Modelling neutrino emission from Active Galactic Nuclei (AGN)

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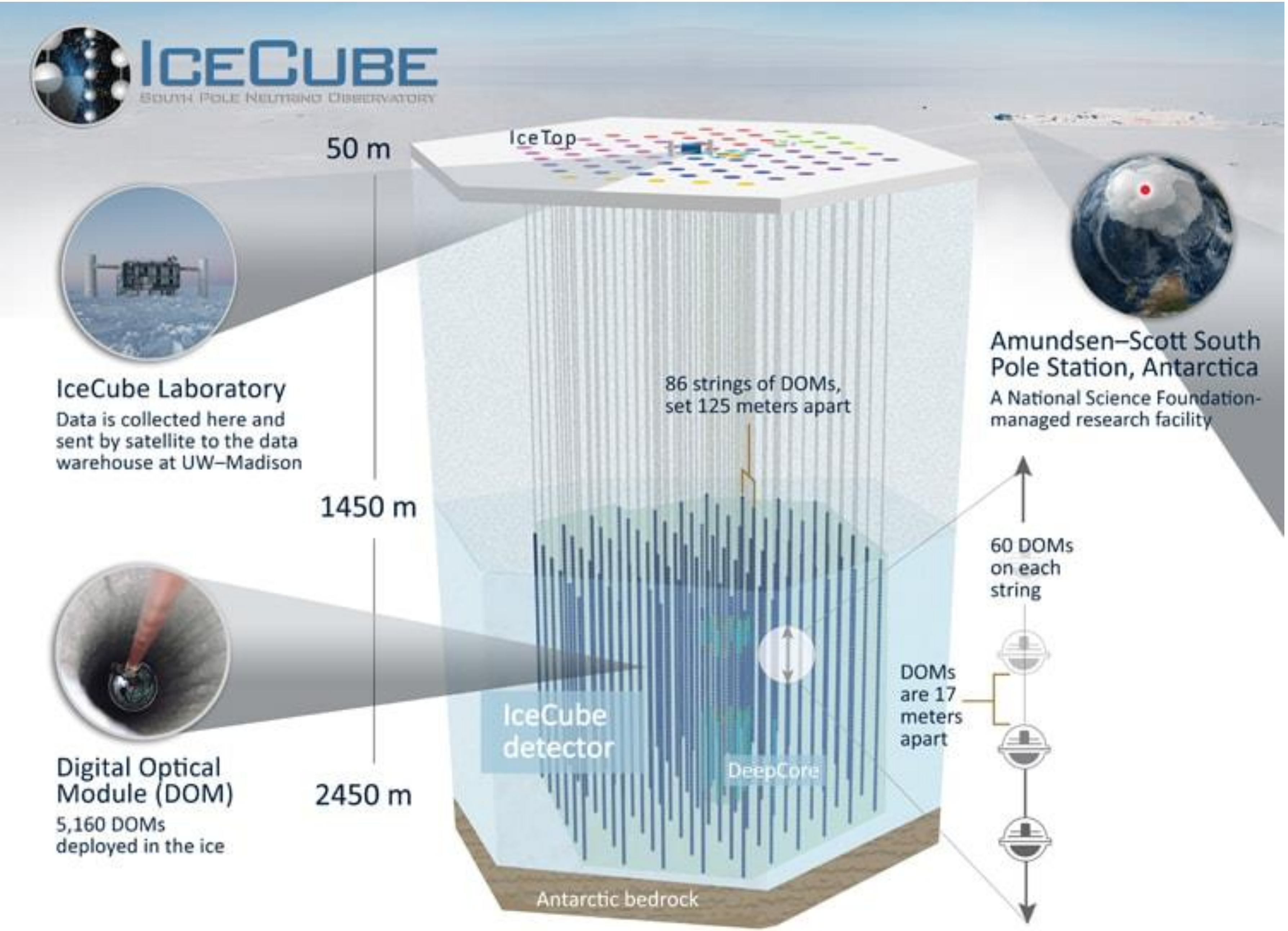
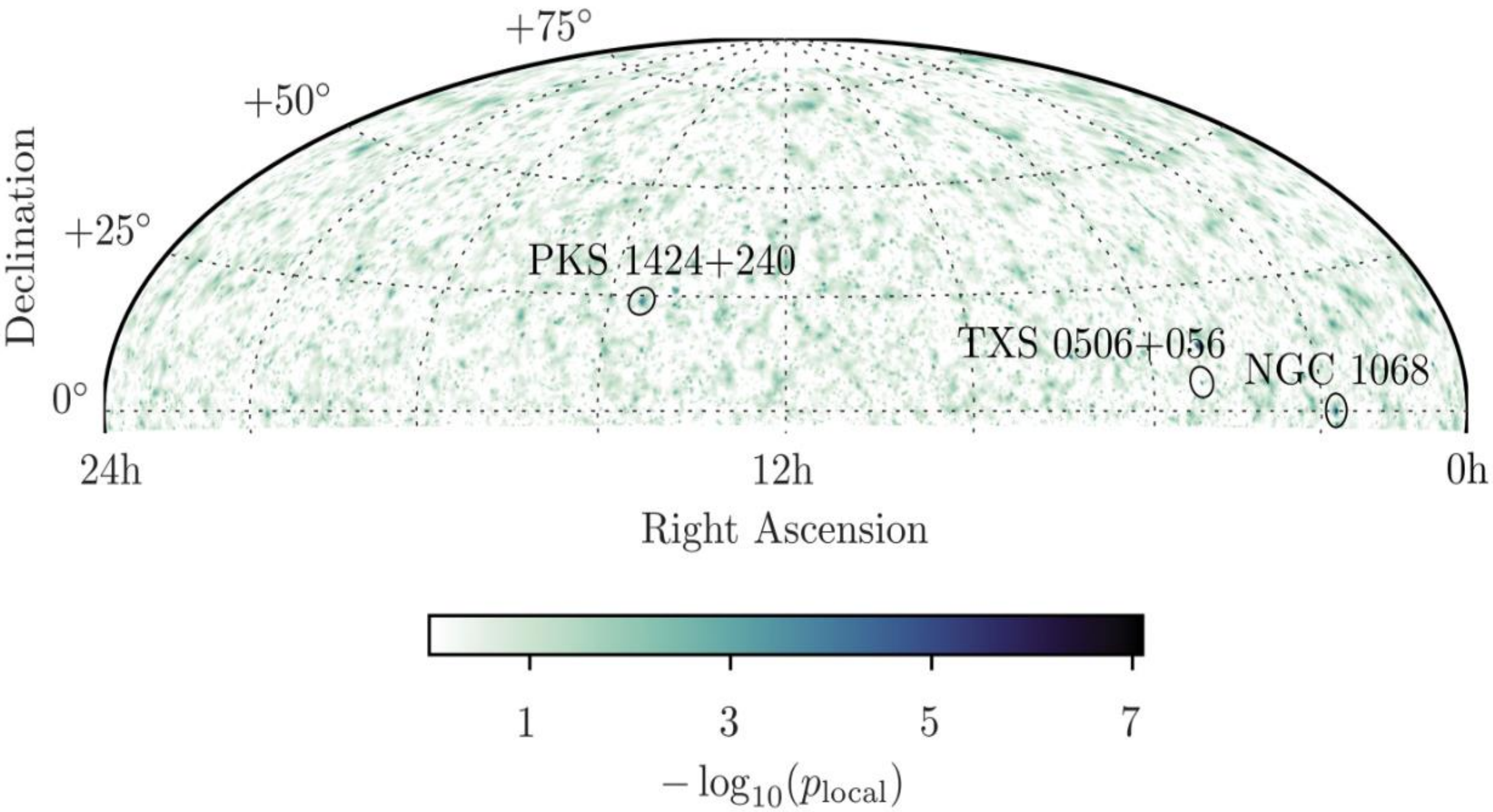


(Credit: icecube.wisc.edu/science/icecube/)

The IceCube Neutrino detector

1. $1\ \mathrm{km}^3$ volume Cherenkov detector
2. Discovered diffuse flux of astrophysical neutrinos
3. Started to pinpoint locations of sources

