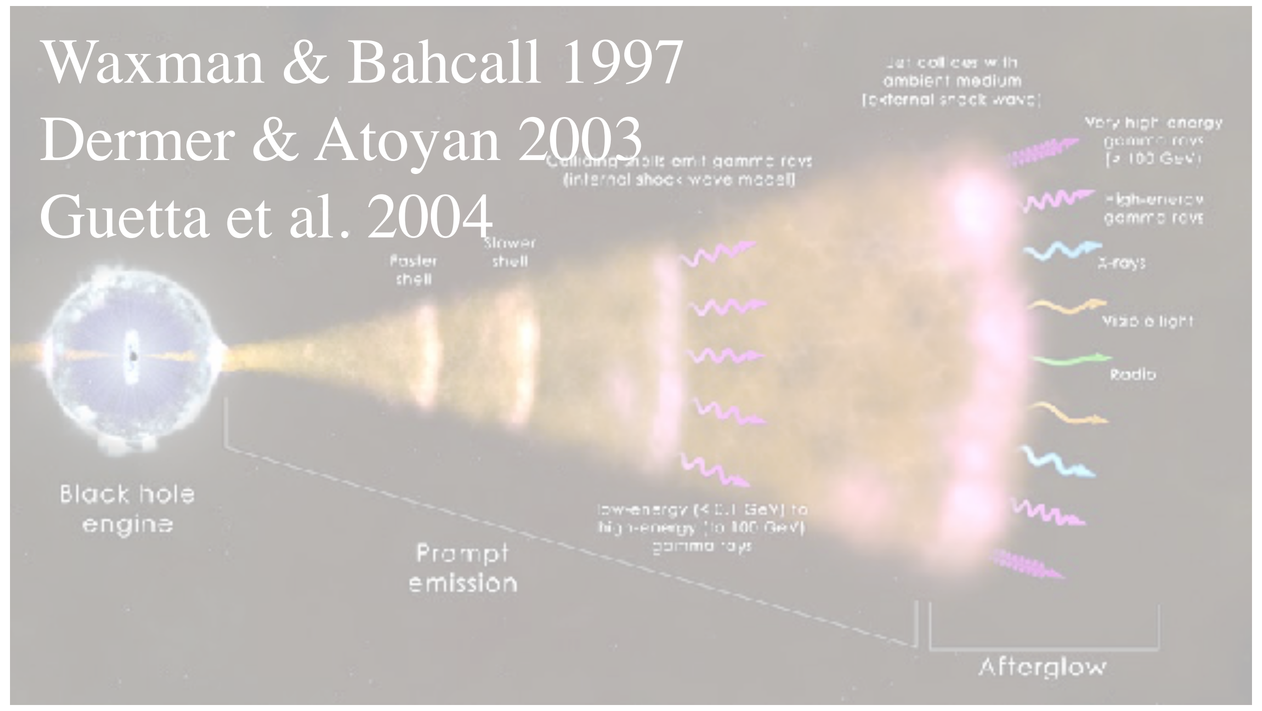
- Stacking analysis:
  862 GeV-emitting blazars
  → No associated neutrinos
  → **Less than 7 % of cosmic neutrino background**

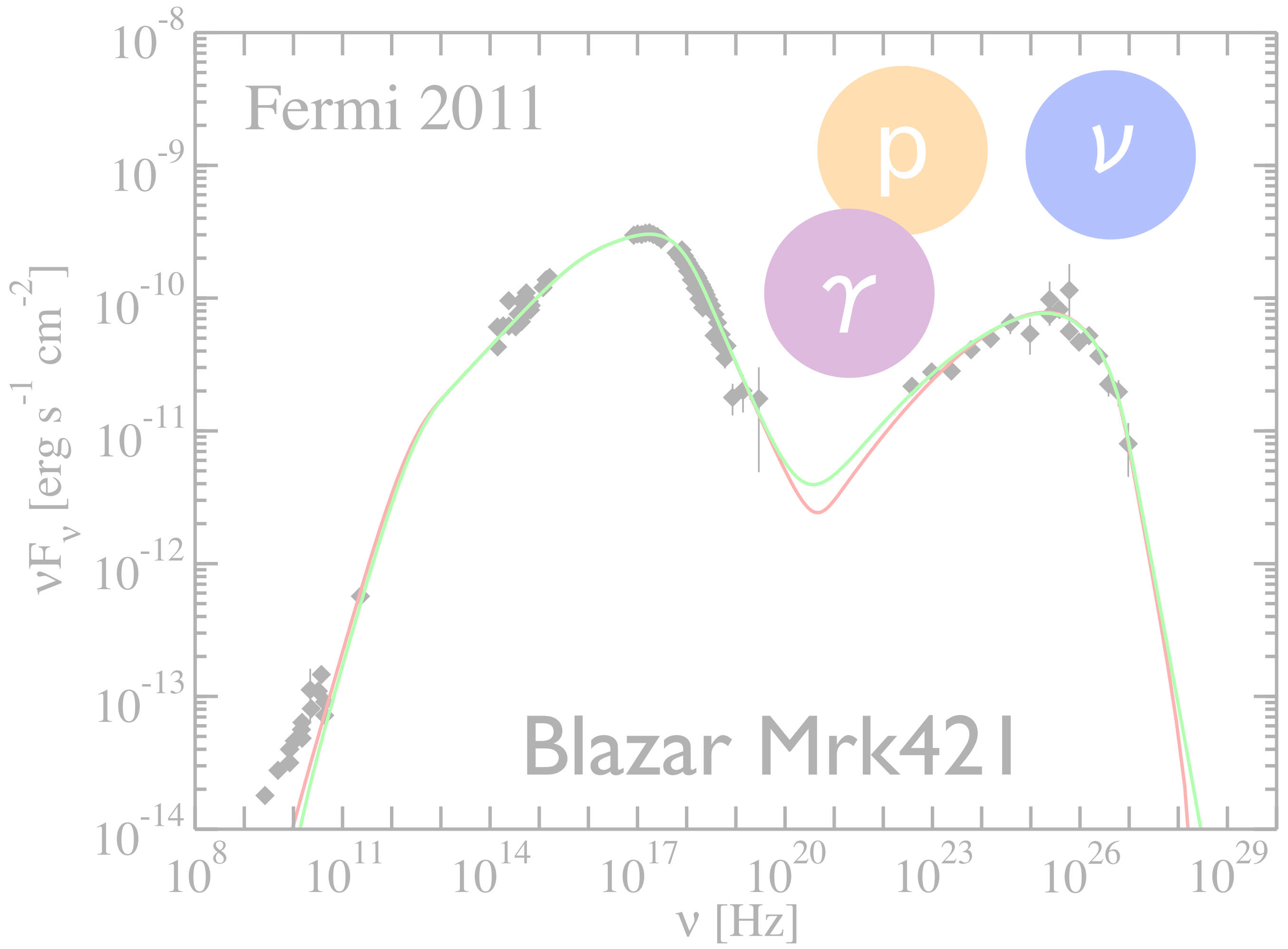
- This constraint is applicable only to Fermi-detected blazars
- Radio-selected blazars are also constrained, although results contradicting among group

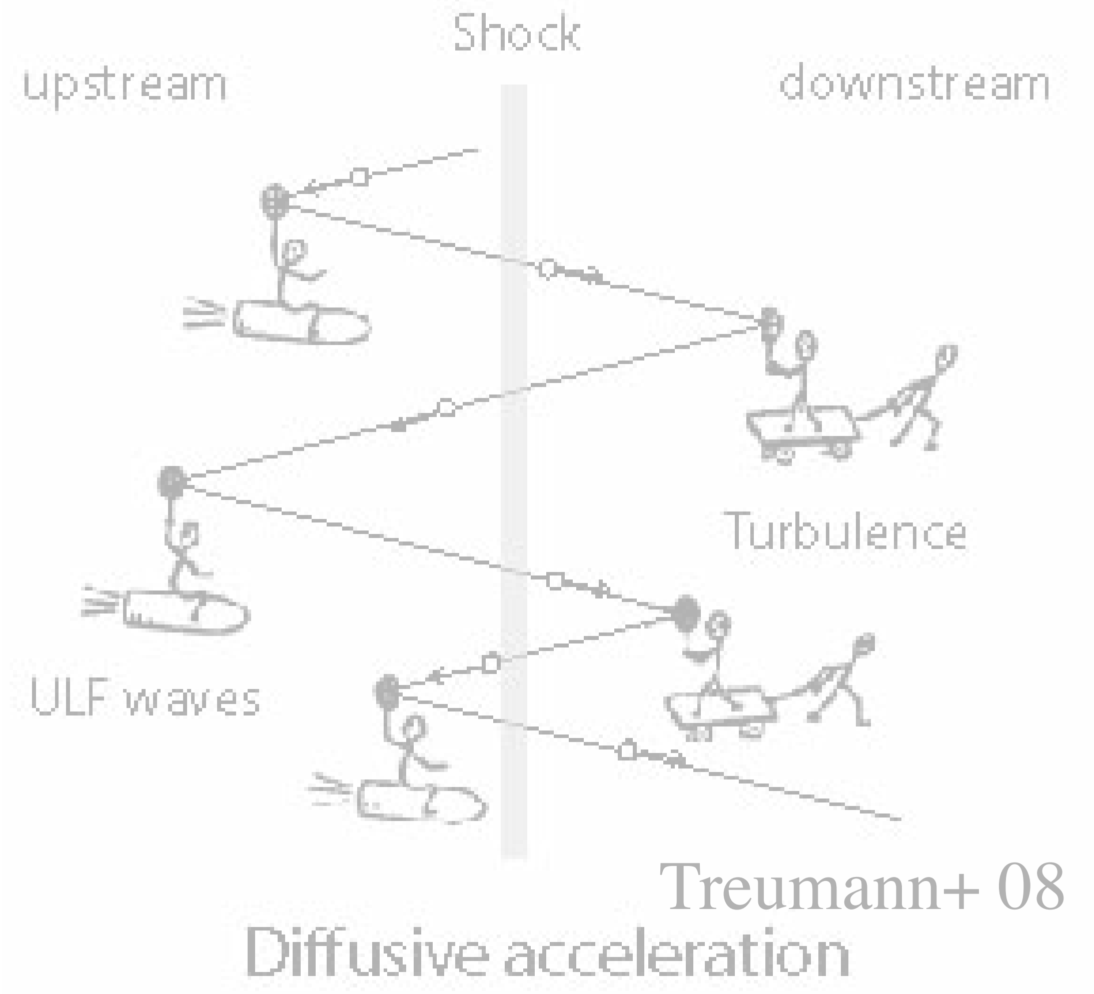
Plavin et al. 2021; Buson et al. 2022; Zhou et al. 2021

Source Candidates

- **Cosmic-ray accelerator** pγ
  - Gamma-ray Bursts
  - Blazars







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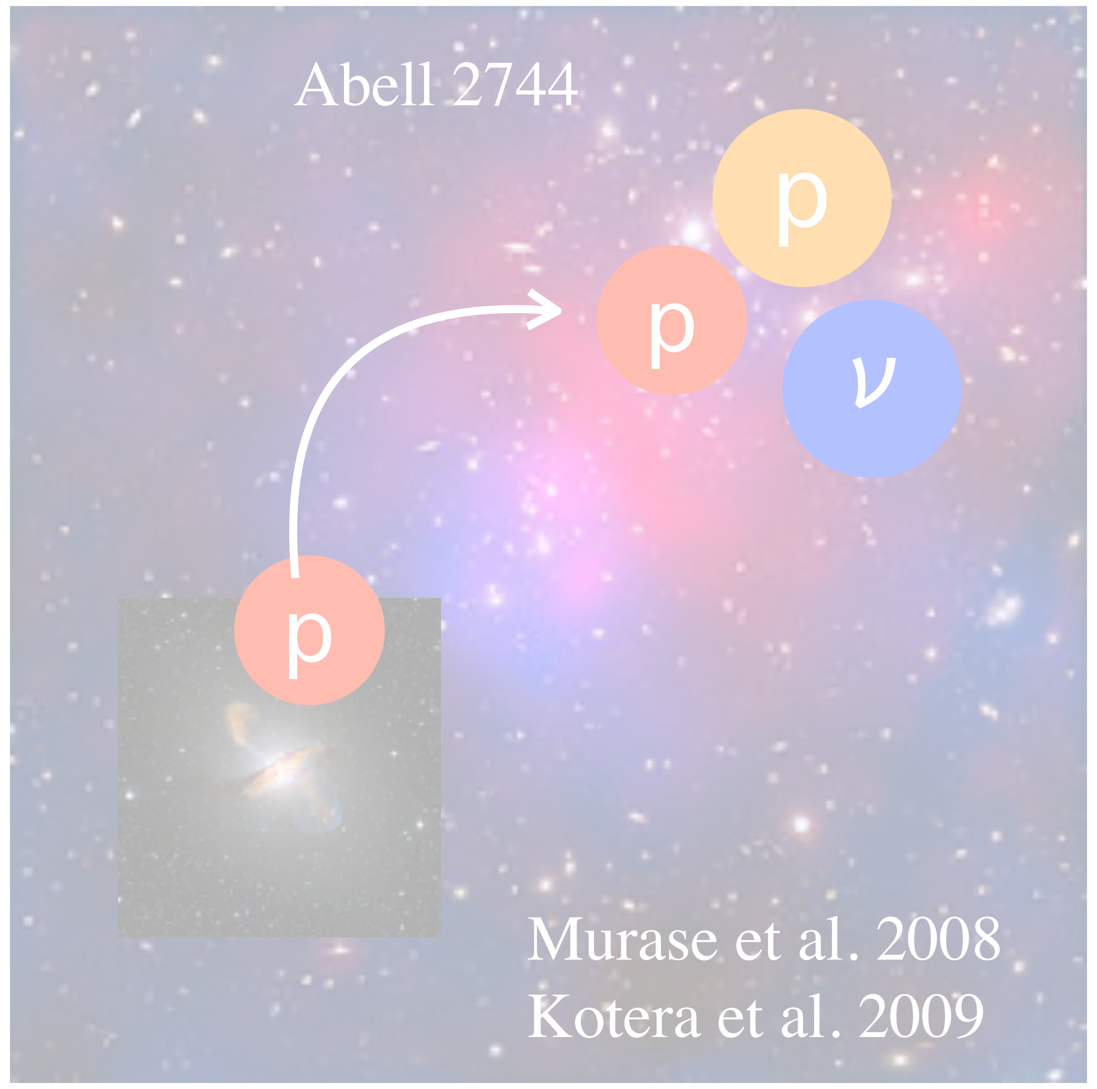
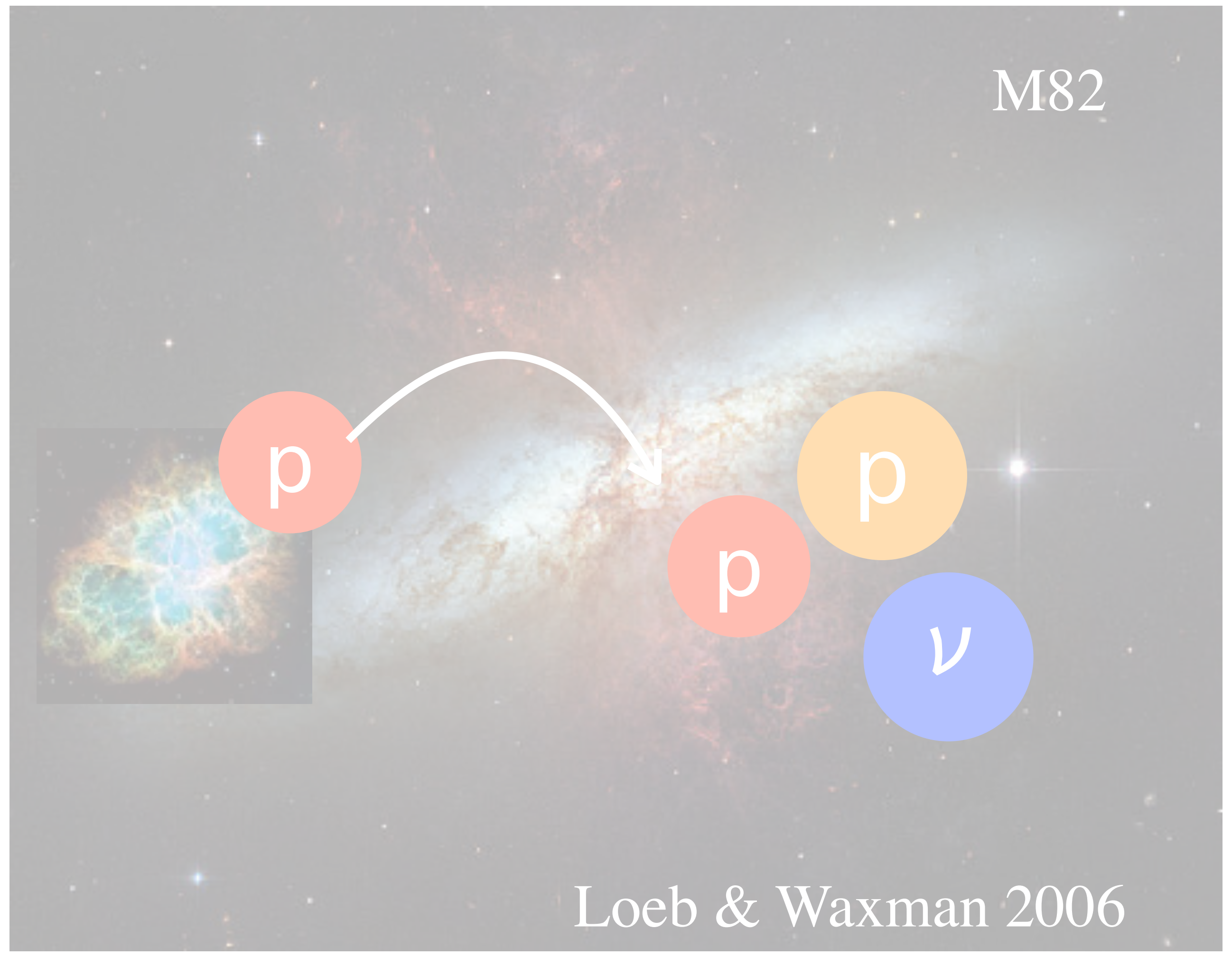
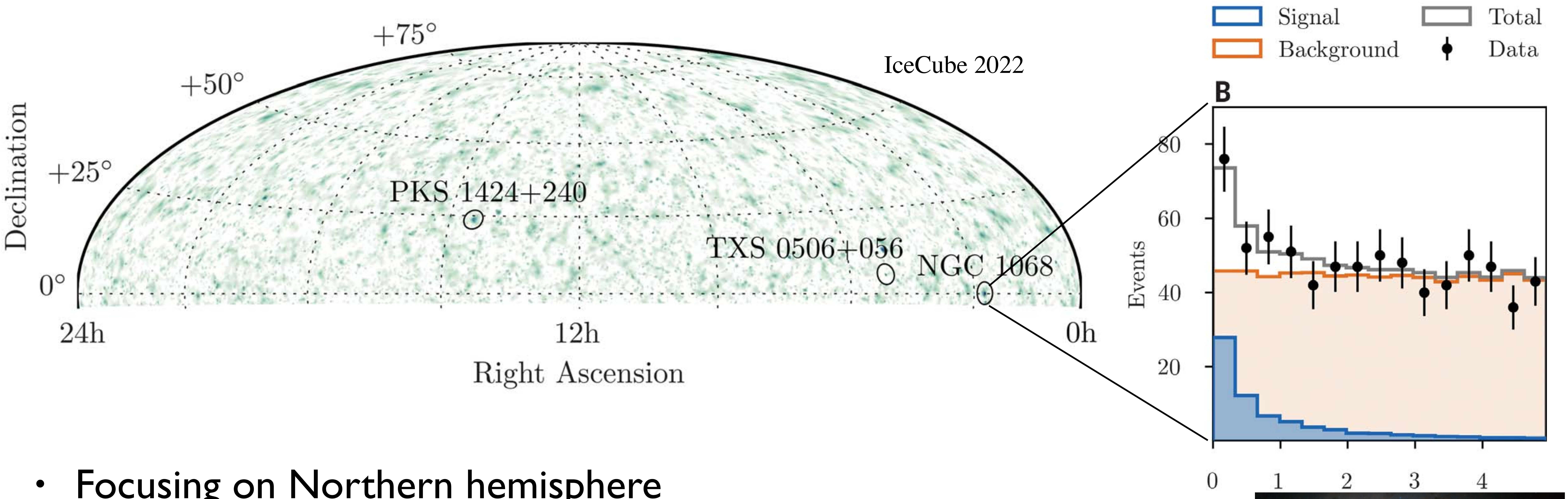