Characteristics of identified point sources



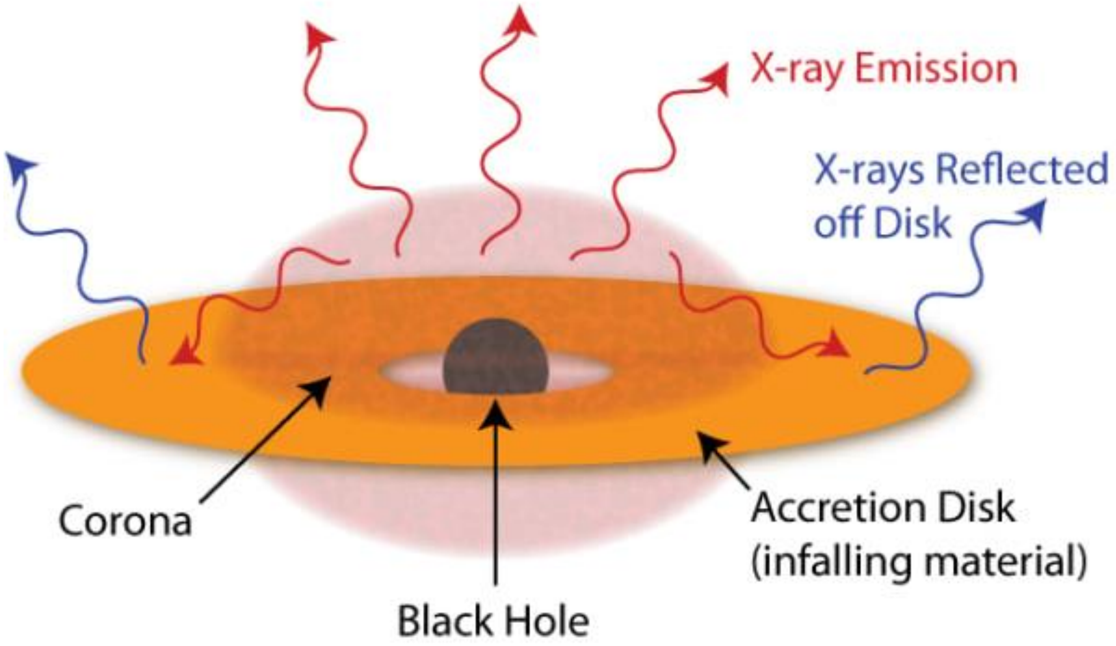
(Credit: IceCube Collaboration, Science 378, 6619, 538-543 (2022))

2 known ν point sources:

1. NGC 1068:
   - Seyfert 2 galaxy
   - $z = 0.0038$
   - Steady source
   - 2011-2020: 79^{+22}_{-20} neutrinos
2. TXS 0506+056:
   - Blazar
   - $z = 0.3365$
   - Transient source
   - Sept 2017: 290 TeV neutrino
   - 2014-2015: 13 ± 5 neutrinos

All are AGNs ($M = 10^7\ M_\odot$)

AGN as an accelerator and a target



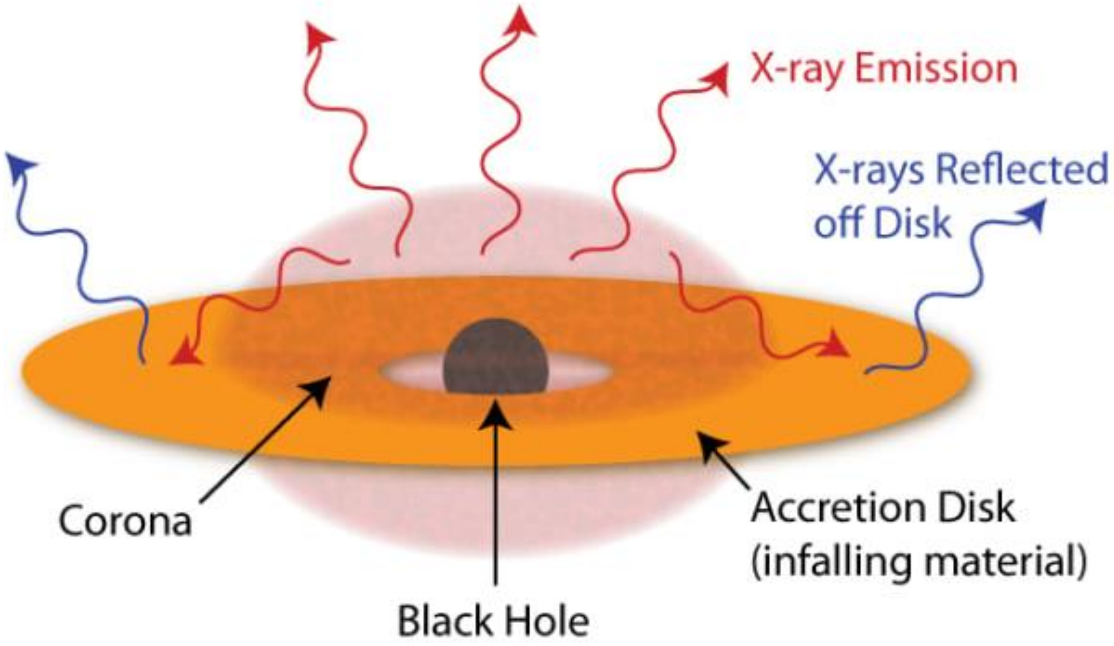
(Credit: D. Wilkins, danwilkins.net/research)

- Supermassive black holes in the center of *active* galaxies:
  - accelerate protons
  - produce neutrinos in the dense targets surrounding them

- **Accelerator:** turbulent magnetic fields associated with accretion disk, in-fall of matter around the black hole

- **Targets:** dense radiation fields (X-rays) and in-falling matter (large optical depth)

AGN as an accelerator and a target



- Supermassive black holes in the center of *active* galaxies:
  - accelerate protons
  - produce neutrinos in the dense targets surrounding them

Our goal: Use dimensional analysis to predict neutrino and gamma-ray fluxes and make comparisons to data.

(Credit: D. Wilkins, danwilkins.net/research)

How are protons accelerated?

Shock Acceleration

- Charged particles are repeatedly reflected between shock wave-fronts

Magnetic Reconnection

- B-fields break & reconnect with other B-fields
- Heat + kinetic energy are released

Plasma Turbulence

- Charged particles scatter off magnetized plasma blobs

Producing astrophysical neutrinos

1. Inelastic proton-proton collision (pp):

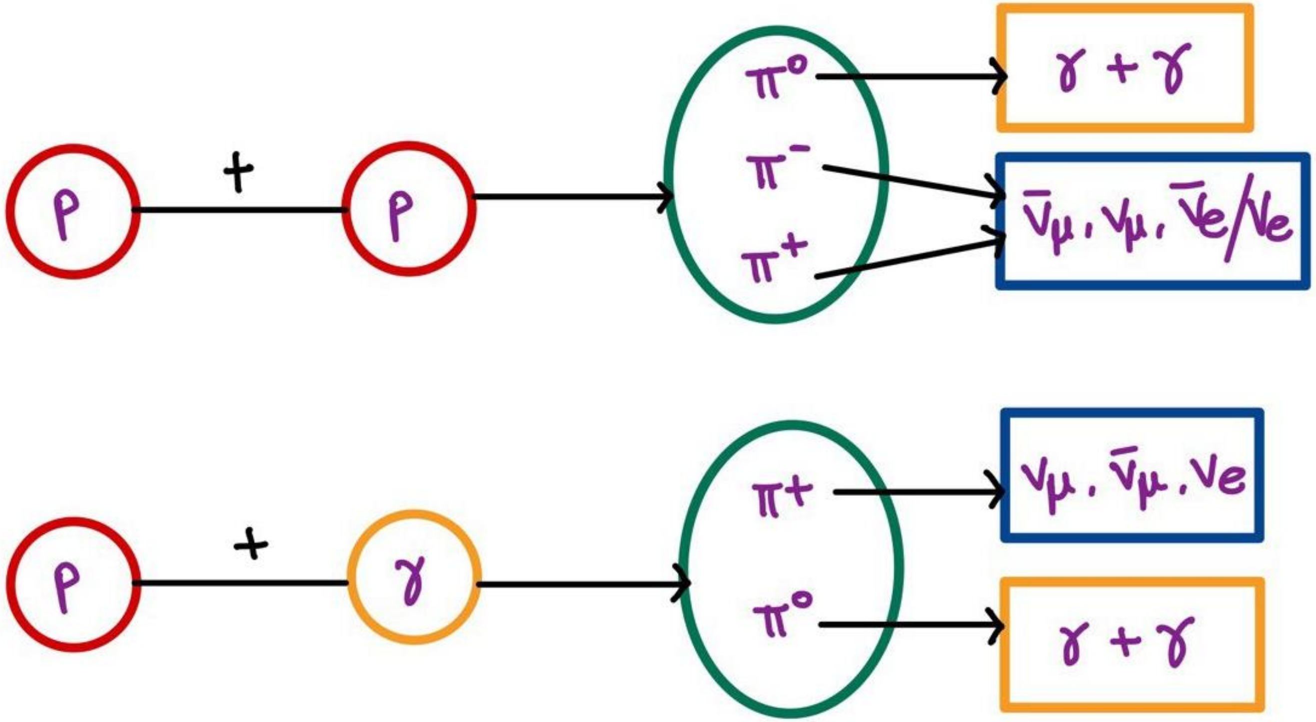
$$p + p \longrightarrow n_\pi\,(\pi^0 + \pi^+ + \pi^-) + X$$