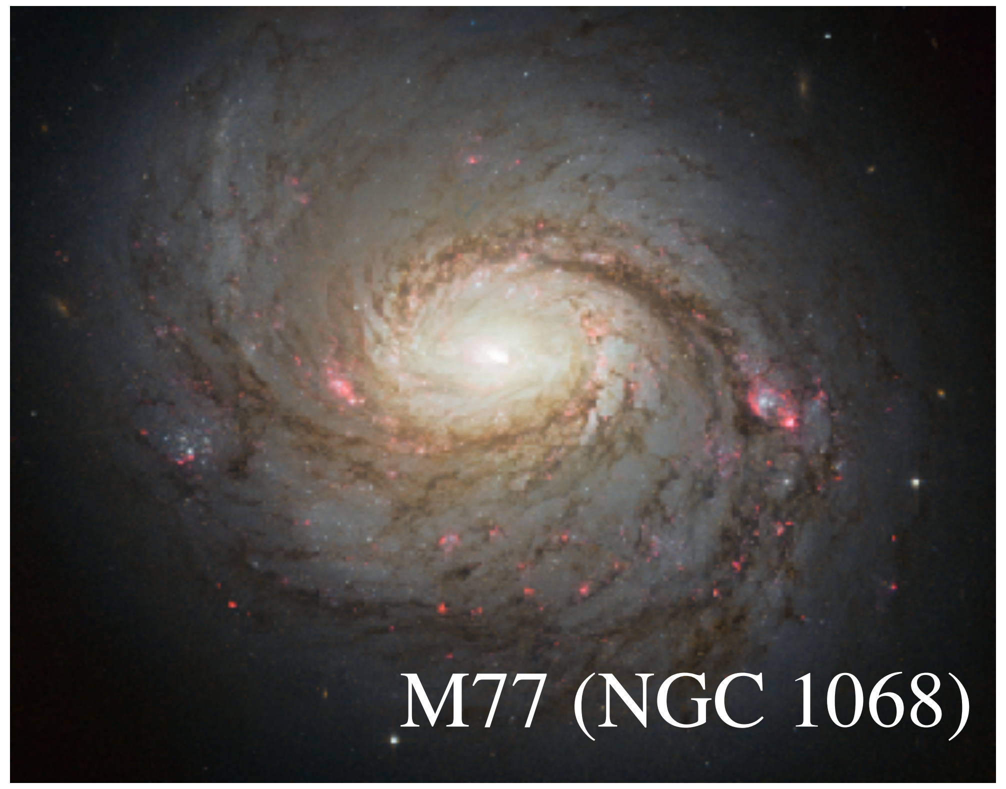


CR accelerators inside reservoir
→ CR trapped in reservoirs
→ Neutrino production by pp

Point Source Search w 10yr data

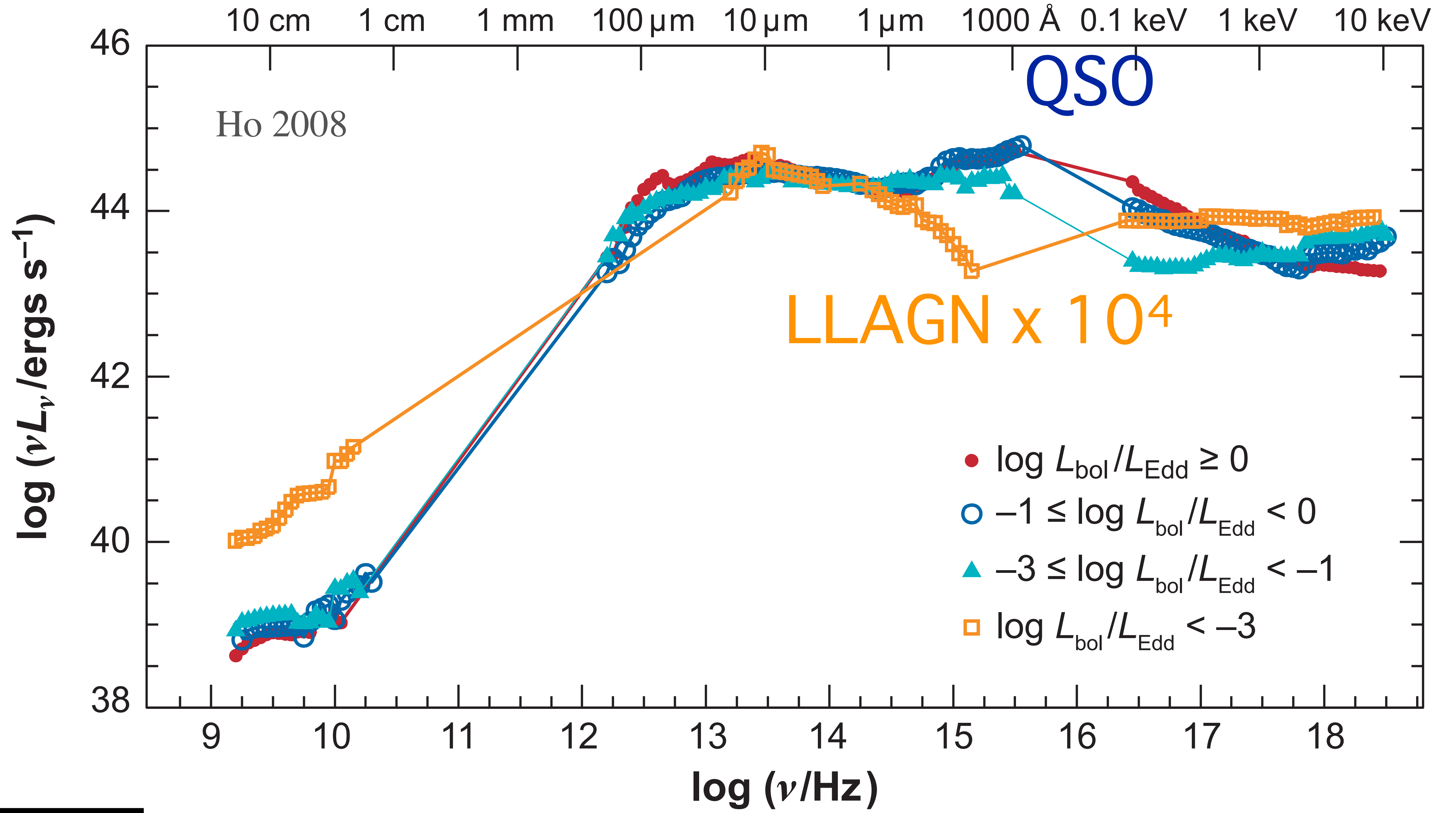


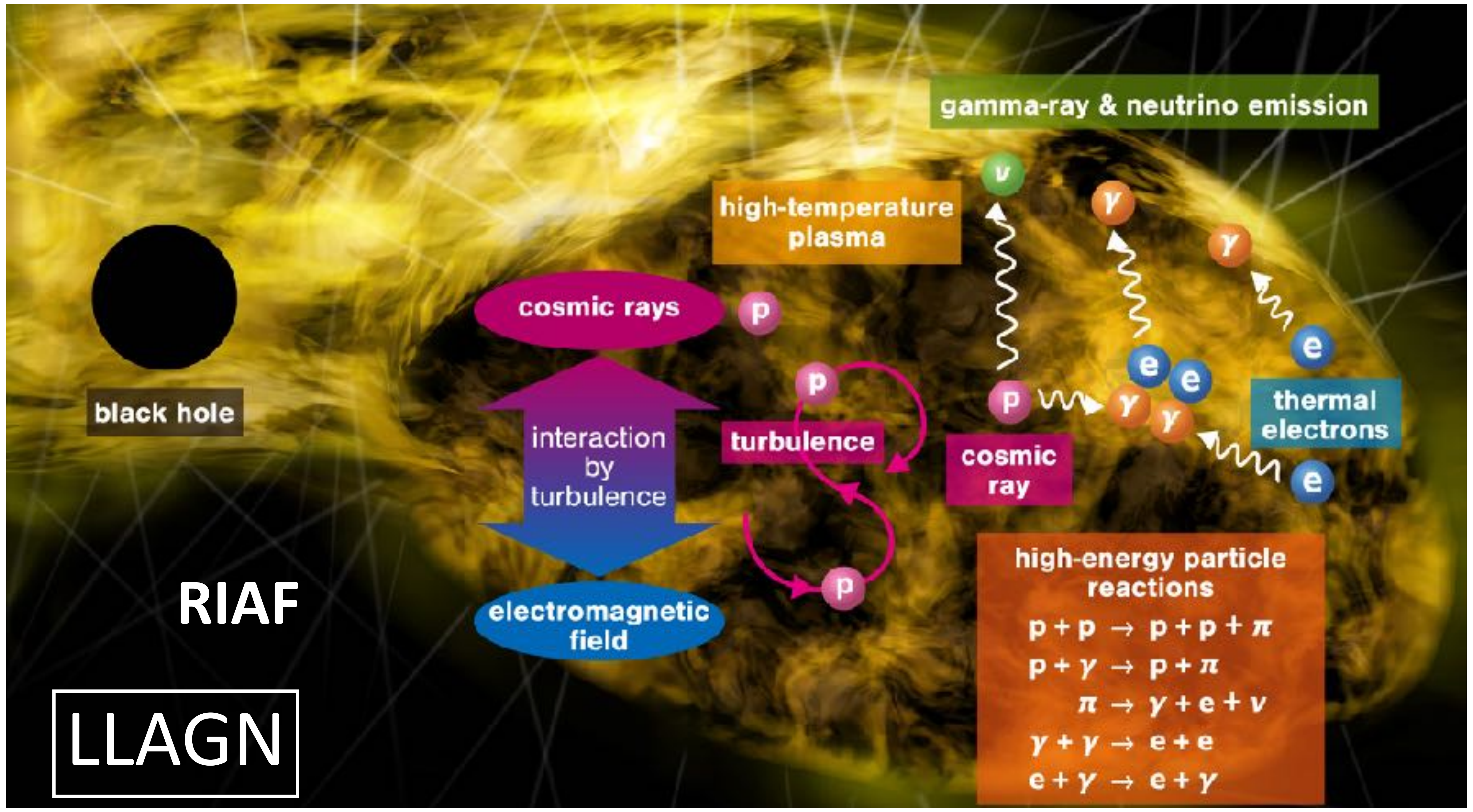
- Focusing on Northern hemisphere
- The brightest spot: NGC1068 (M77)
  80 Neutrino events coming from NGC1068
  → evidence of neutrino signal from nearby Seyfert (4.2 σ)

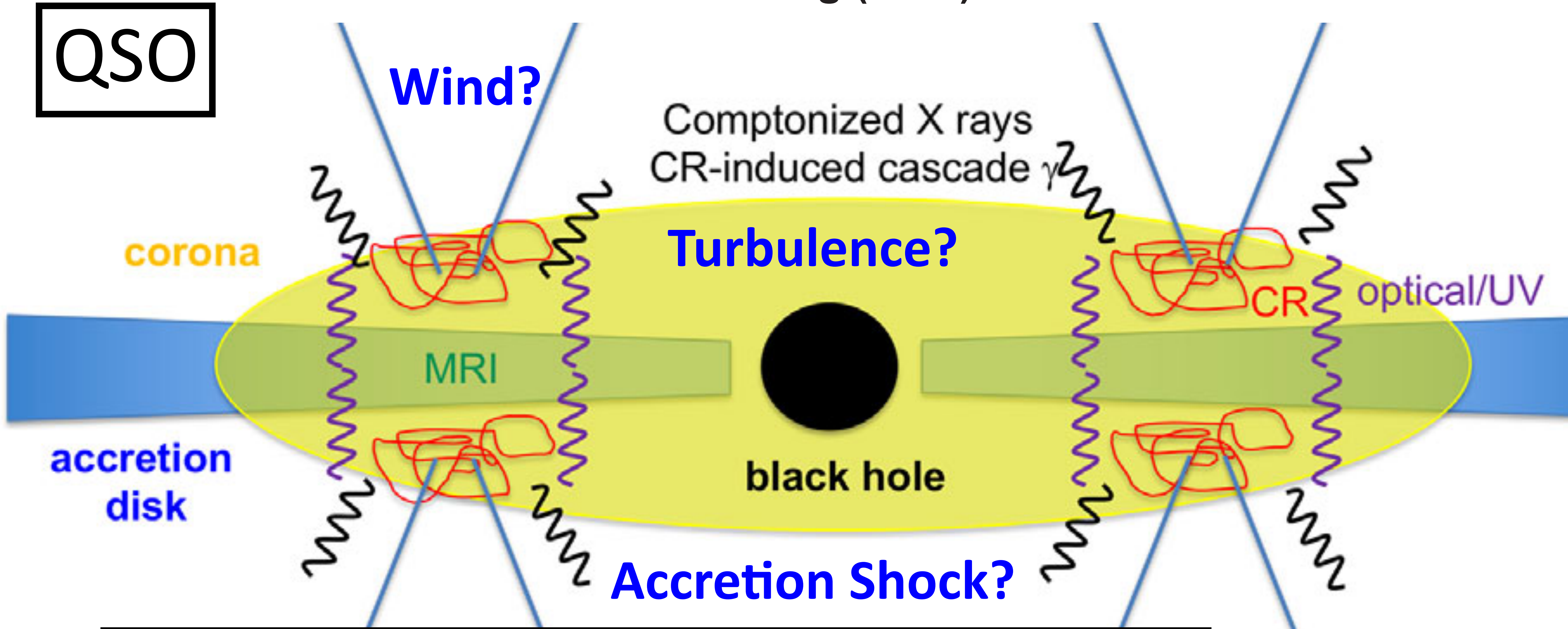


AGN Accretion Flows

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





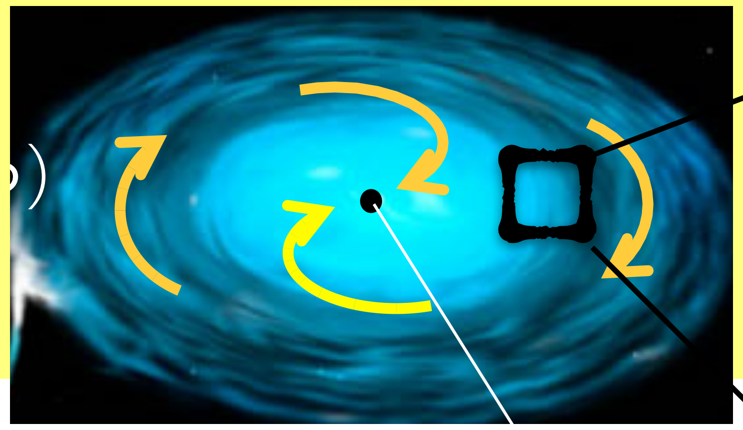


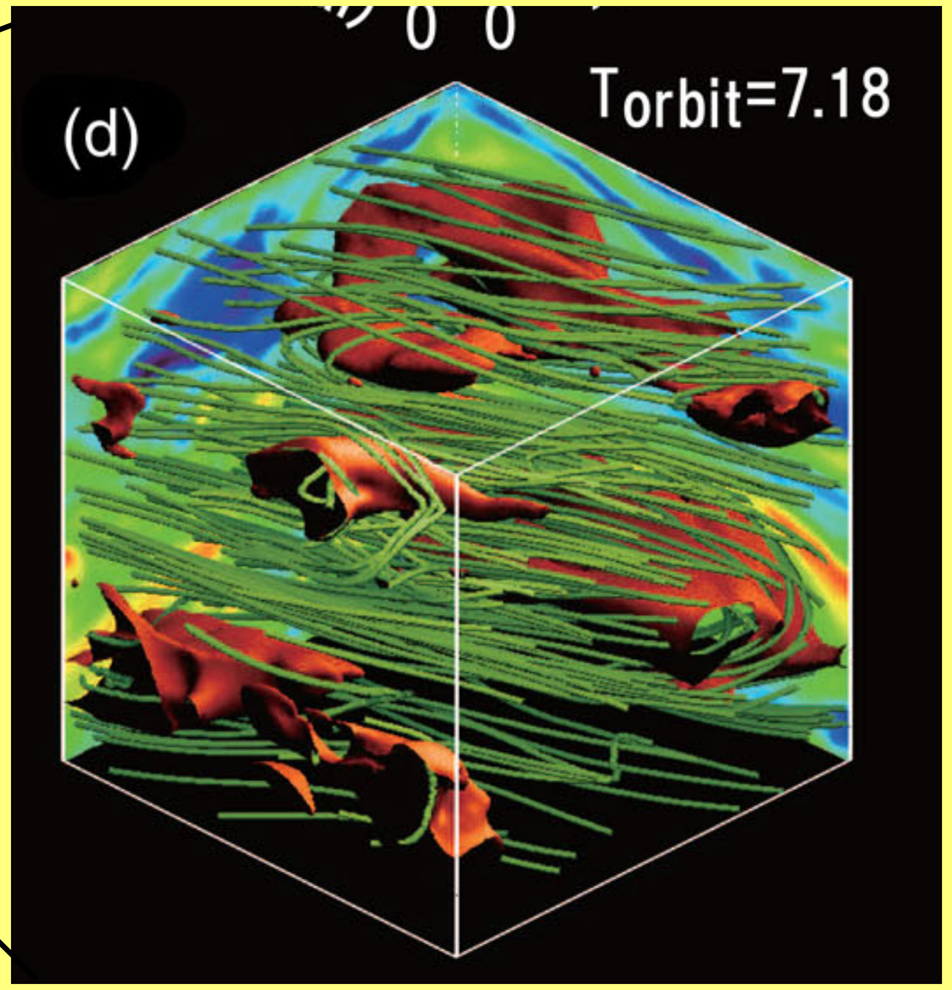
Protons in coronae & RIAFs are collisionless → Non-thermal proton production

Particle Acceleration in Accretion Flows

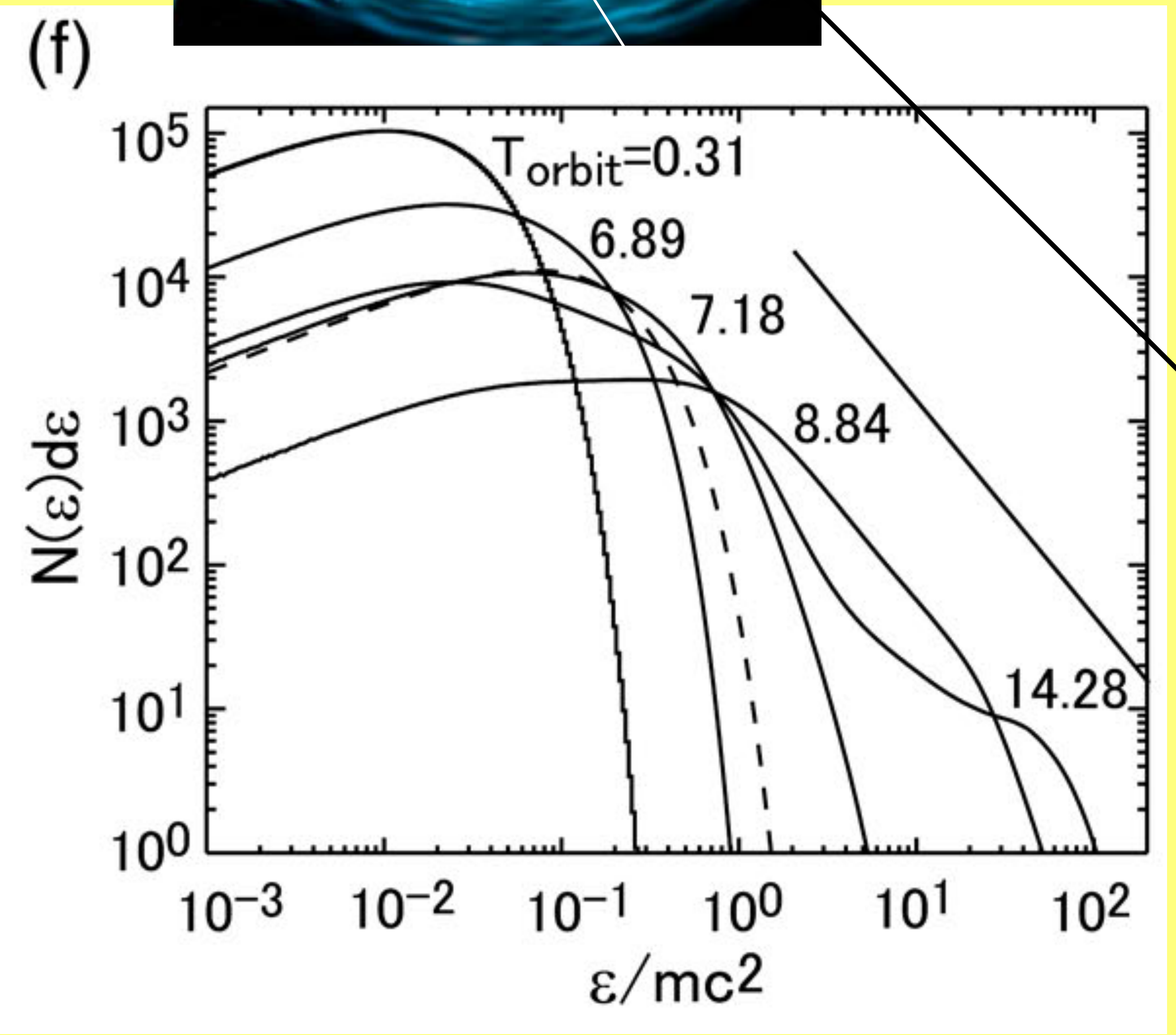
Particle-In-Cell Simulations in shearing box

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





MRI turbulence

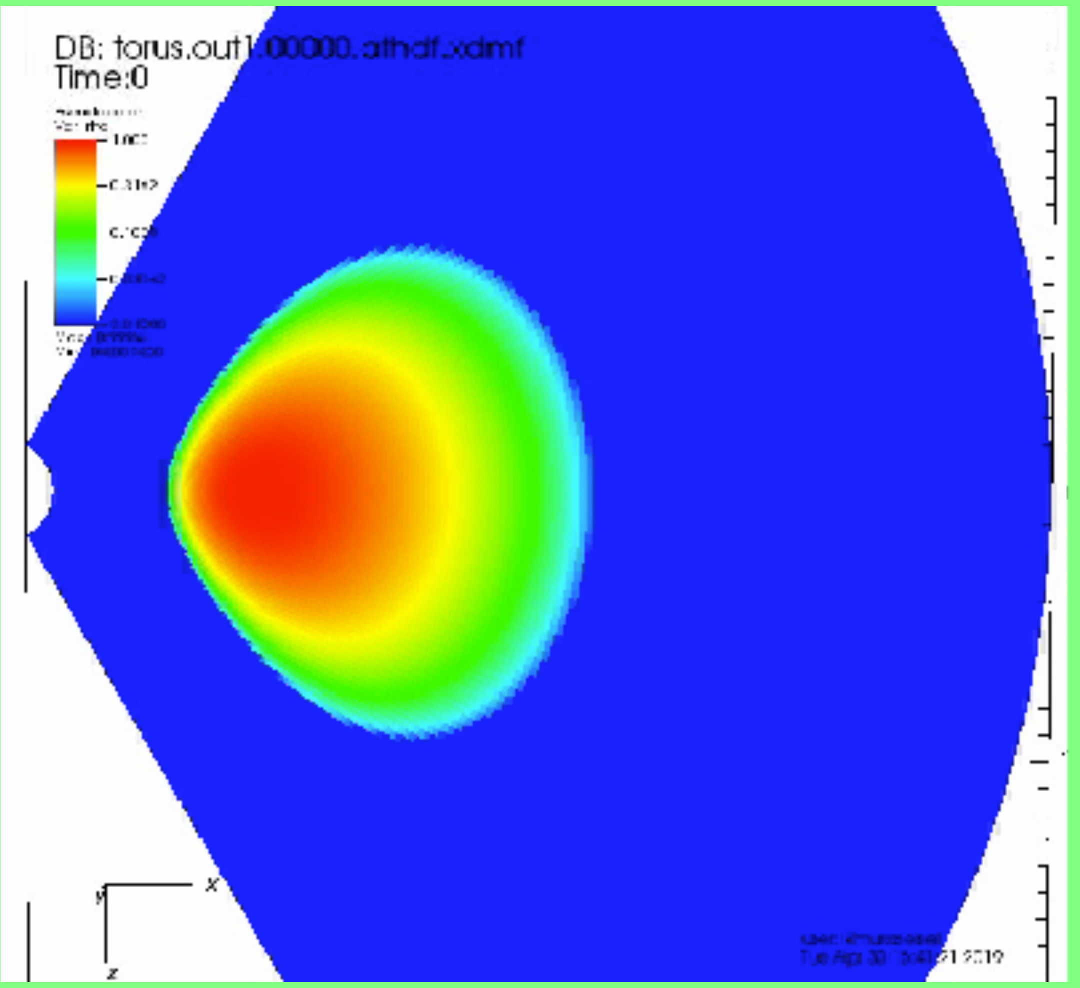


Non-thermal tail

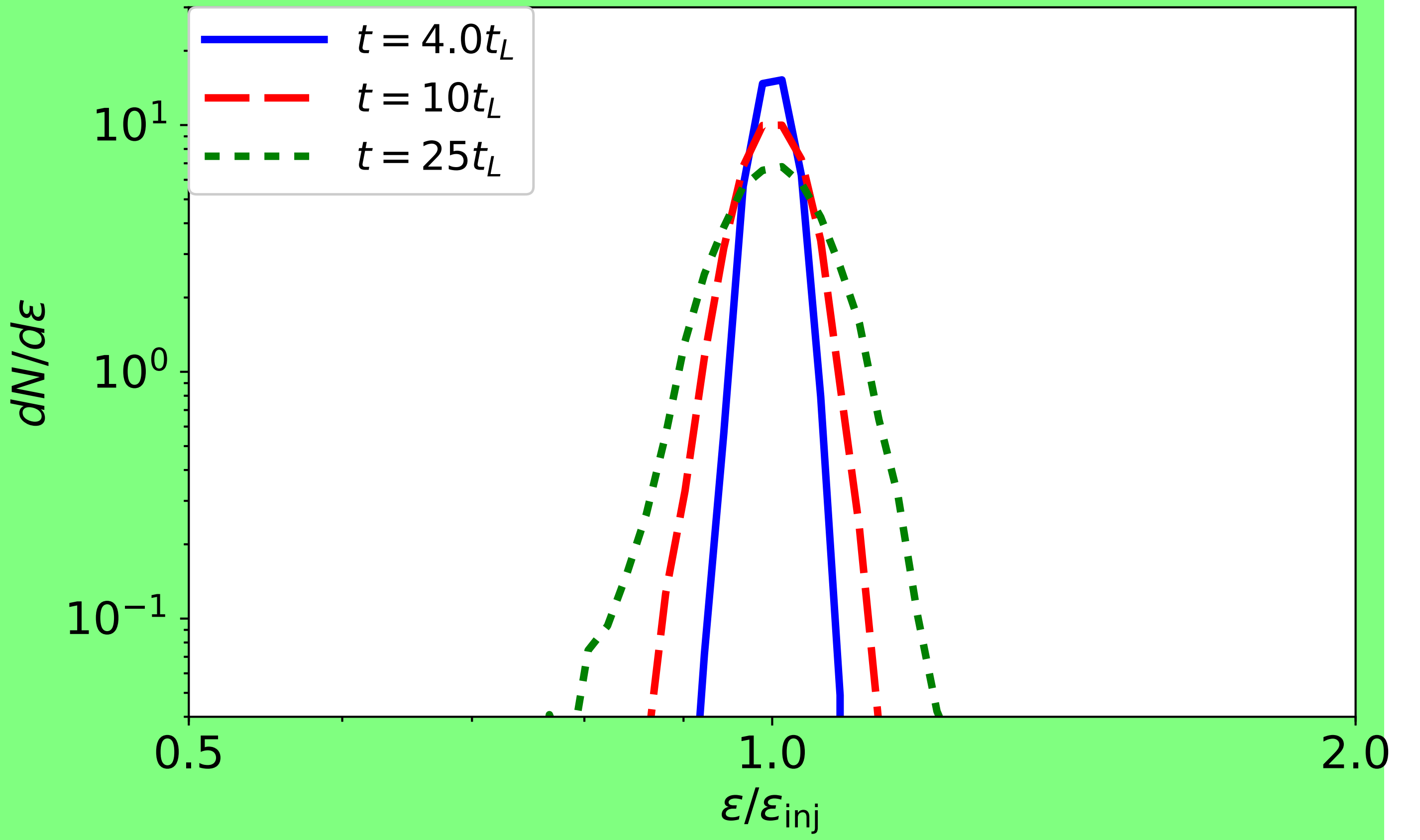
MHD + Test particle simulation

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

MHD Turbulence



Evolution of Distribution function



Diffusion in E space

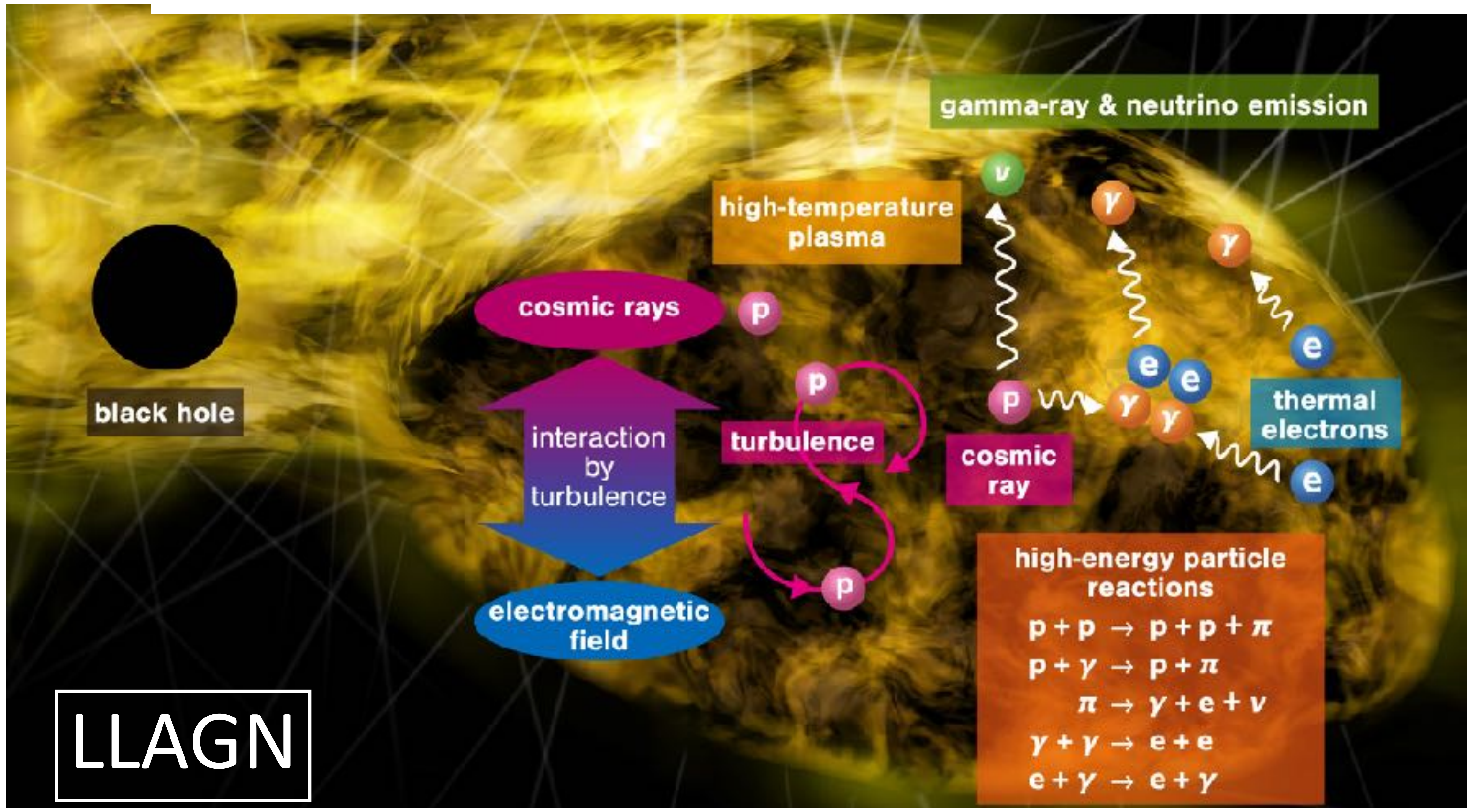
Stochastic acceleration by interaction with MHD turbulence