2. Photomeson production (pγ):

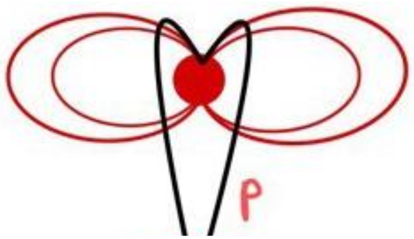
$$p + \gamma \longrightarrow n + \pi^+$$
$$p + \gamma \longrightarrow p + \pi^0$$

- Pionic neutrinos and gamma-rays:

$$\pi^+ \longrightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^0 \longrightarrow \gamma + \gamma$$



Producing neutrinos in AGNs

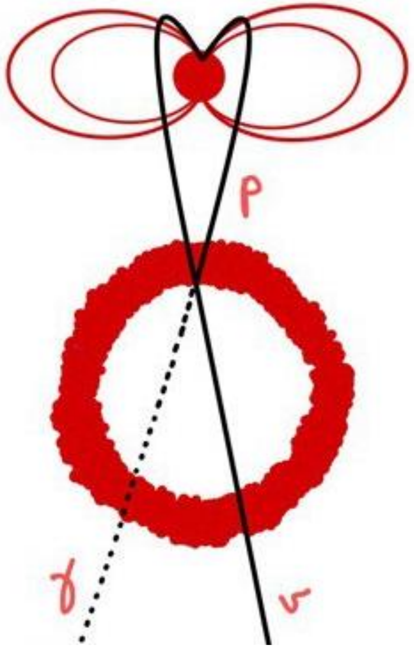


Accelerator
(black hole)

1. Proton injection rate:

$$Q_p(E_p) = Q_{p,0}\left(\frac{E_p - m_p c^2}{E_{p,0}}\right)^{-\gamma_p}$$

Producing neutrinos in AGNs



Accelerator
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$\gamma, p -$ target
(enveloping
black hole)

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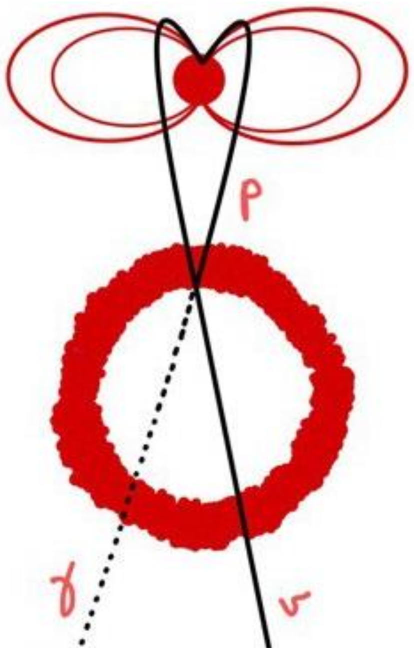
2. Neutrino production rate:

$$Q_\nu(E_\nu) = 192(1 - e^{-\tau_{pp}})\, Q_{p,0}\left(\frac{24\, E_\nu}{E_{p,0}}\right)^{-\gamma_p} \qquad (pp)$$

$$Q_\nu(E_\nu) = 60(1 - e^{-\tau_{p\gamma}})\, Q_{p,0}\left(\frac{20\, E_\nu - m_p c^2}{E_{p,0}}\right)^{-\gamma_p} \qquad (p\gamma)$$

(Credit: F. Halzen, ArXiv:2202.00694 & Tjus et al., Phys. Rev. D 89, 123005)

Producing neutrinos in AGNs



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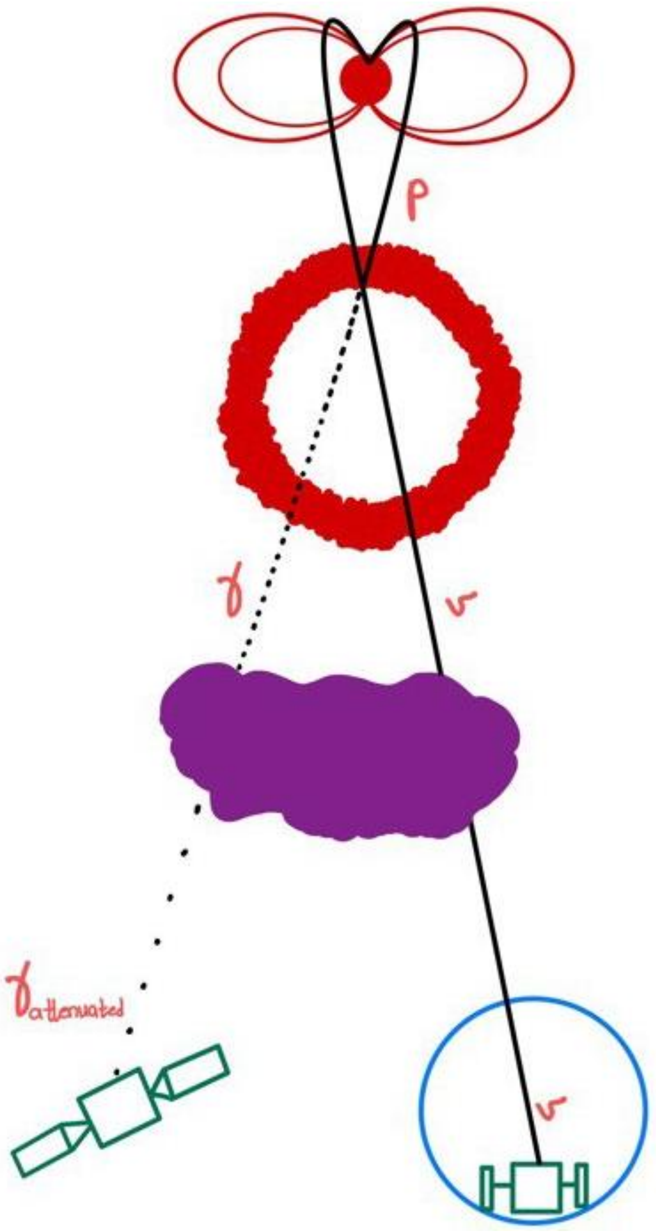
3. Neutrino flux detected:

$$\phi_\nu^{\mathrm{PS}}(E_\nu) = \phi_0^{100\ \mathrm{TeV}}\left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma_{astro}} = \frac{(1+z)^2}{4\pi d_L^2} Q_\nu((1+z)E_\nu)$$



Accelerator
(black hole)

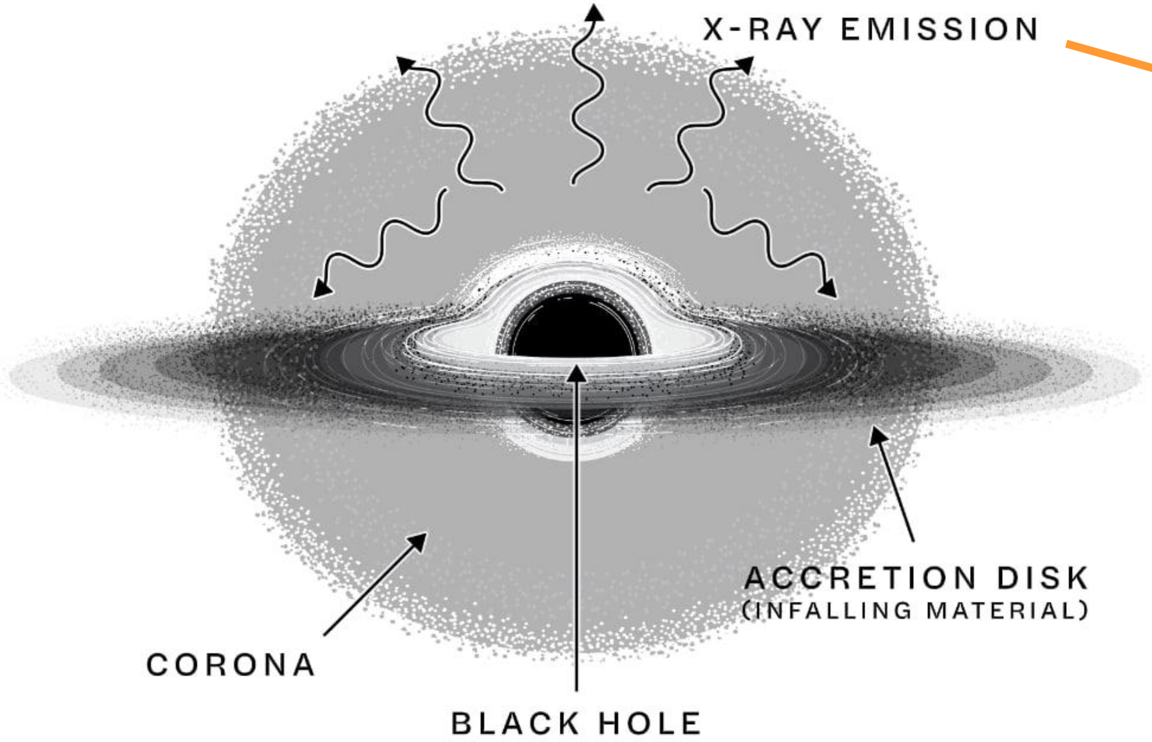
$\gamma, p -$ target
(enveloping
black hole)

Opaque medium
(EBL, etc)

Detectors
(Fermi LAT,
IceCube)

Optical depth of target

Corona-disk model:



Schwarzschild Radius

X-ray luminosity

$$\tau_{p\gamma} \simeq \kappa_{p\gamma}\sigma_{p\gamma}Rn_X = 10^2 \left(\frac{R_s}{R}\right)\left(\frac{1\ \text{keV}}{E_X}\right)\left(\frac{L_X}{L_{edd}}\right)$$

Inelasticity

Cross sectional area

X-ray column density

X-ray energy

Eddington luminosity

For NGC 1068 $\left(M = 10^7\ M_{\odot}\right)$:

$R \leq 10\ R_S$ → ν produced very close to the black hole

(Credit: F. Halzen, ArXiv:2305.07086)

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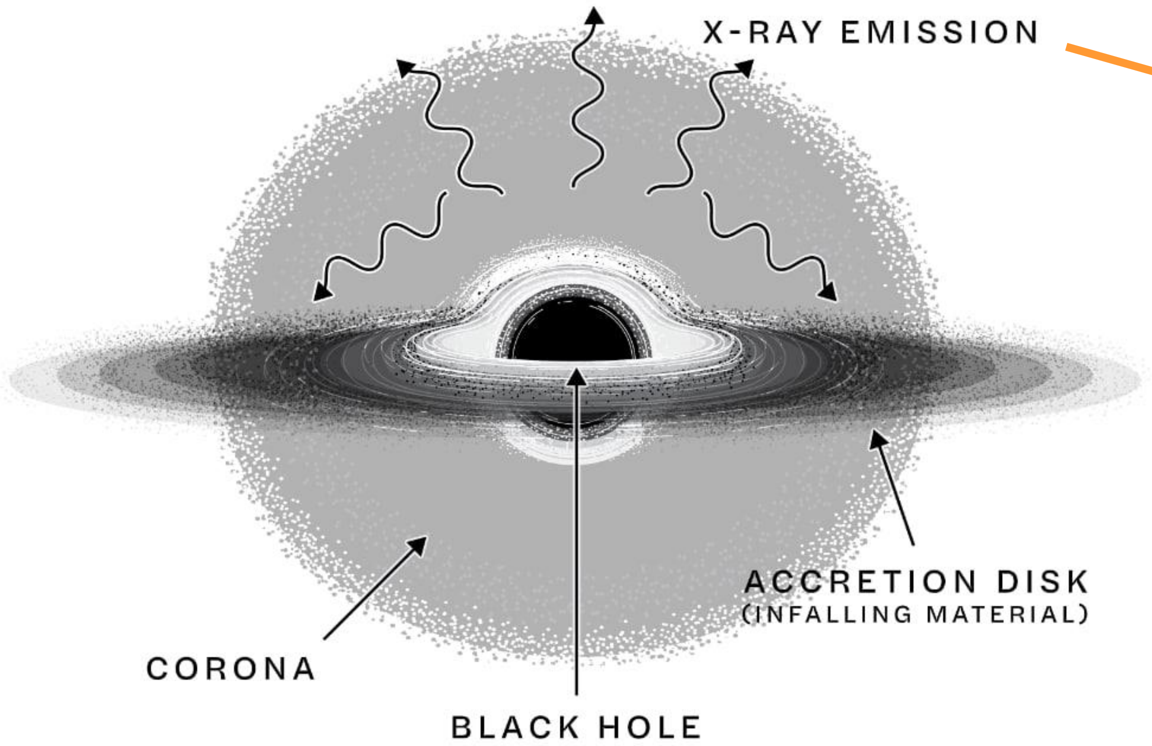