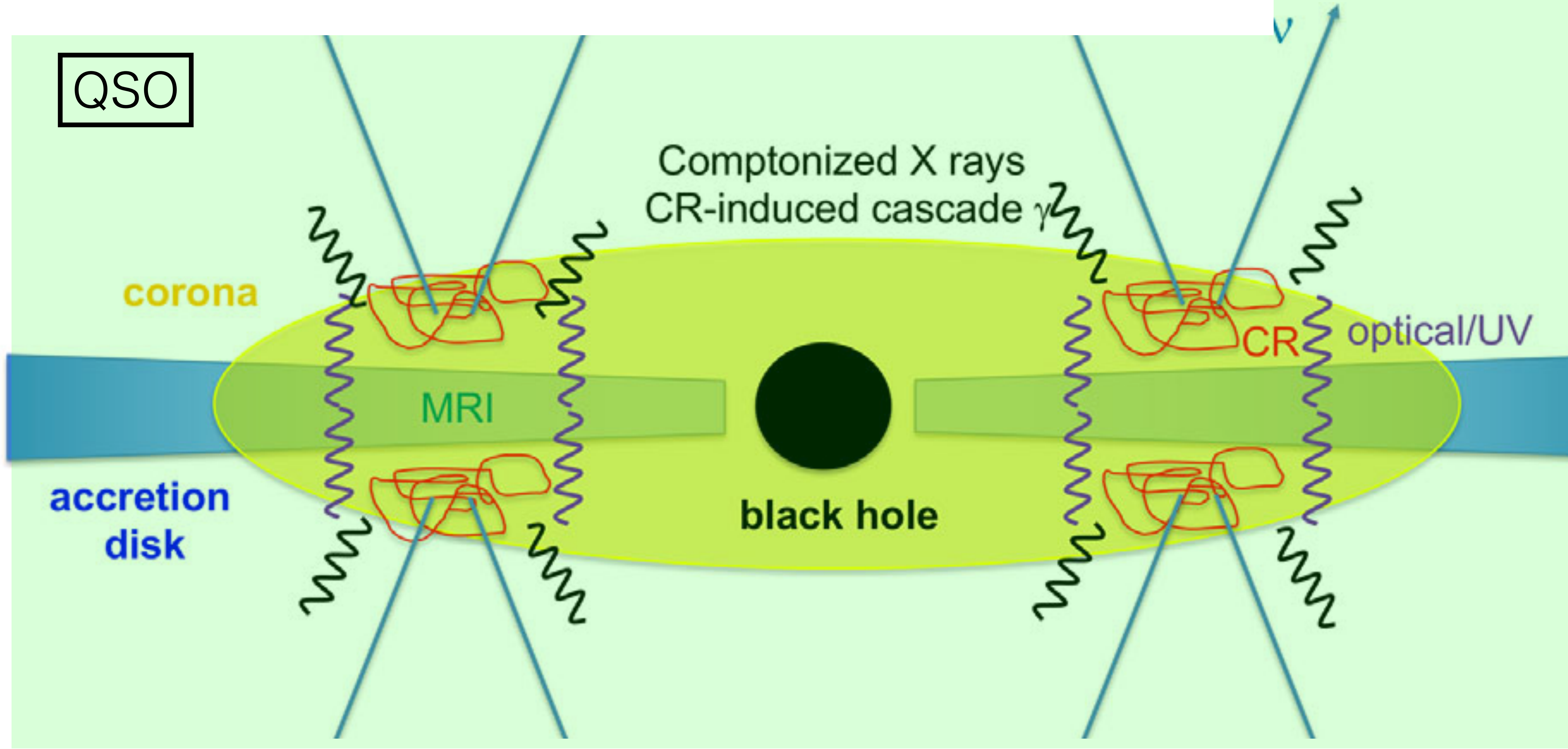
Magnetic reconnection → relativistic particle production

Interaction with Turbulence → further energization

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

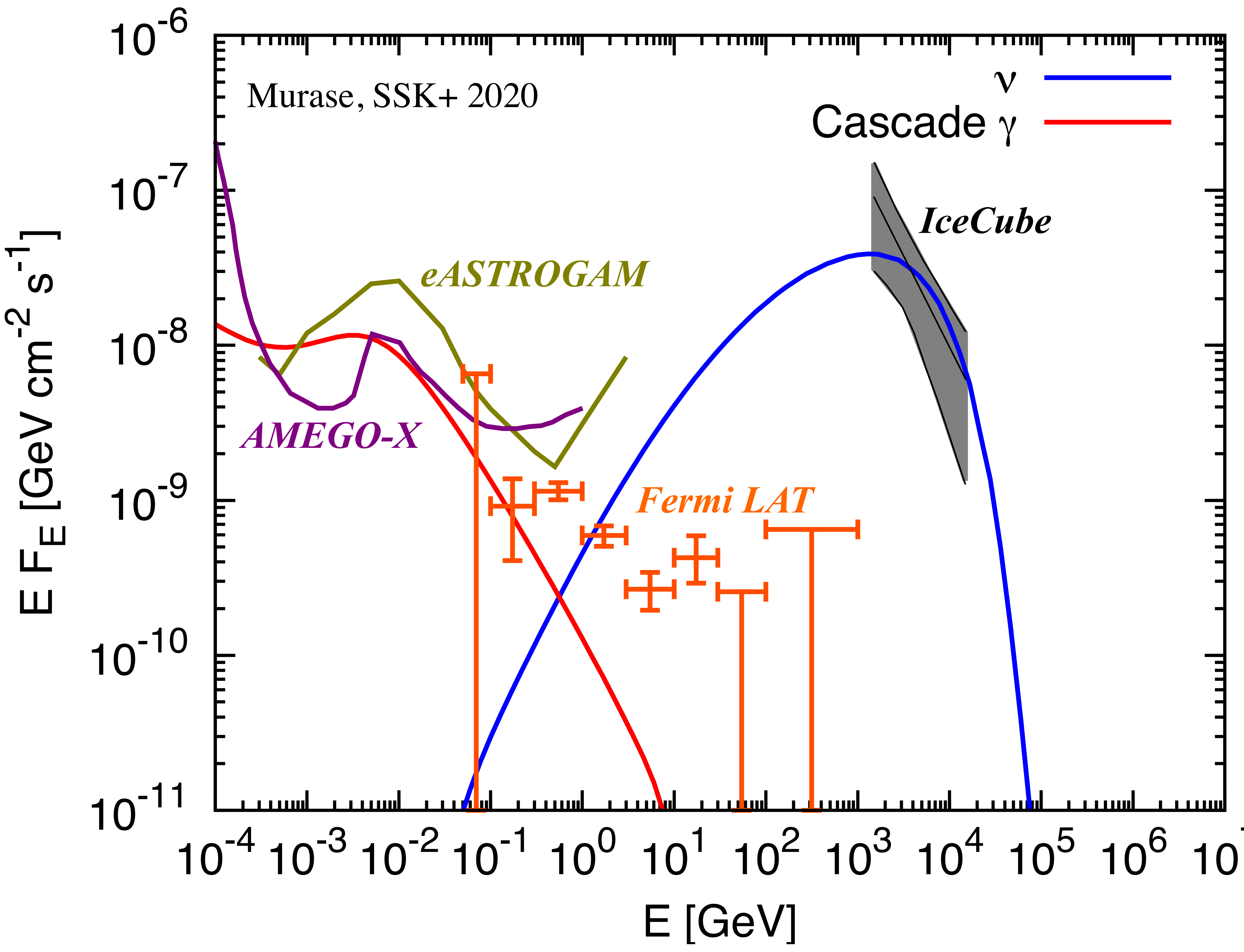
$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\mathrm{esc}}} + \dot{n}^{(\mathrm{IC})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{ff})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{syn})}_{\varepsilon_\gamma}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

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

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**

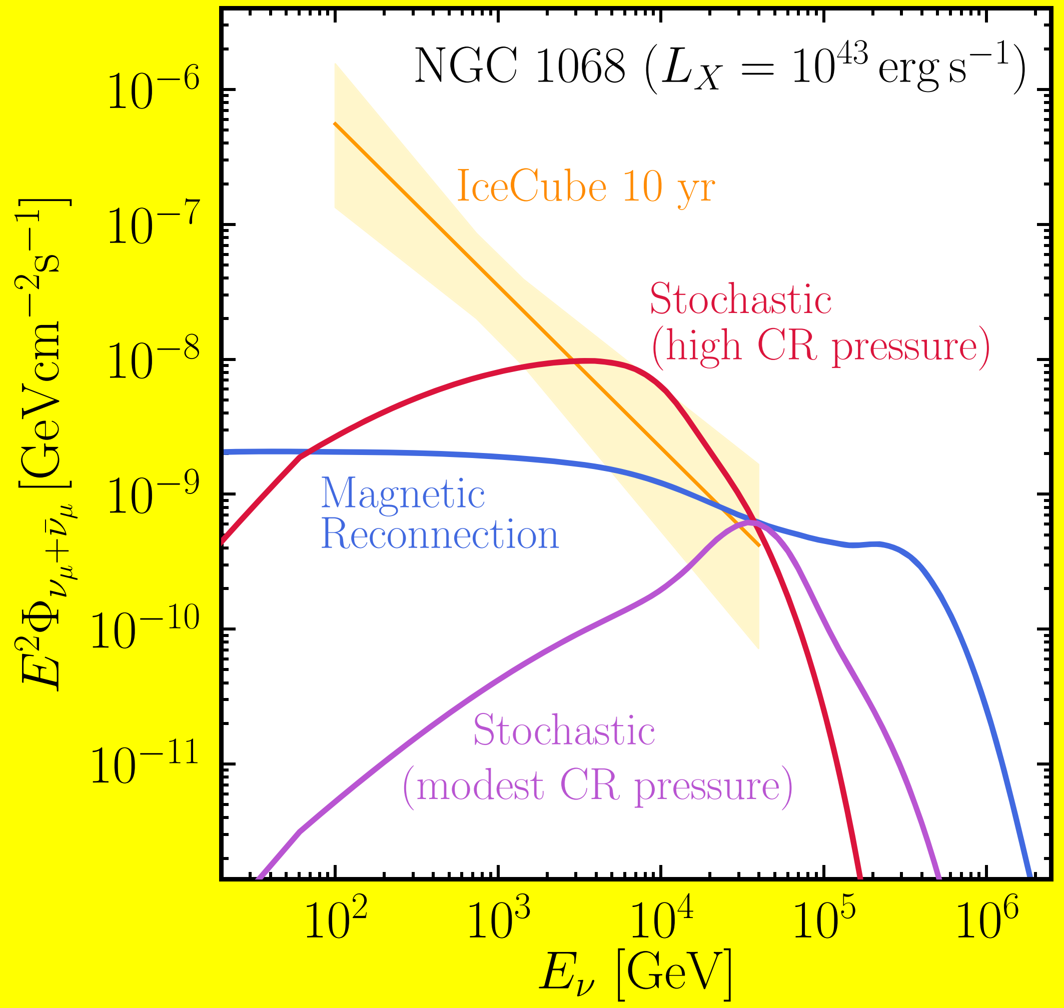


Nearby Seyfert galaxies

Kheirandish, Murase, SSK 2021

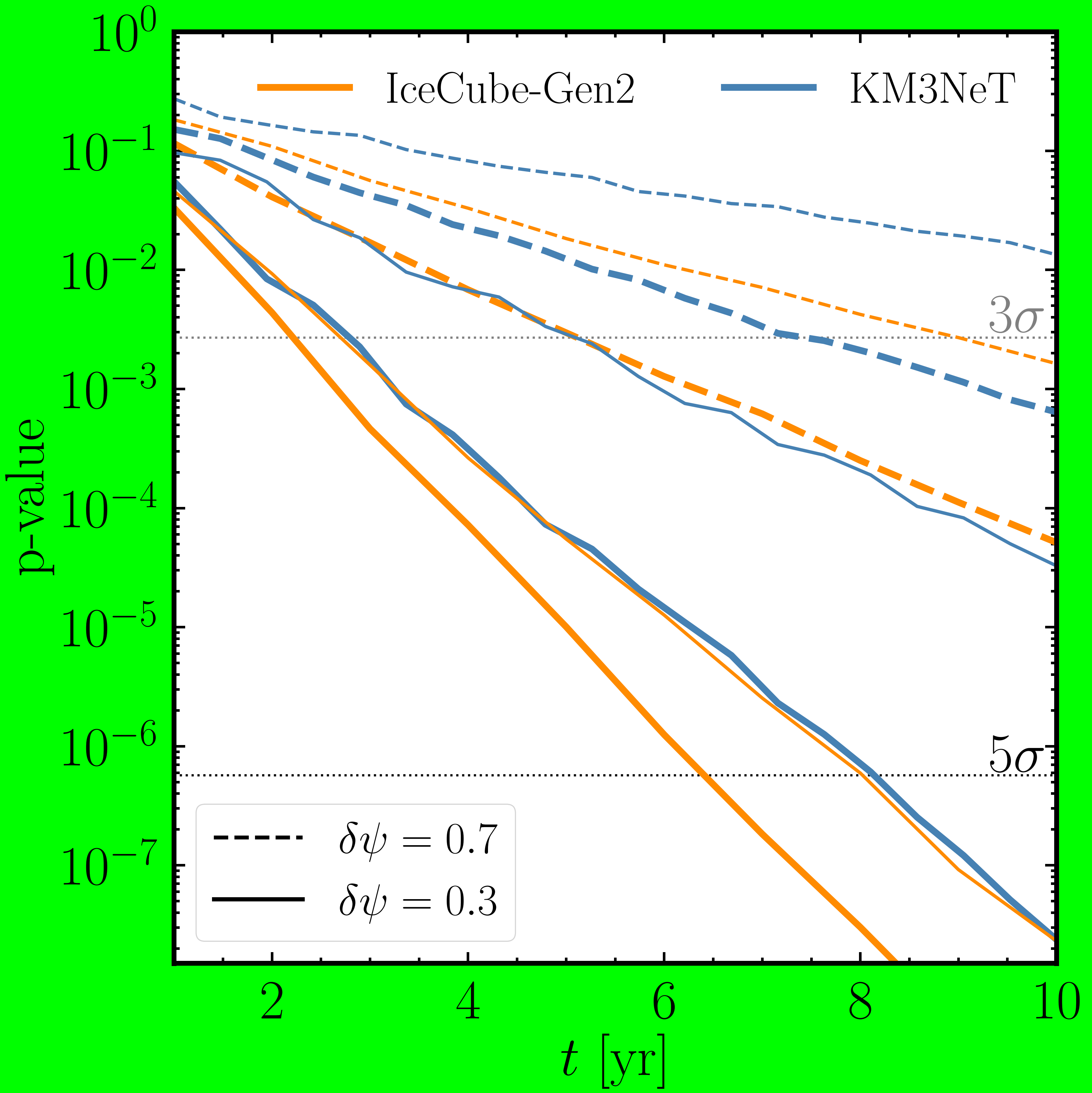
- Our model predicts $L_\nu \propto L_X$
  —> list up bright ν-source candidates