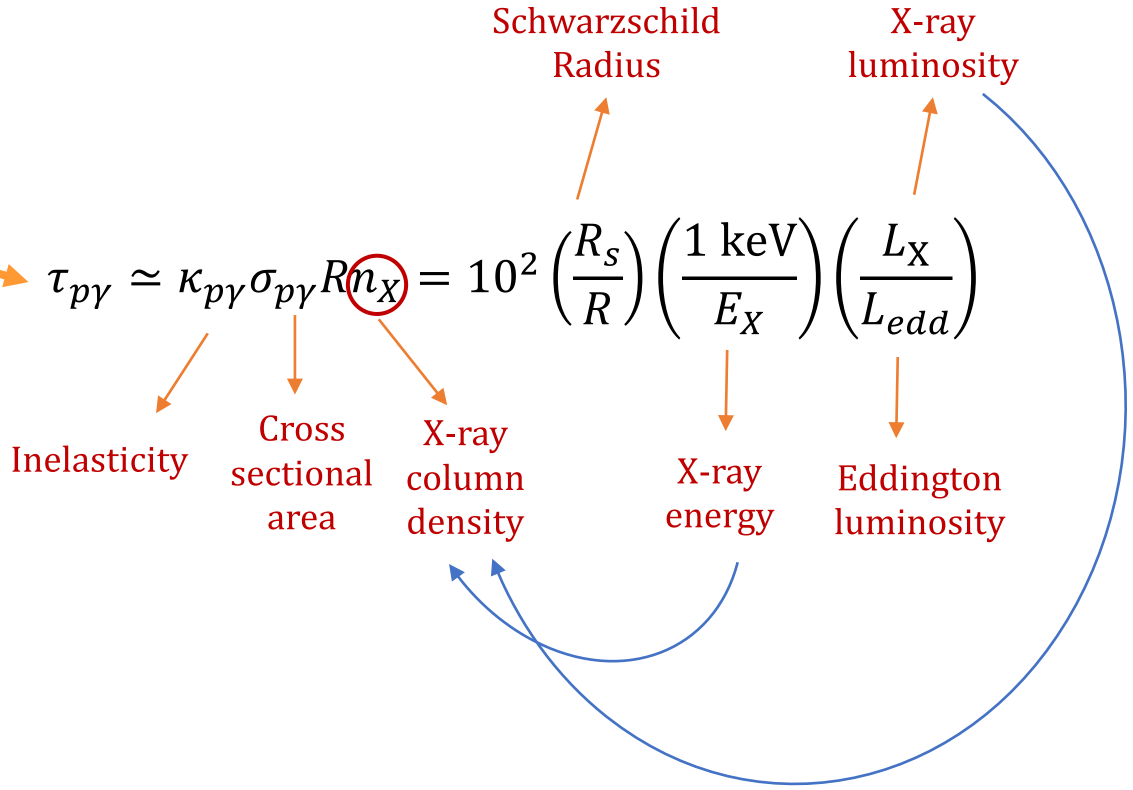

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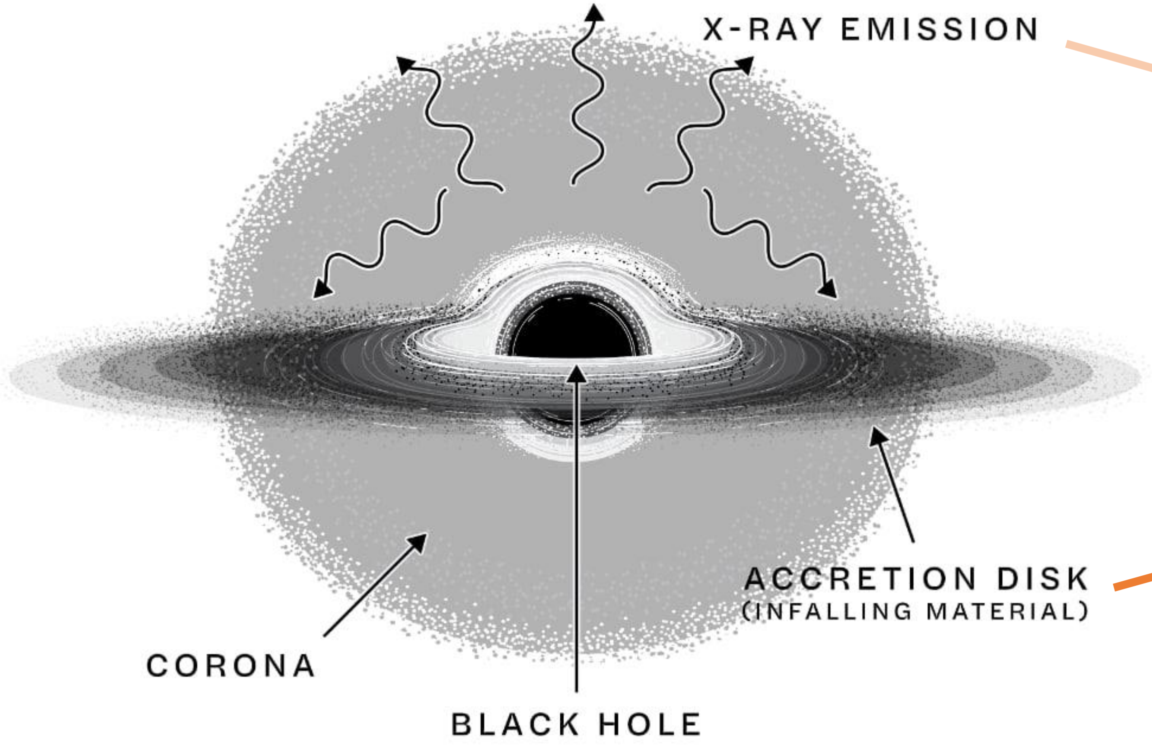
Optical depth of target

In-fall (shock-wave) model:



$$\tau_{p\gamma} \simeq \kappa_{p\gamma}\sigma_{p\gamma}Rn_X = 10^2\left(\frac{R_s}{R}\right)\left(\frac{1\text{ keV}}{E_X}\right)\left(\frac{L_X}{L_{edd}}\right)$$

$$\underbrace{\overbrace{\kappa_{pp}}^{\text{Inelasticity}}\,\overbrace{\sigma_{pp}}^{\text{Cross sectional area}}\,\overbrace{N_H}^{\text{Proton column density}}}\!\!\!\quad \tau_{pp} \simeq \kappa_{pp}\sigma_{pp}N_H\left(\frac{c}{\underbrace{v_{ff}}_{\text{Free-fall velocity}}}\right)$$

Inelasticity

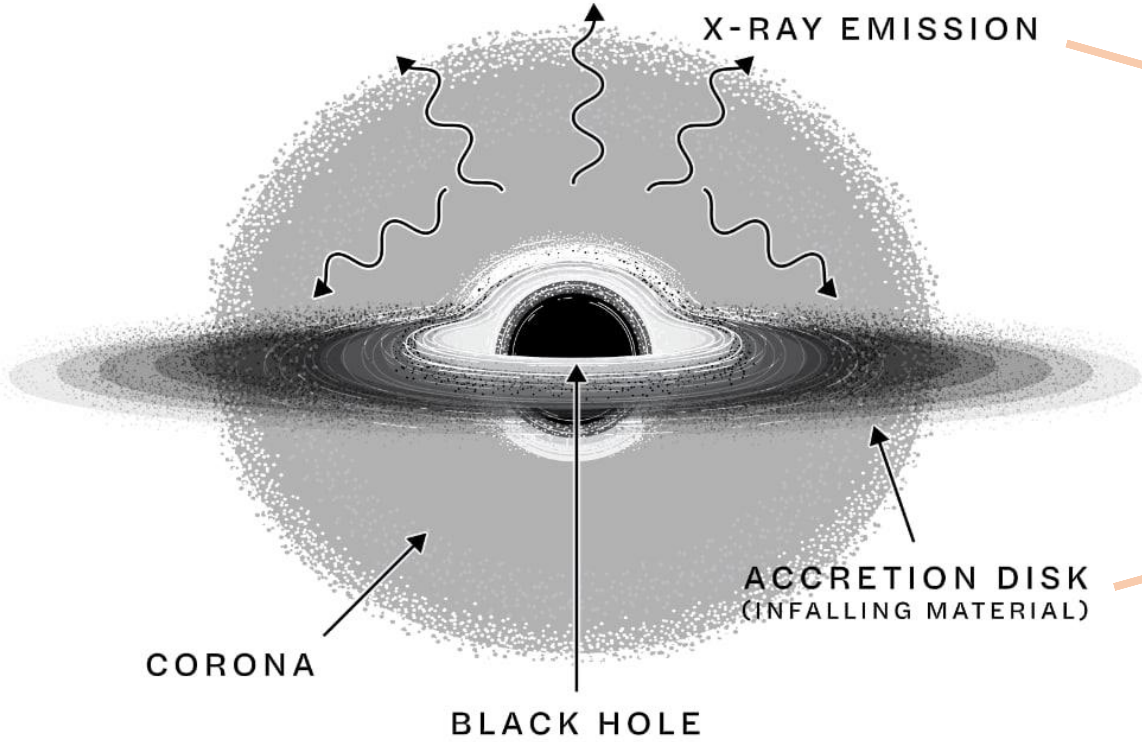
Cross sectional area

Proton column density

Free-fall velocity

(Credit: F. Halzen, ArXiv:2305.07086)