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



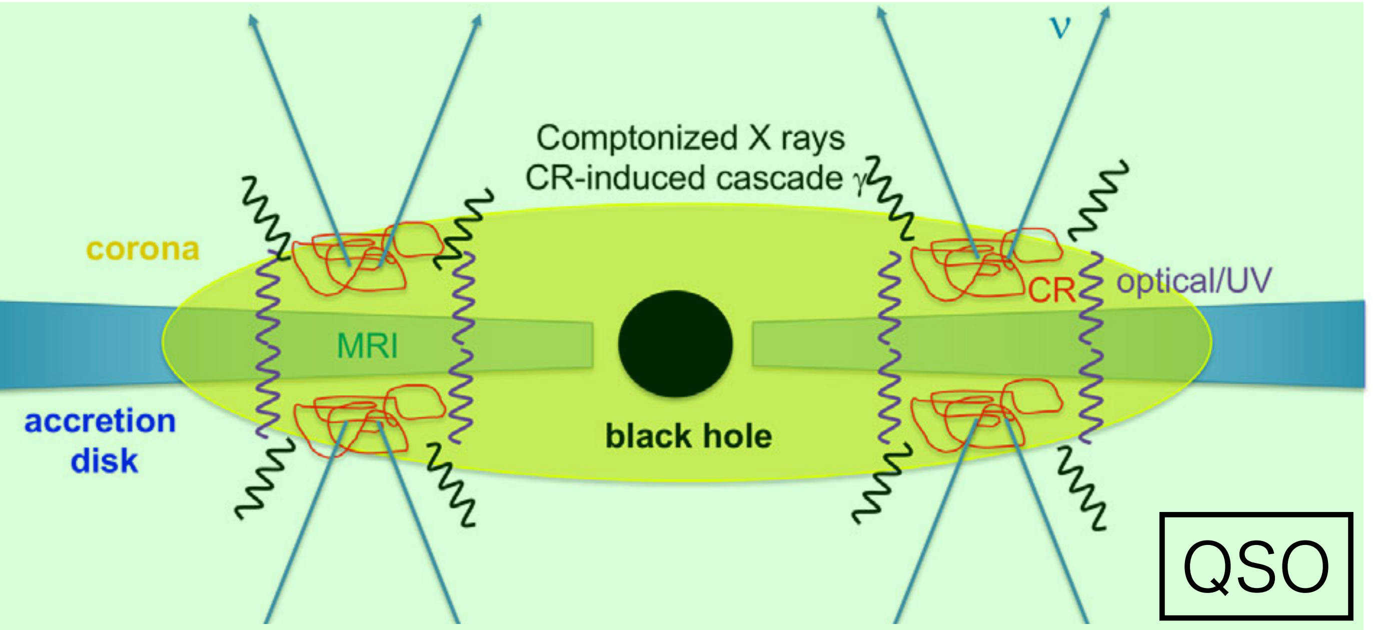
- **Our model predicts that NGC 1068 should be detected first**
- This list is based on BASS catalog
  we need to examine X-ray data quality

- Stacking nearby Seyferts

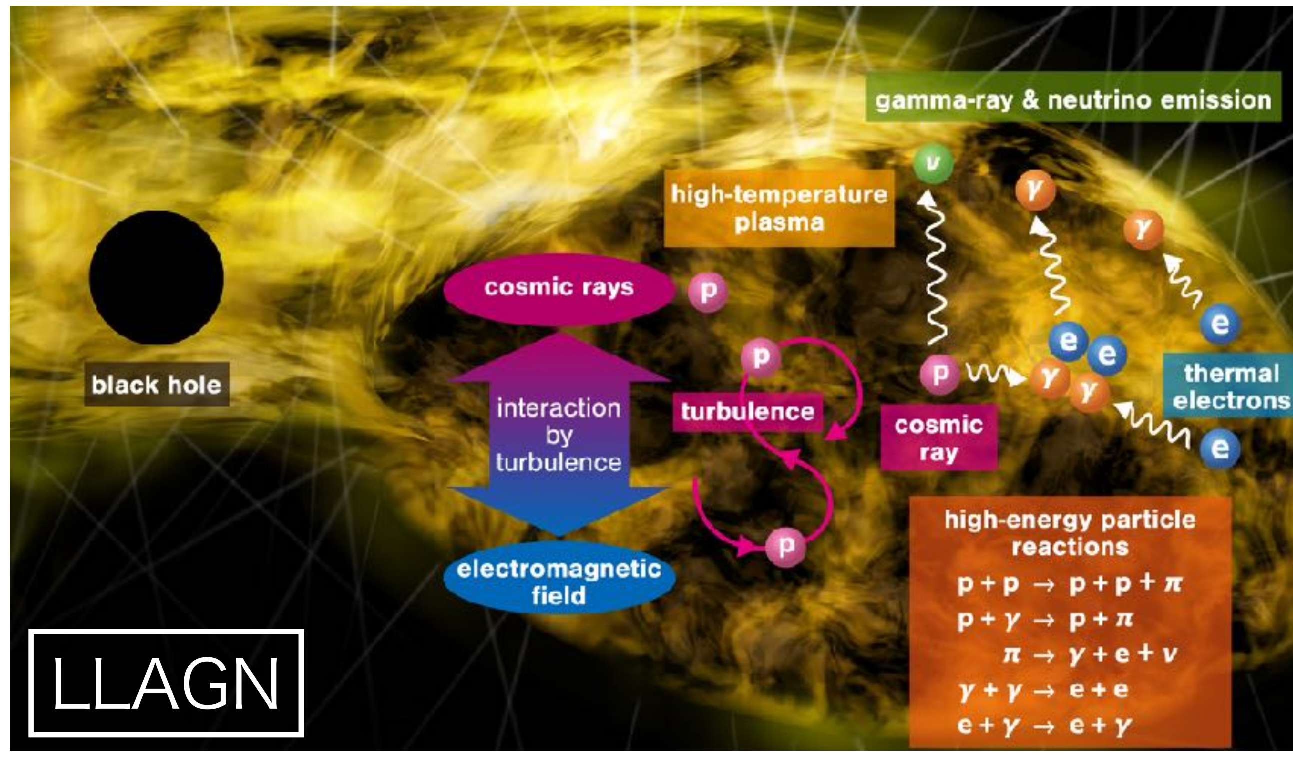


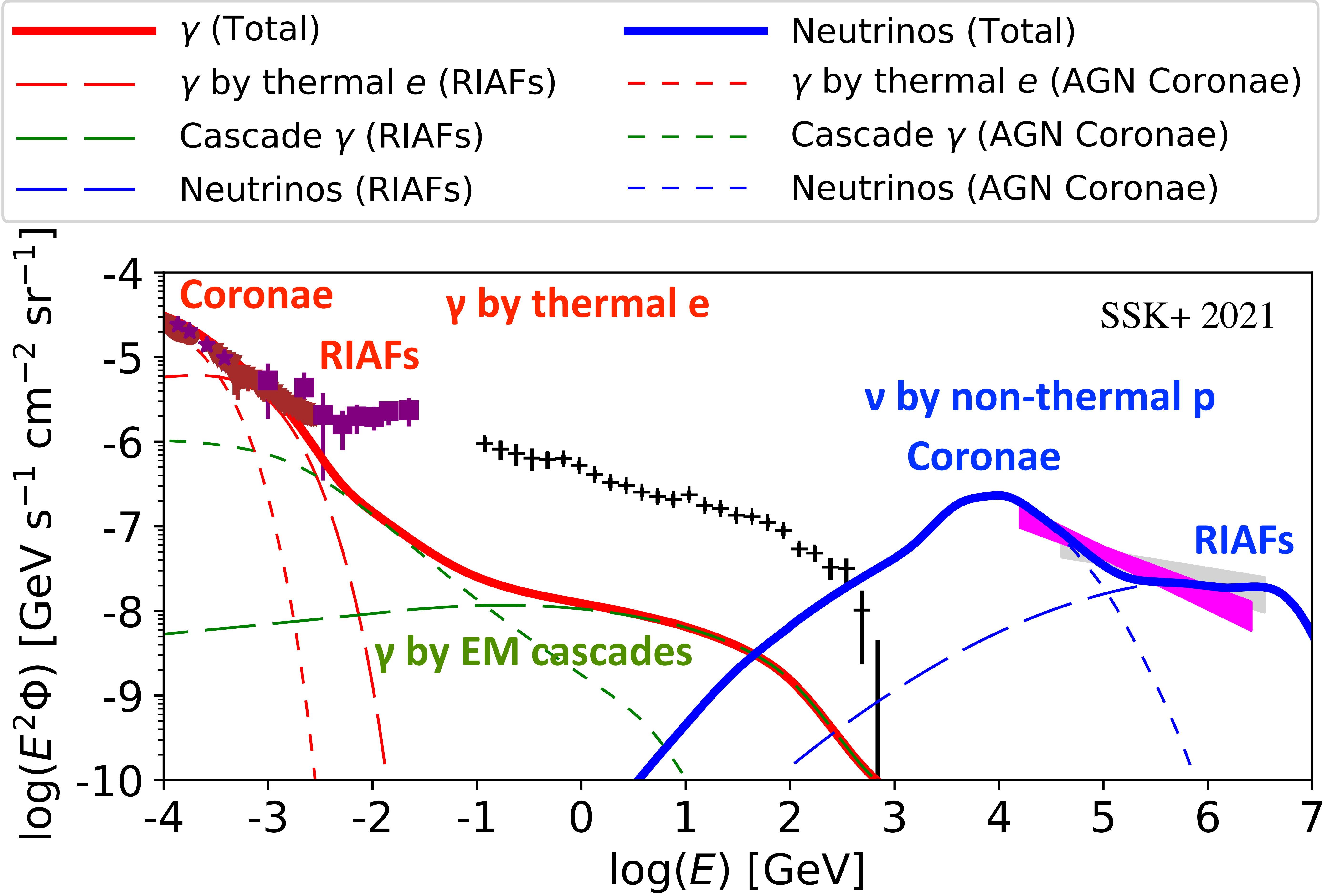
- Future detectors should detect ν from AGN
  —> **testable by future neutrino experiments**

Cosmic High-energy Background from RQ AGNs



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





- 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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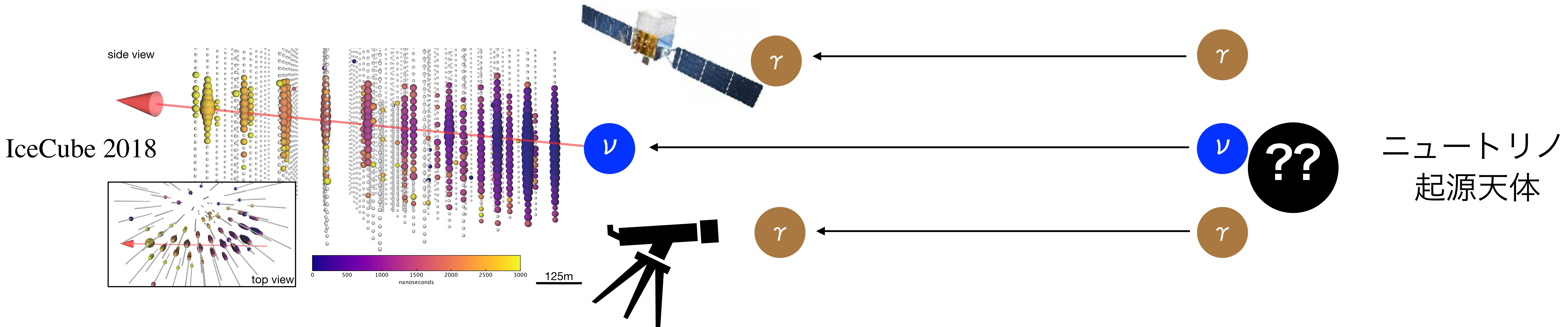
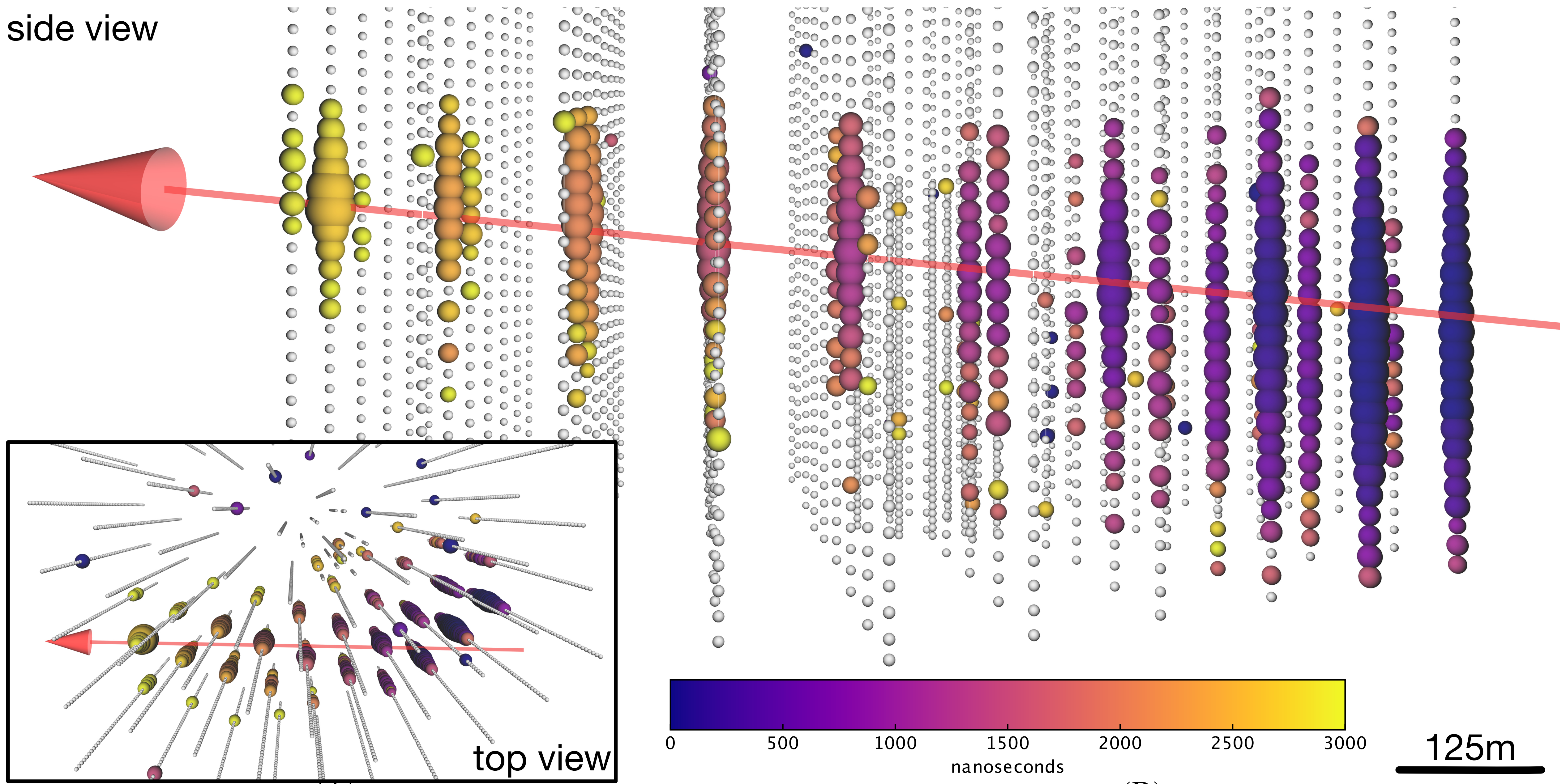
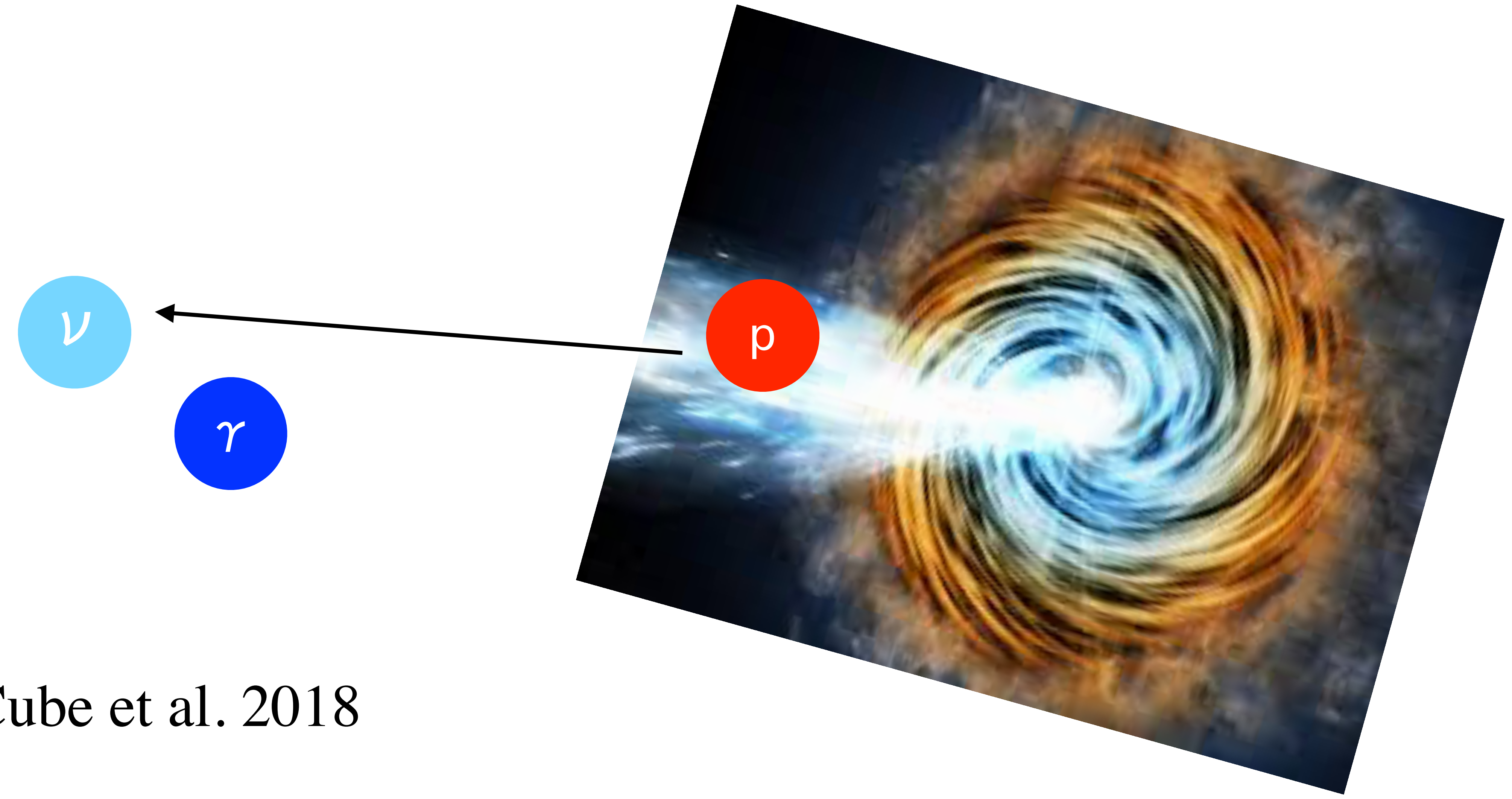


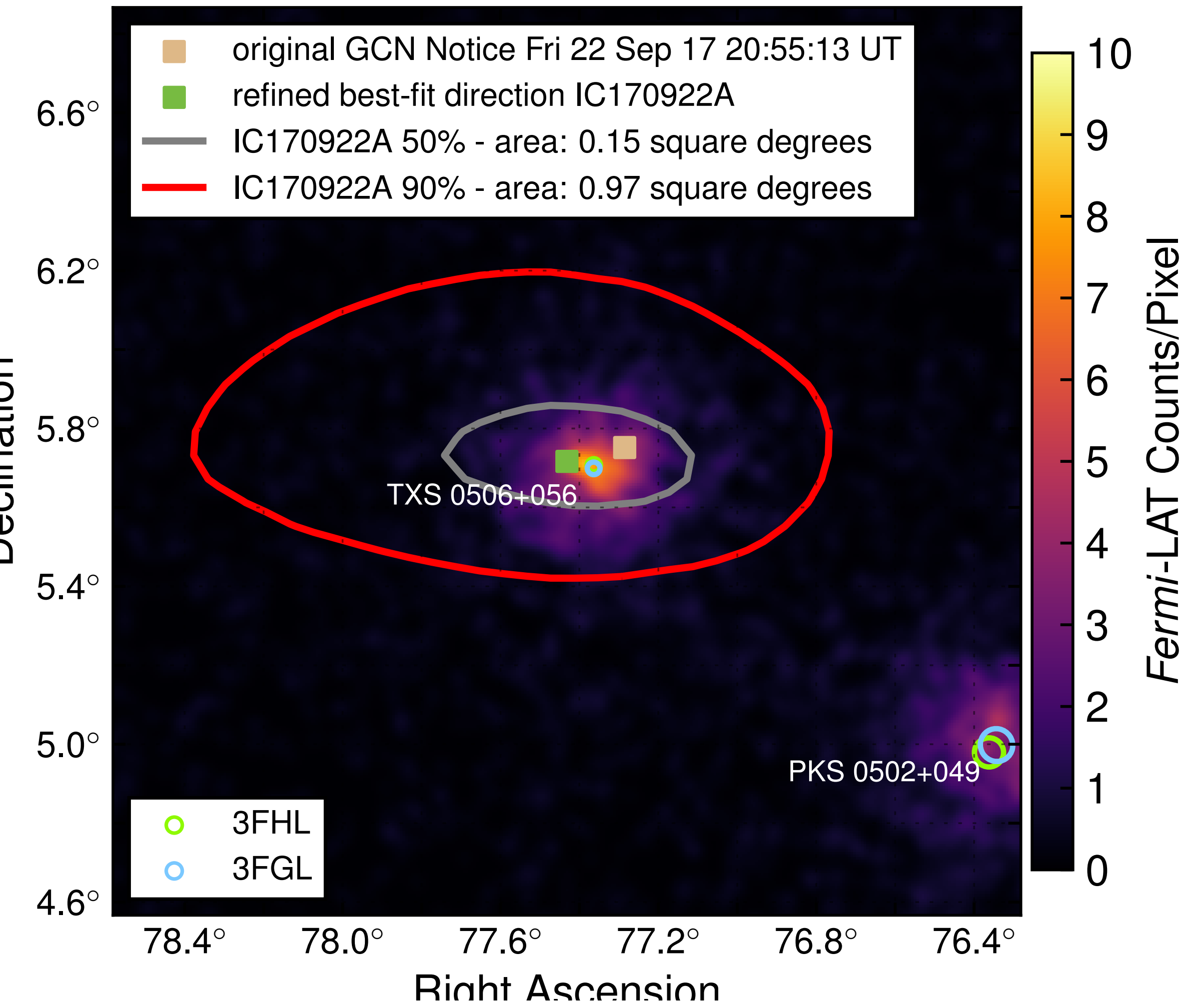
IC170922A & TXS0506+056

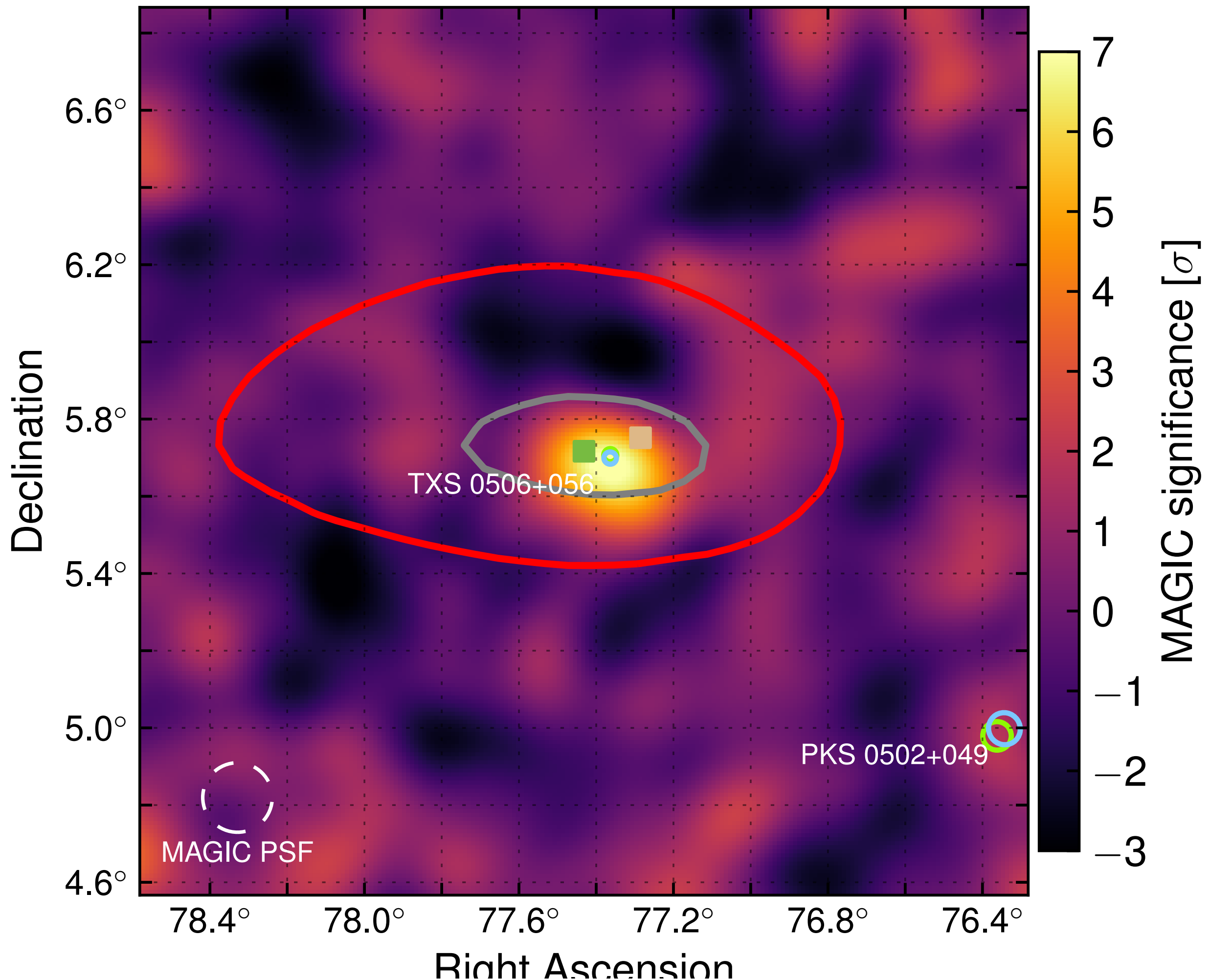


(A) (B)



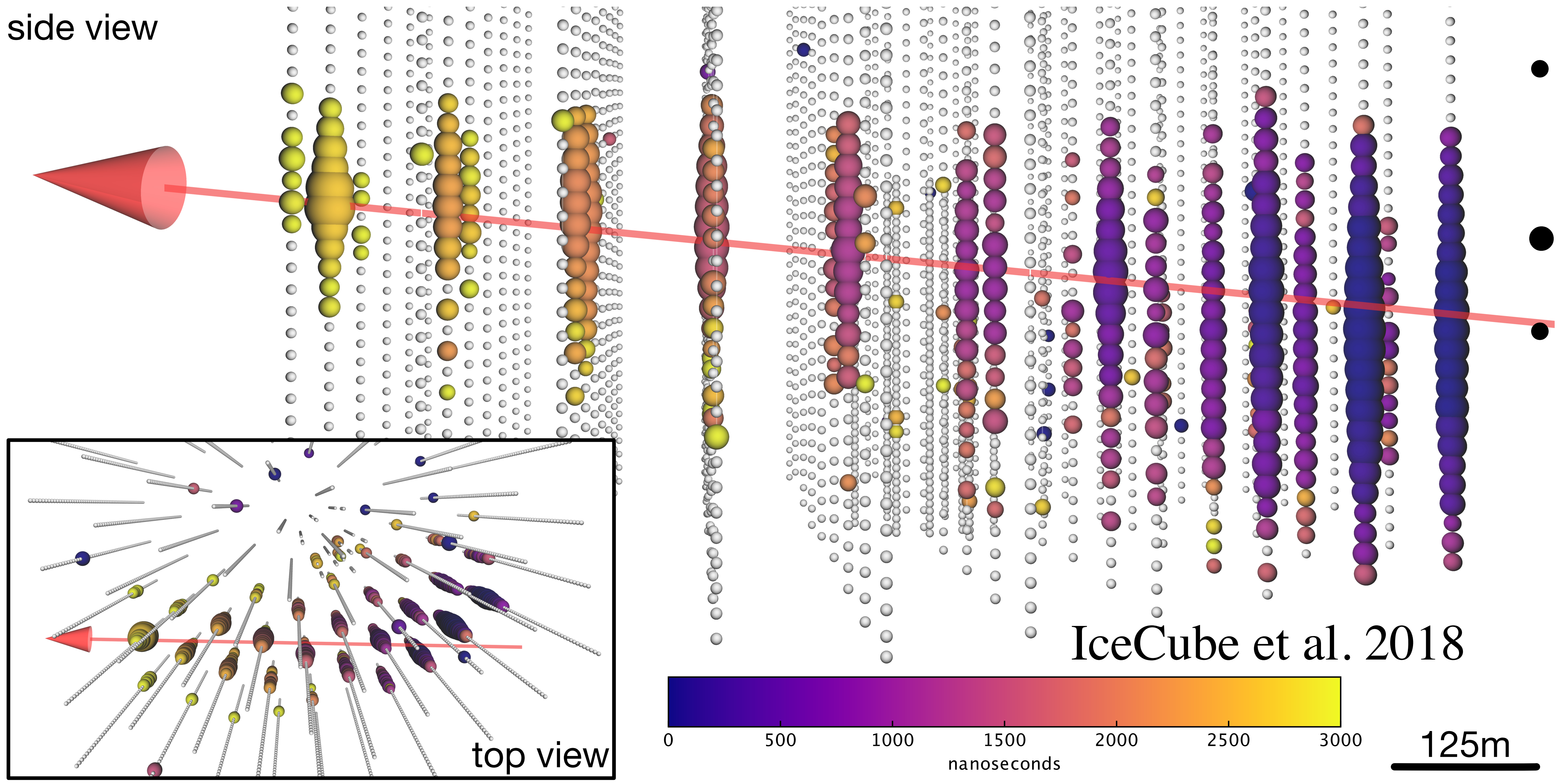
IceCube et al. 2018





- Flaring blazar, TXS 0506+056, is found in the error region of IC170922A
- Chance coincident probability: ~ 0.3% → 3σ significance
- **First significant association of cosmic neutrino sources**

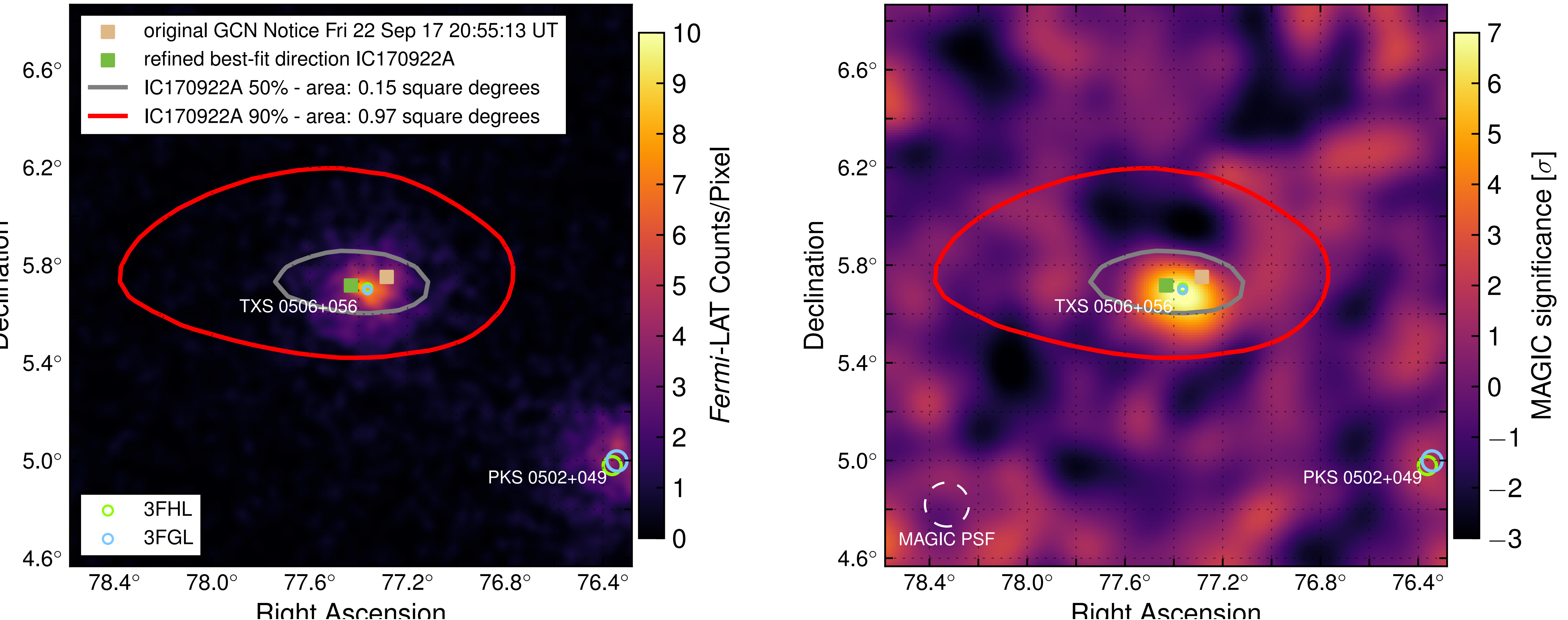
IC170922A & TXS0506+056

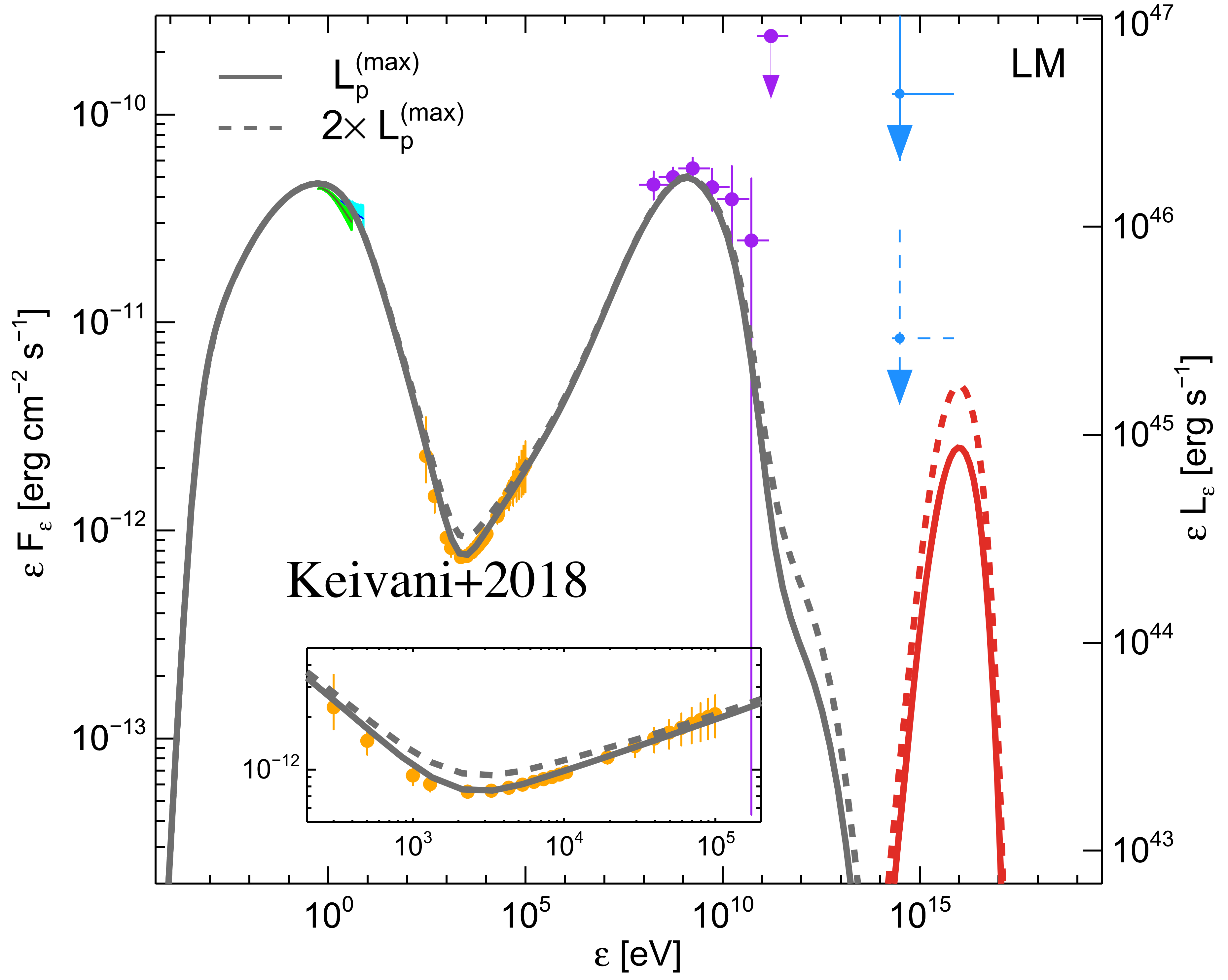


(A) (B)