Optical depth of target



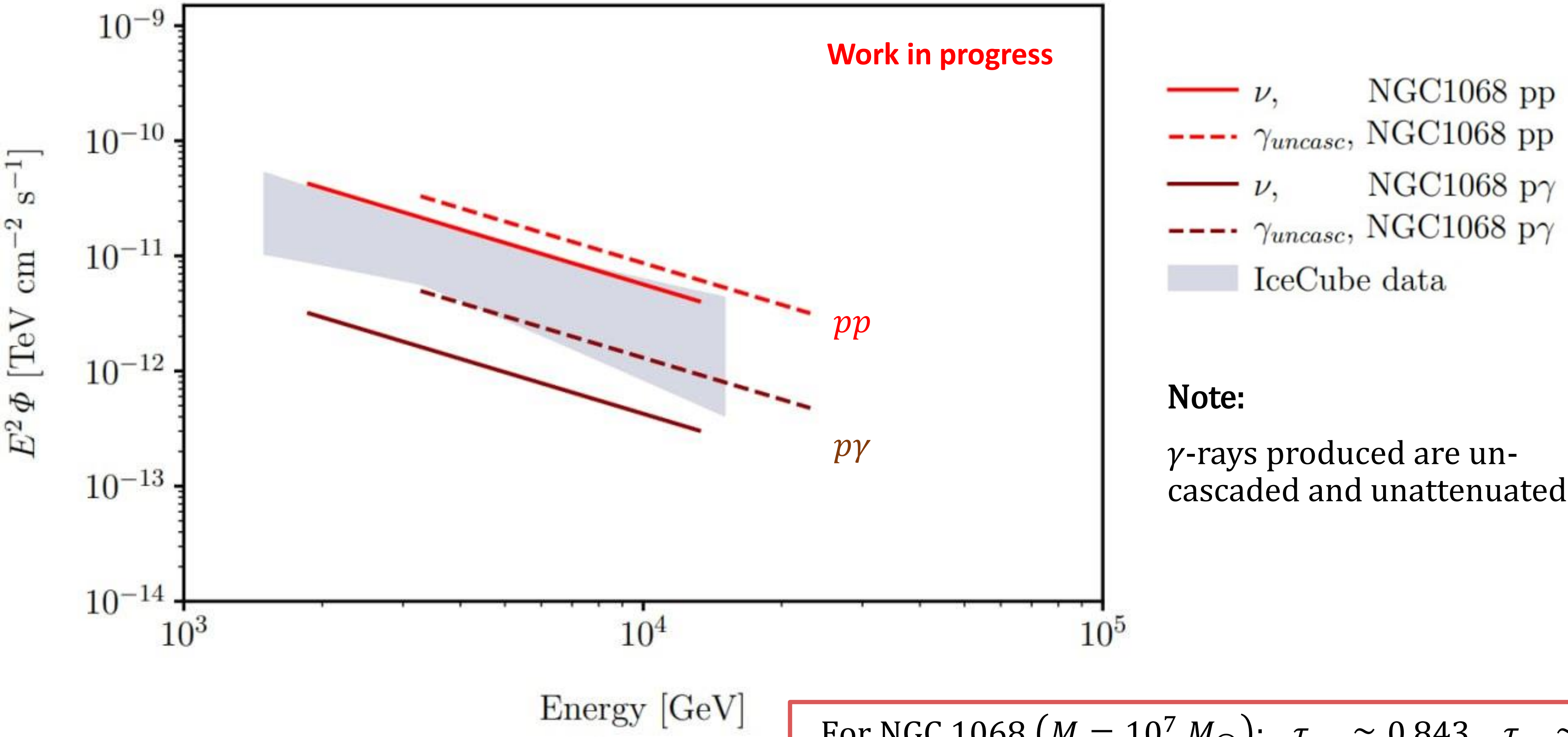
$$\tau_{p\gamma} \simeq \kappa_{p\gamma}\sigma_{p\gamma} R n_X = 10^2 \left(\frac{R_s}{R}\right)\left(\frac{1\ \mathrm{keV}}{E_X}\right)\left(\frac{L_X}{L_{edd}}\right)$$

$$\tau_{pp} \simeq \kappa_{pp}\sigma_{pp} N_H \left(\frac{c}{v_{ff}}\right)$$

For NGC 1068 $\left(M = 10^7\ M_\odot\right)$: $\tau_{pp} \simeq 0.843$, $\tau_{p\gamma} \simeq 0.1$

(Credit: F. Halzen, ArXiv:2305.07086)

Neutrino and intrinsic γ-ray spectrum



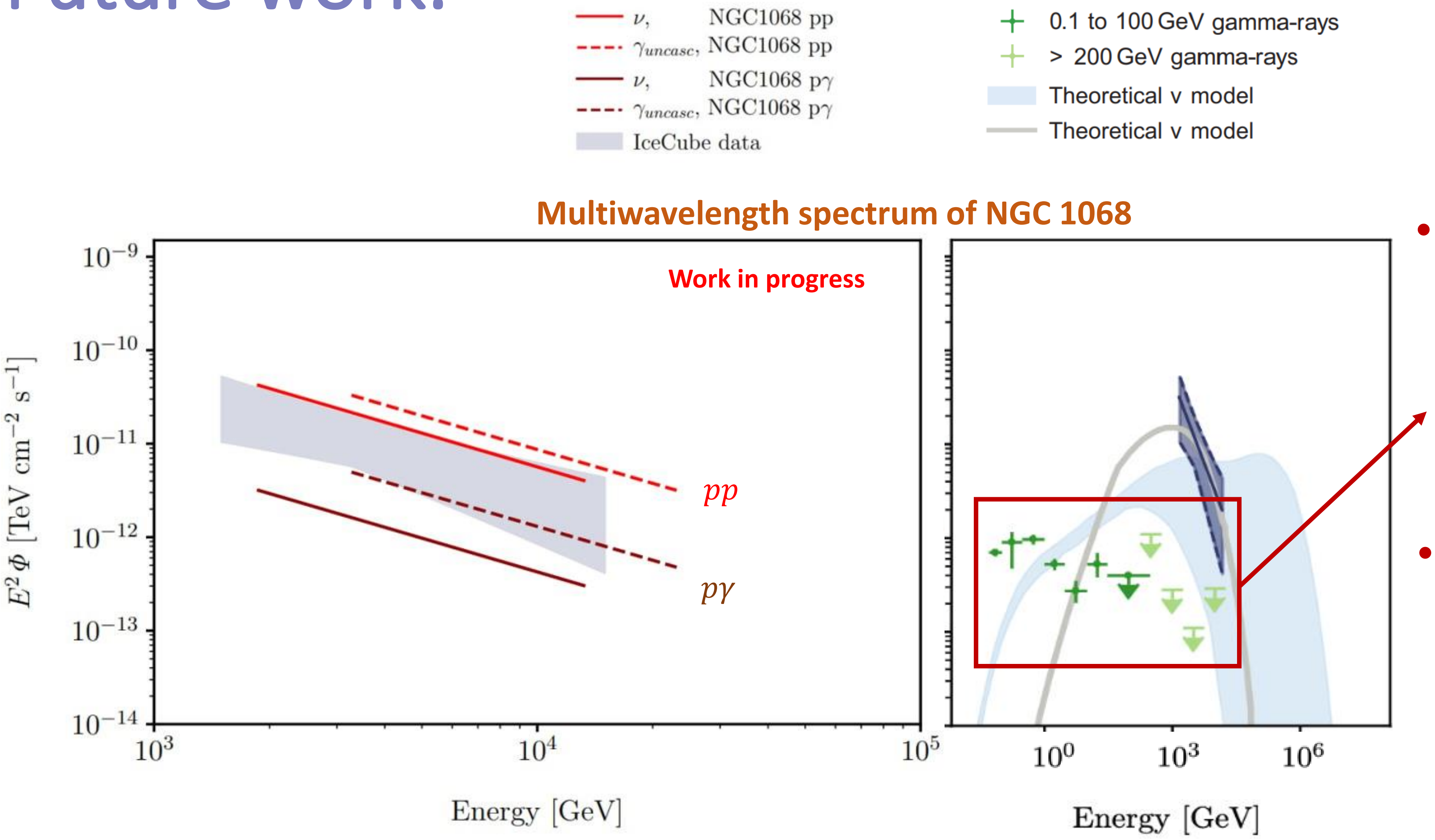
Note:

γ-rays produced are un-cascaded and unattenuated.