Keivani+2018; Gao+2019 etc

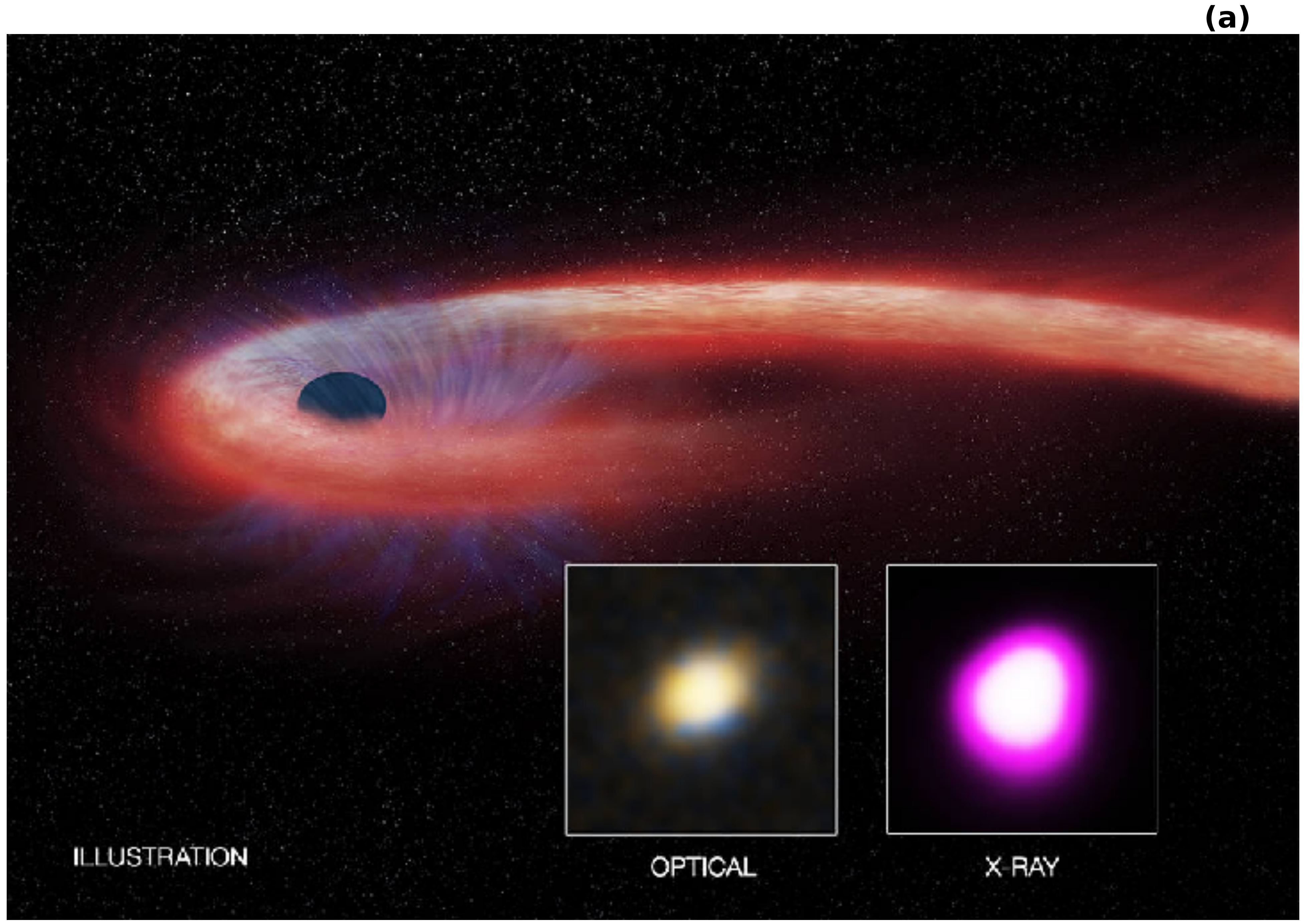
- Many theorists modeled multi-messenger signal by one-zone approximation
- **X-ray data is the most constraining**
- Challenging to achieve expected flux, but 1-10% flux can be achieved reasonably

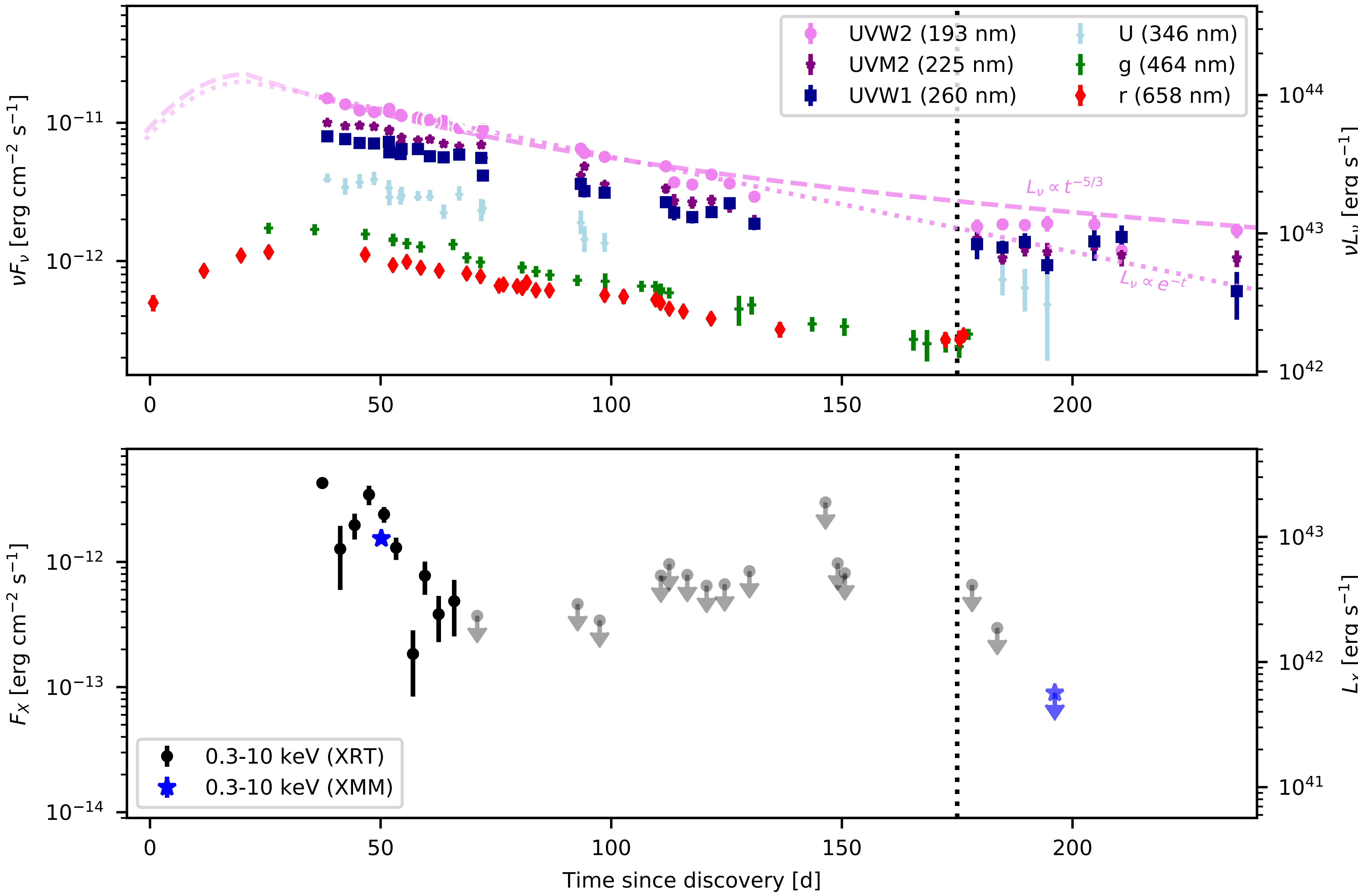




Tidal Disruption Events (TDE)

Stein+ 2021; Reusch+ (incl. SSK) 2022

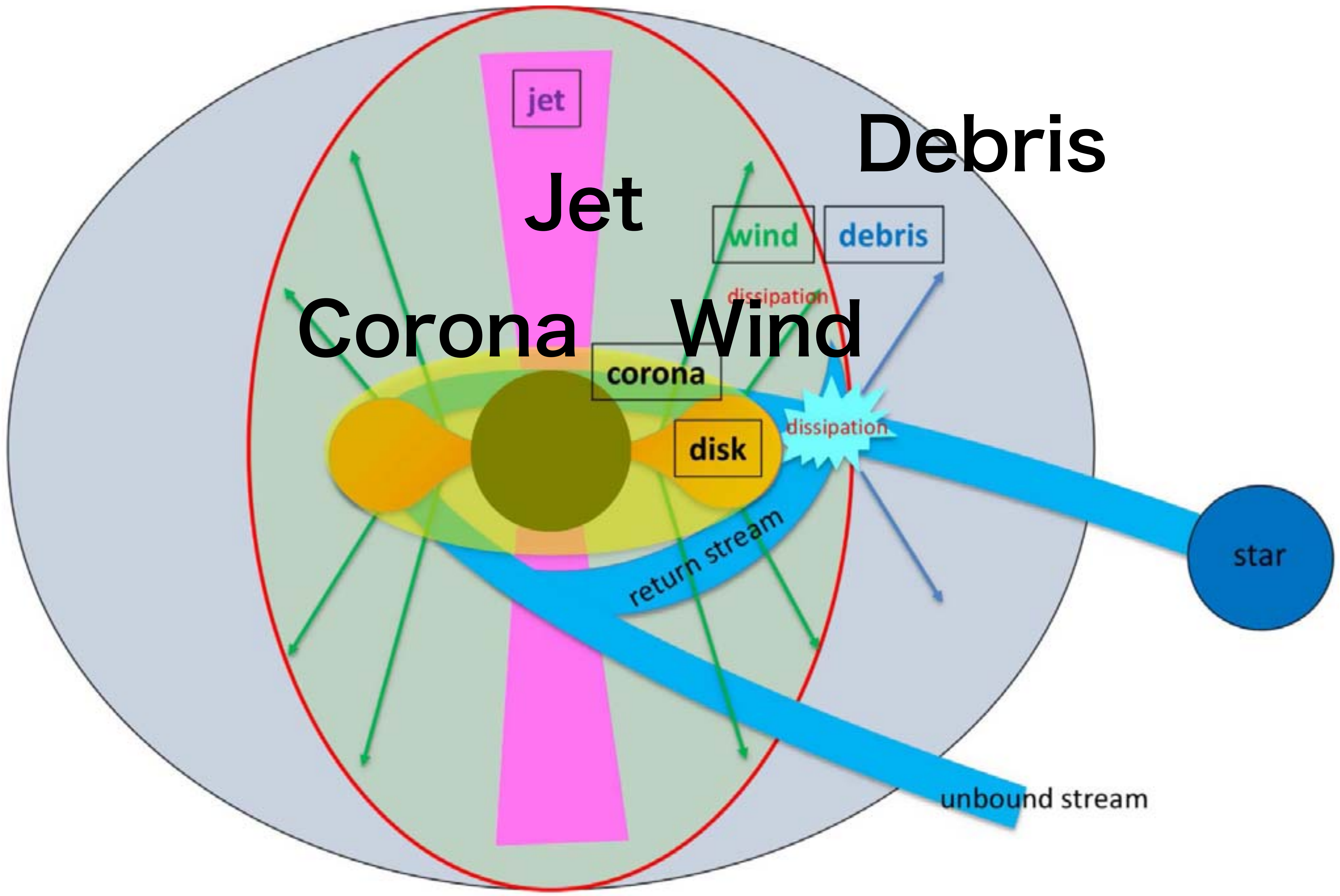




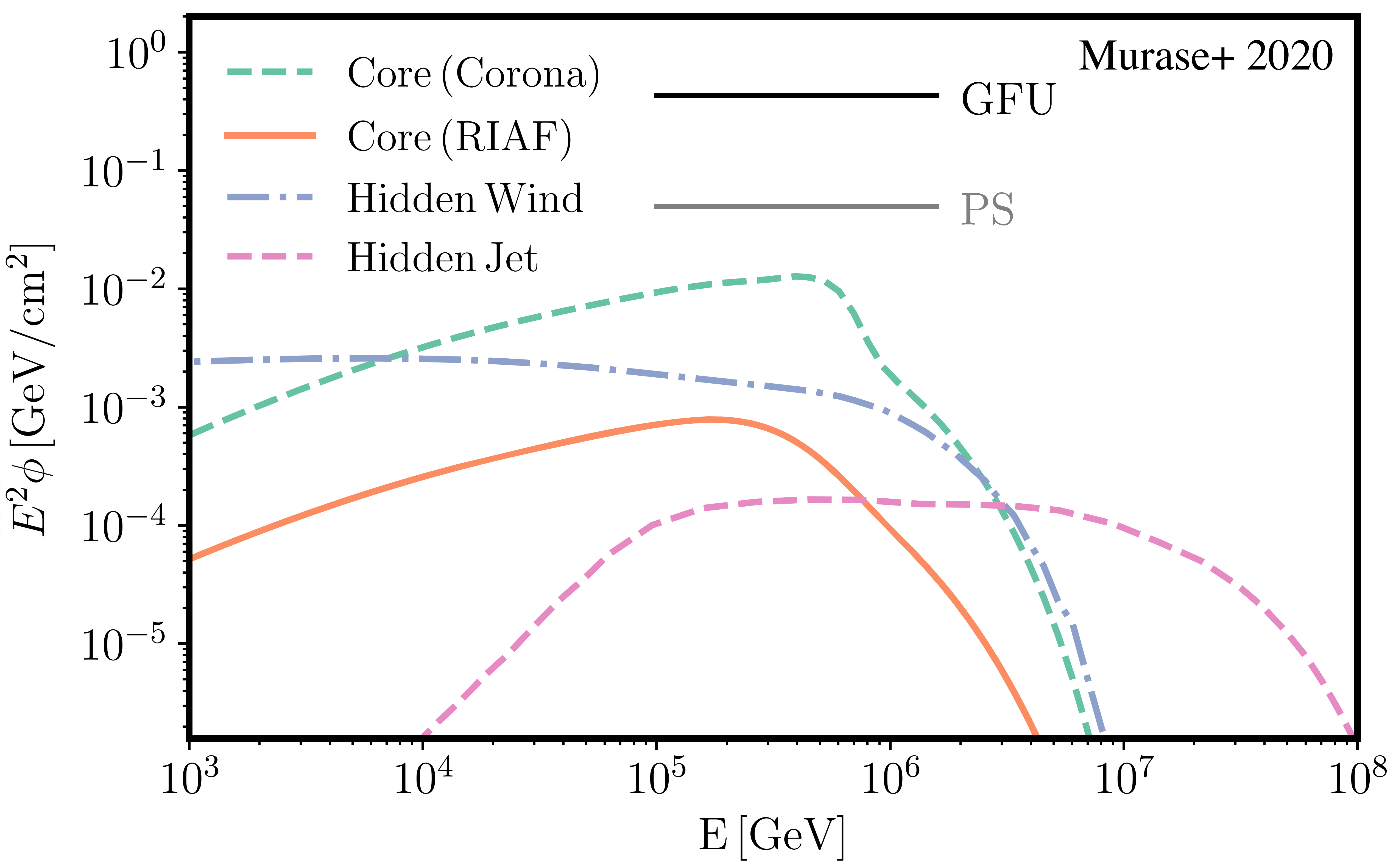
- Star is torn apart by SMBH
  —> luminous & long duration transient
- **Details of physical processes unknown**
- 2 associations of IceCube events with TDEs (3.5σ)? IC191001 <=> AT2019dsg ; IC200530 <=> AT2019fdr
- Mysterious time delay: Neutrino coming at 100 - 400 days after opt/UV peak