For NGC 1068 $\left(M = 10^7\, M_\odot\right)$: $\tau_{pp} \simeq 0.843, \quad \tau_{p\gamma} \simeq 0.1$

(Credit: IceCube Collaboration, Science 378, 6619, 538-543 (2022))

Future work:

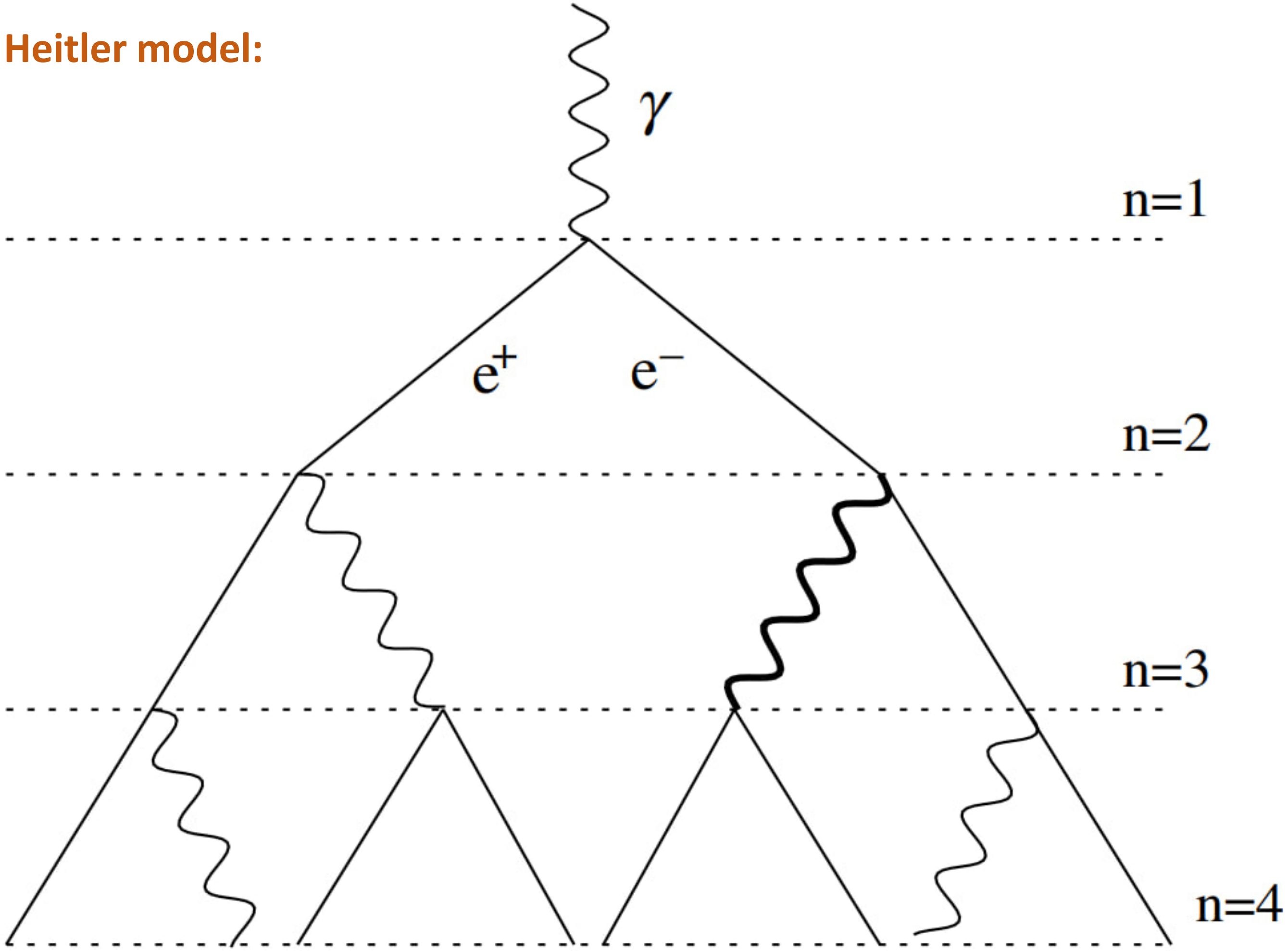

Multiwavelength spectrum of NGC 1068

- These pionic γ-rays lost energy in the target and appear in the MeV-GeV range.
- **Next step:** Modelling how they cascade in NGC 1068

(Credit: IceCube Collaboration, Science 378, 6619, 538-543 (2022))

Future work: How do EM cascades develop?

Heitler model:



(Credit: J. Matthews, Astroparticle Physics 22 (2005) 387–397)

1. $e^{\pm}$ lose energy at each level via:
   - Pair production: $\gamma \rightarrow e^+ + e^-$
   - One-photon bremsstrahlung
2. Development stops when γ-rays are below pair-production threshold energy

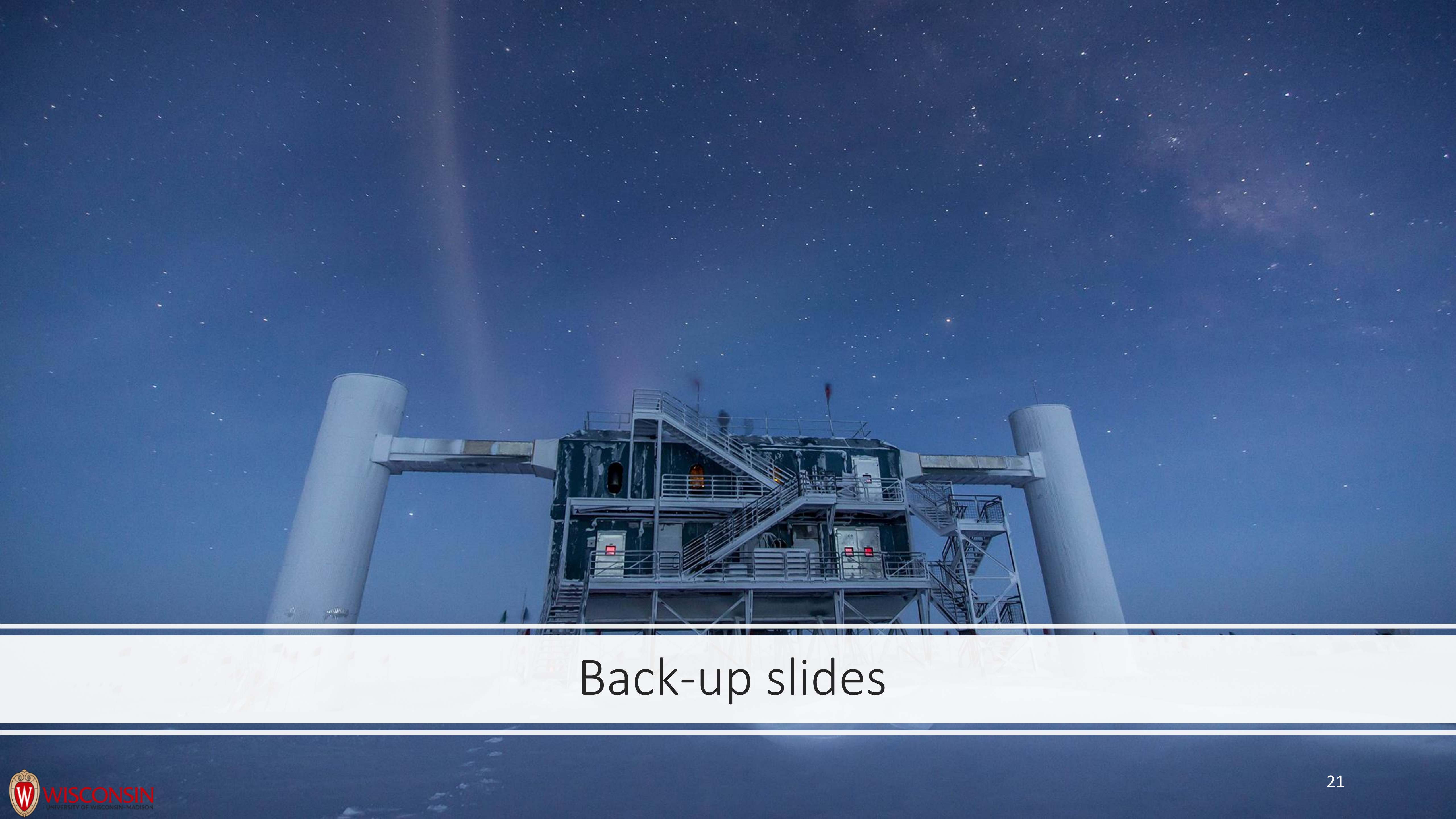
Summary

1. Neutrino production rate depends on optical depth of target

2. Observation of γ-ray flux accompanying the neutrino spectrum at lower energy levels

3. **Ongoing work:**
   - Calculate the cascaded and attenuated $\gamma-$ray flux and compare it to data
   - Extend the model to sources like TXS 0506+056

Thank you!