Neutrino Emission Models for TDEs

Fang+ 2017; Senno+ 2017;Winter+ 2020



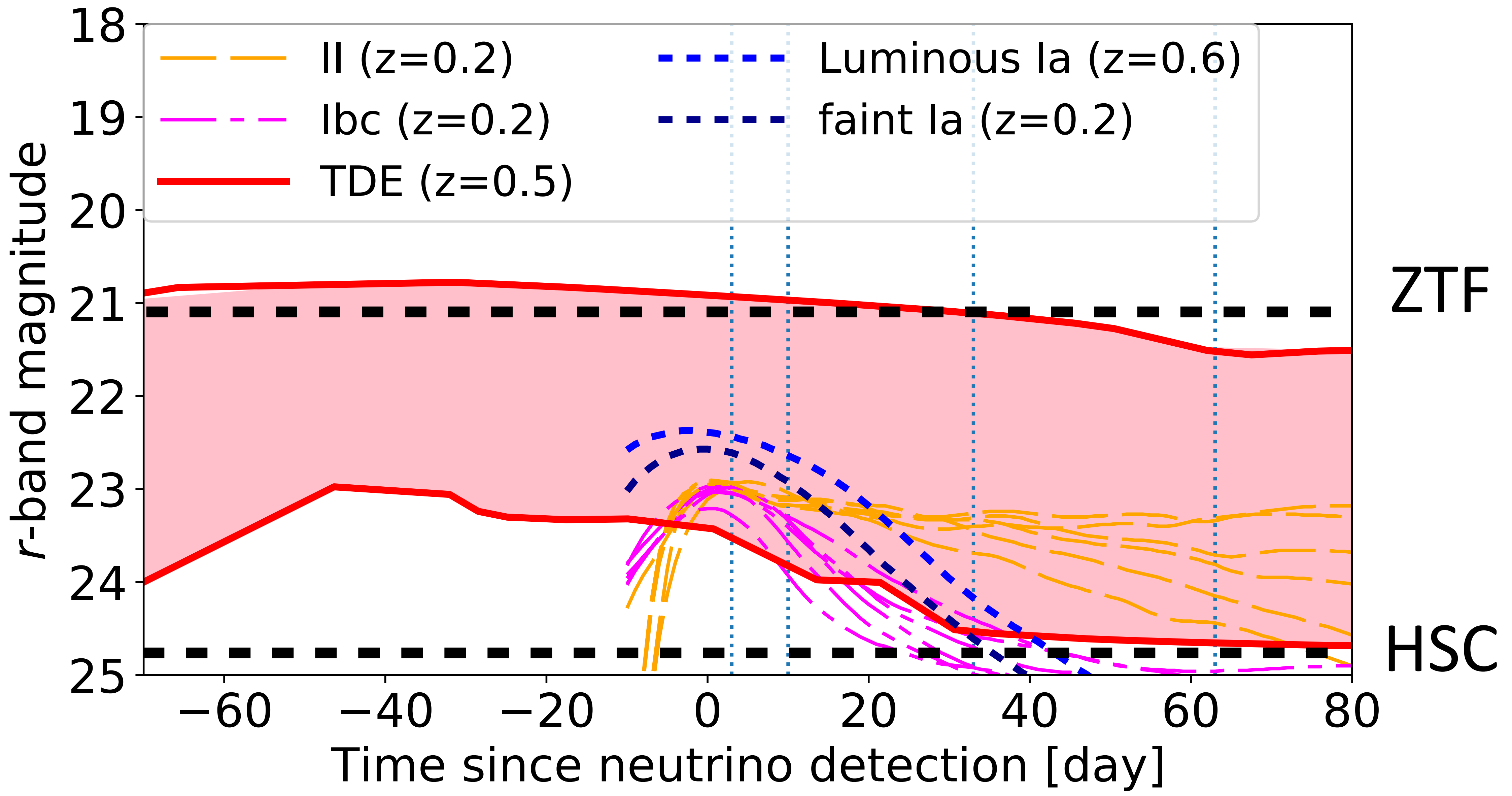
Murase, SSK + 2020 ApJ

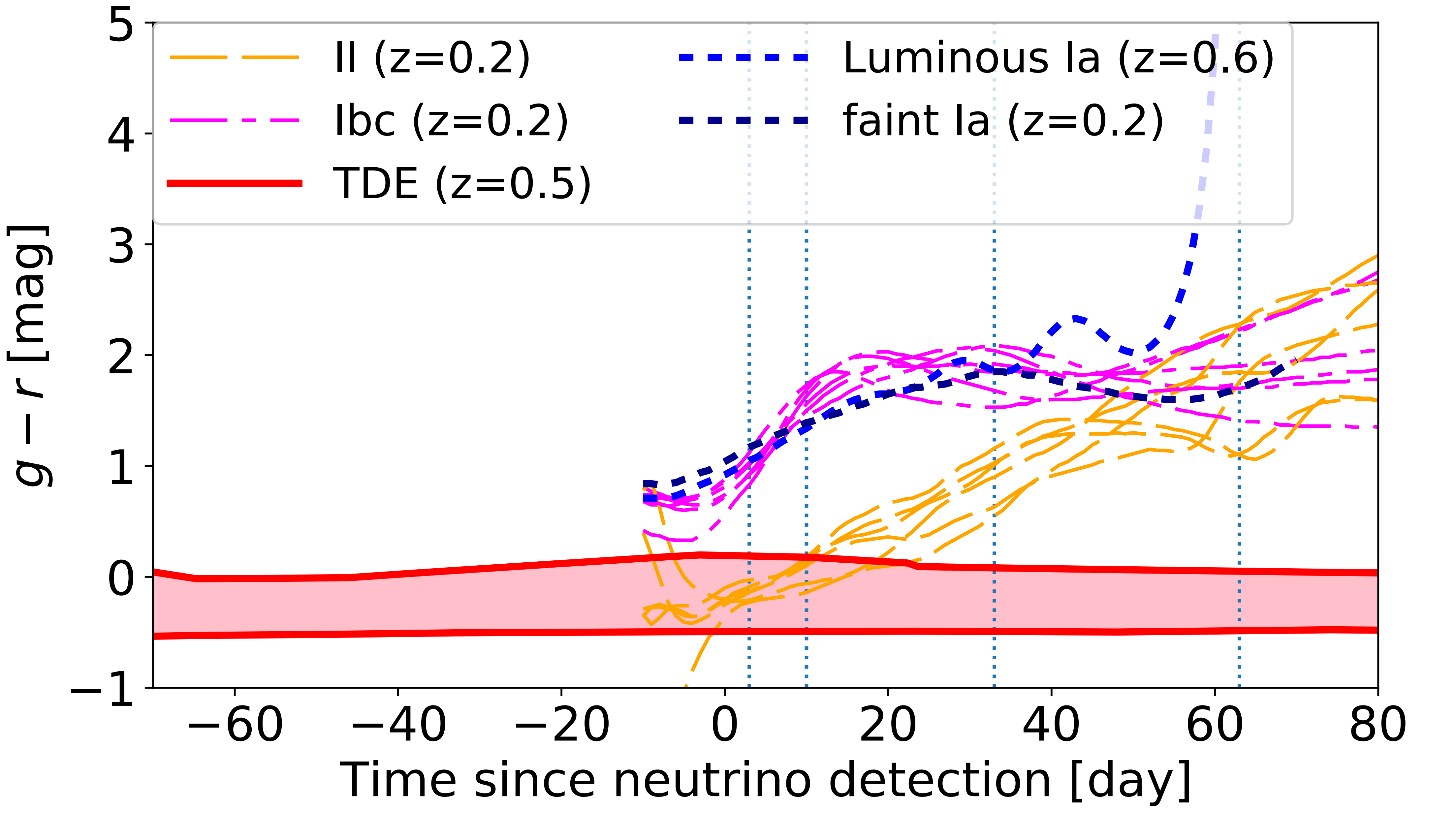


- Corona model : possible (High neutrino flux; time delay: state transition of disks)
- Wind model : challenging (High neutrino flux; time delay: delayed interaction etc)
- Jet model : unlikely (Low neutrino flux : time delay: target photon evolution)

Test for TDE-neutrino paradigm

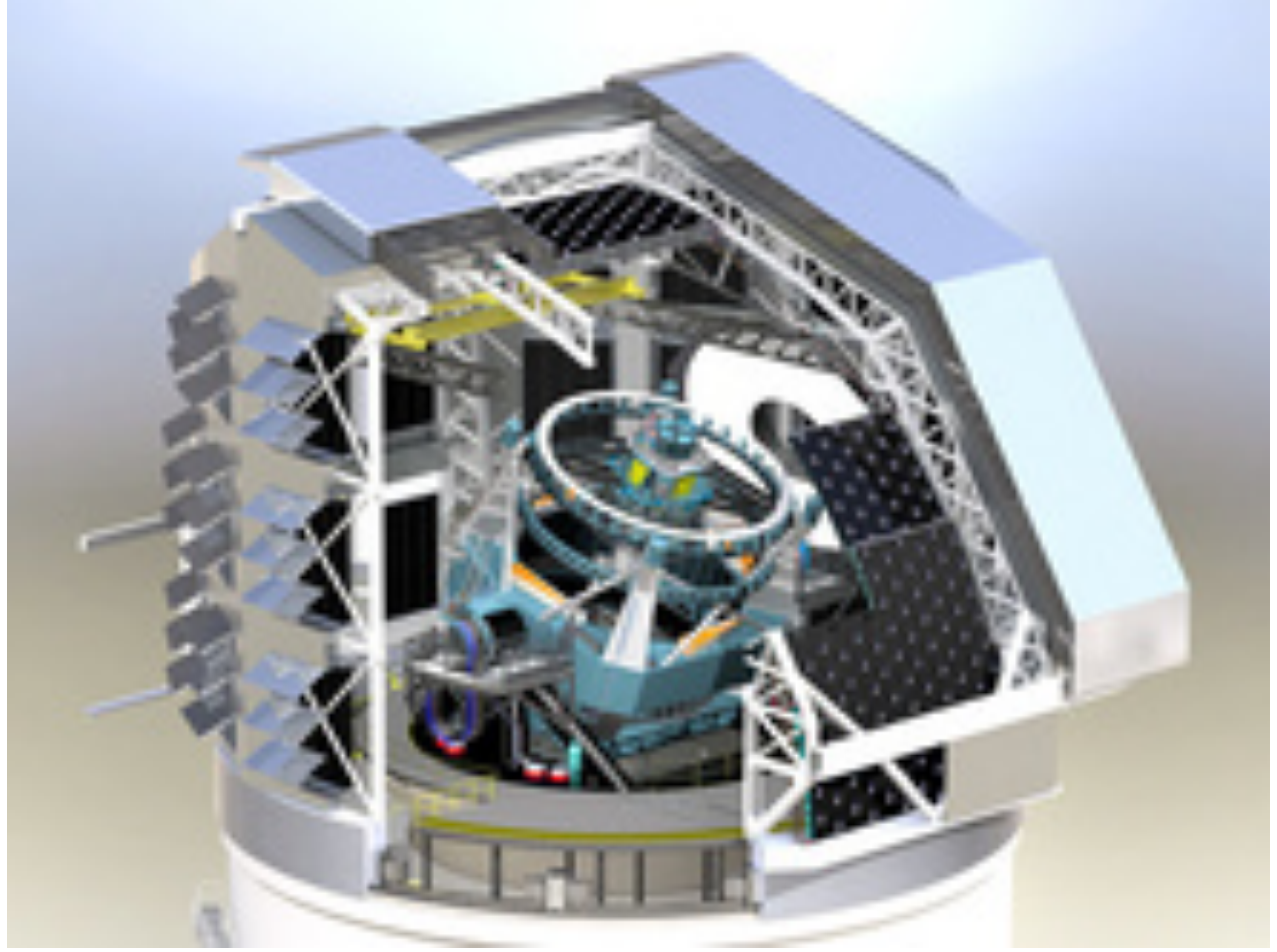
- Expected distance to typical neutrino emitting TDEs: $z \sim 0.5 - 1$(TDE@z=0.5: 21-24 mag)
  —> **Deep photometric observation** (limiting magnitude for 4m telescope: 24 mag)
- Neutrino error region: 1 deg^2
  —> **Need Wide field of view** (typical FoV: 0.03 deg^2)
- Currently, only **Subaru/HSC can achieve these two features**
- **Let us search for slow-blue transients** (ToO proposal accepted by Subaru 23A, B)



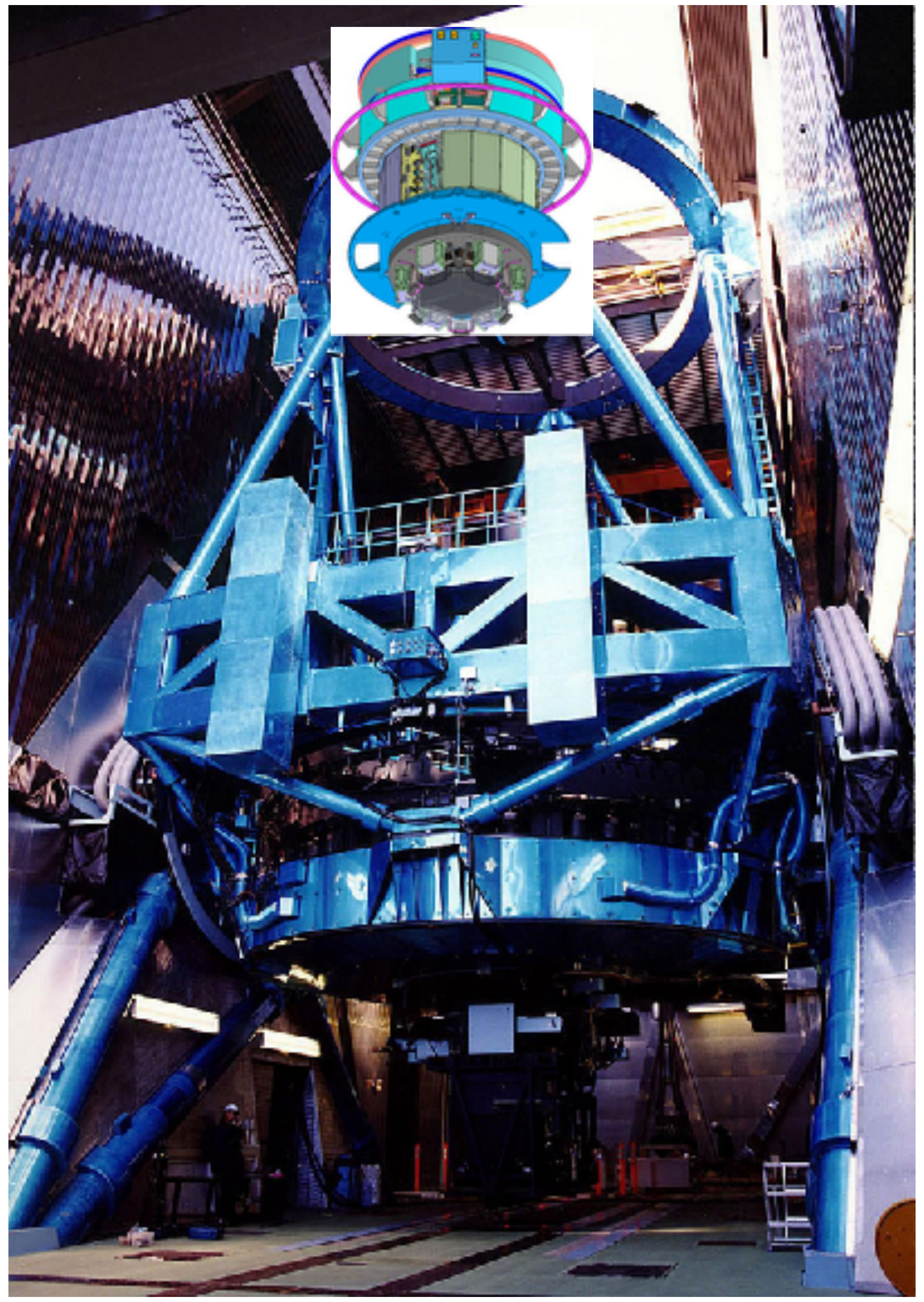


Future prospects of optical follow-up

- Vera Rubin Observatory (LSST):
  - Wide & Deep photometric survey
  - limiting magnitude < 23 mag



- Subaru PFS:
  - Wide FoV multi-object spectroscopy
  - Possible to perform spectroscopy to all the transients in neutrino error region



We can identify TDE & Jetted SNe as neutrino sources

Summary

- Origin of cosmic neutrinos are a new big mystery in astrophysics
- Previously popular models are already disfavored
- **AGN accretion flow models can explain cosmic neutrino background**
  <— Future MeV-GeV γ & TeV-PeV neutrino observation robustly test our model
- TDE-neutrino associations are reported, but situation is controversial.
  <— future optical follow-up is essential to test the TDE-neutrino paradigm