Back-up slides

How much γ-rays are produced?

- The multi-messenger relation:

$$\frac{K_\pi}{4} E_\gamma^2 Q_\gamma\left(E_\gamma\right) \approx \frac{1}{3} E_\nu^2 Q_\nu(E_\nu)$$

$K_\pi = 1\ (p\gamma)$ or $2\ (pp)$

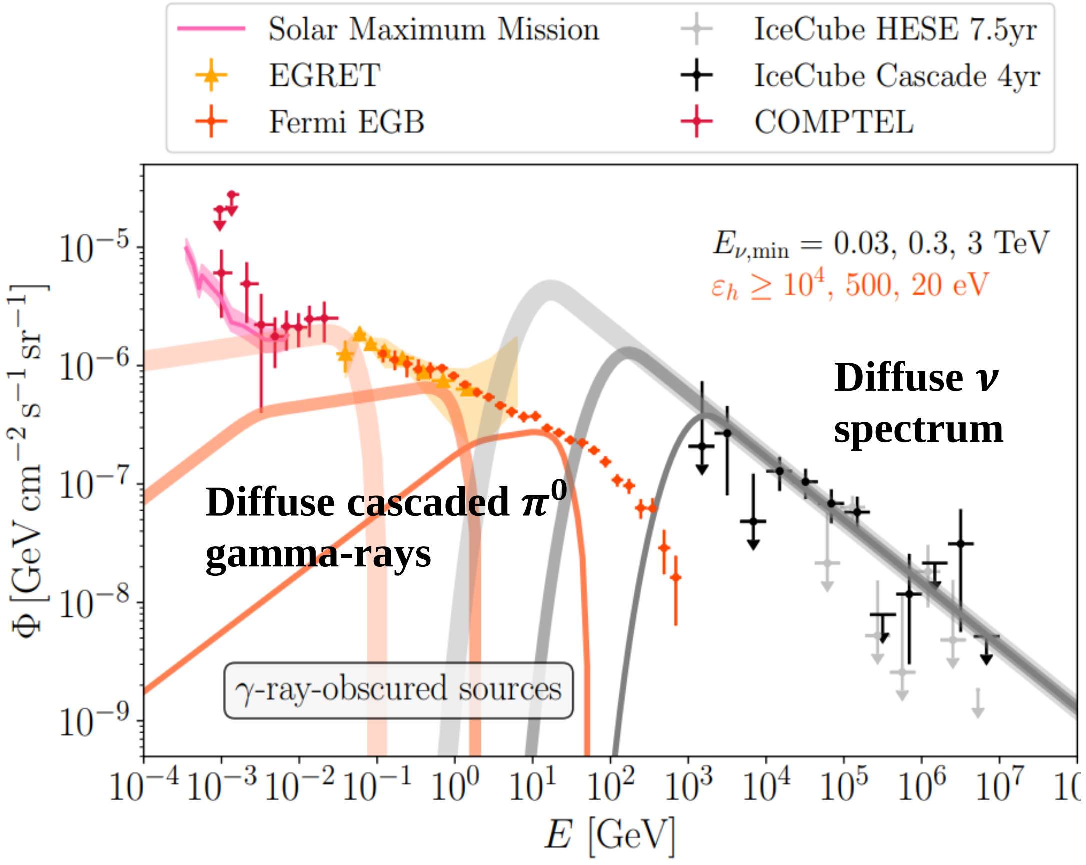
Gamma-ray production rate

Neutrino production rate

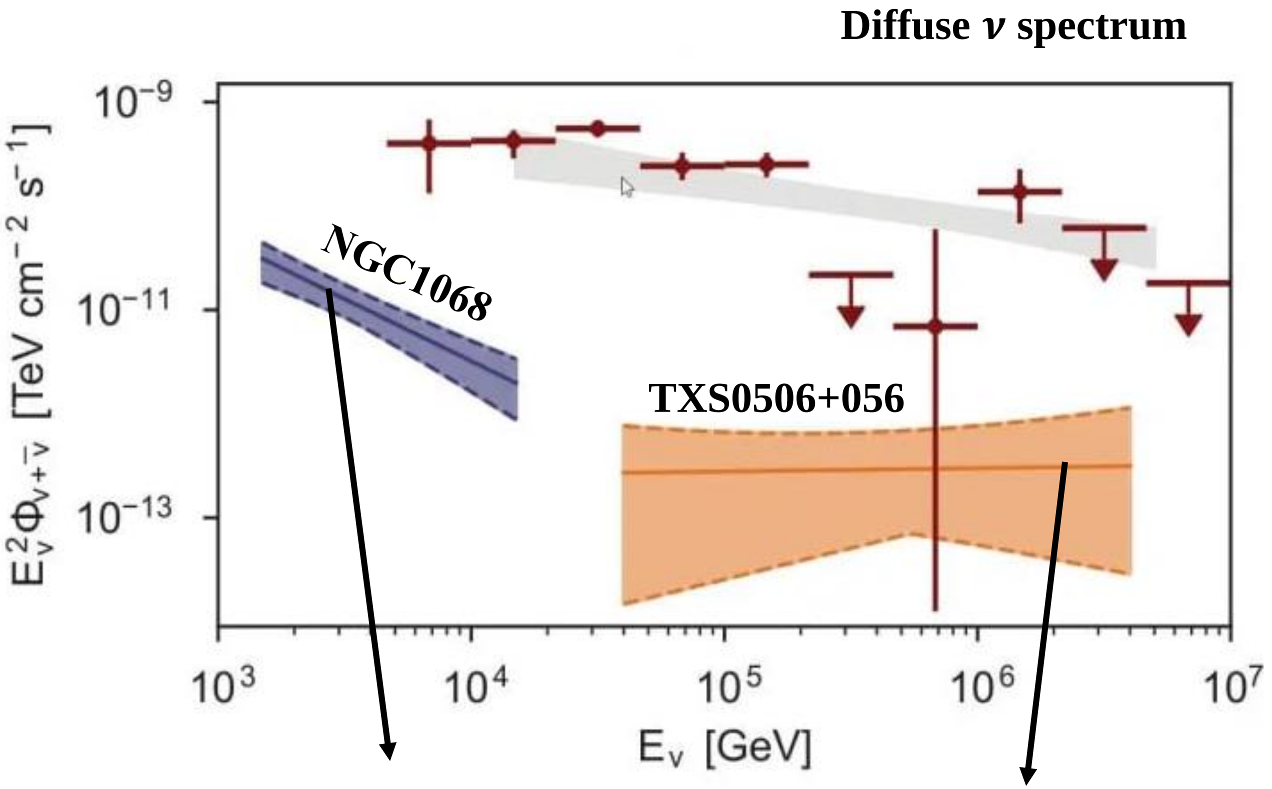
Note: The factor of 1/3 is due to averaging over the 3 neutrino flavours

(Credit: K. Fang et al, ArXiv:2205.03740)

Future work: Proposed Methodology



(Credit: K. Fang et al, ArXiv:2205.03740)



Each contribute ~1% of total astrophysical diffuse flux

(Credit: IceCube Collaboration et al., Science 378 (2022) 538-543)