Astrophysical Neutrinos
with a focus at High Energies

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ΕΛΛΗΝΙΚΗ ΑΣΤΡΟΝΟΜΙΚΗ ΕΤΑΙΡΕΙΑ
HELLENIC ASTRONOMICAL SOCIETY

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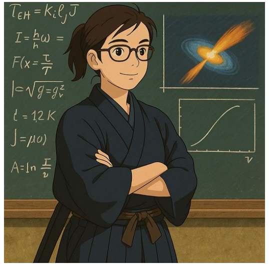
DEPARTMENT OF PHYSICS

A few words about me



- Assistant professor, Physics Department, NKUA, Greece
  - Lecturer for courses “Introduction to Astrophysics”, “High-Energy Astrophysics” (undergrad+MSc), Physics Labs

- Main research interests
  - Non-thermal radiative processes
  - Particle acceleration processes
  - Multi-messenger modeling of high-energy astrophysical sources
    - Steady sources: AGN jets, coronae
    - Transient sources: GRBs

Lecture plan

- **Lecture 1:** Astrophysical Origins of Neutrinos
  - Introduction
  - Neutrino production mechanisms
  - Astrophysical sources of neutrinos
  - Experimental neutrino highlights

- **Lecture 2:** Neutrinos from AGN
  - Active galactic nuclei (AGN)
  - Theoretical background
  - AGN multi-messenger models
  - Multi-messenger case studies: TXS 0506+056, NGC 1068

Goals

1. Build intuition about the origin of astrophysical neutrinos from TeV to EeV energy scales

2. Focus on physical conditions leading to neutrino production in compact sources, such as active galactic nuclei (AGN), and familiarize with source modeling

3. Understand how neutrinos tie in with cosmic rays and gamma-rays in a broader astrophysical context

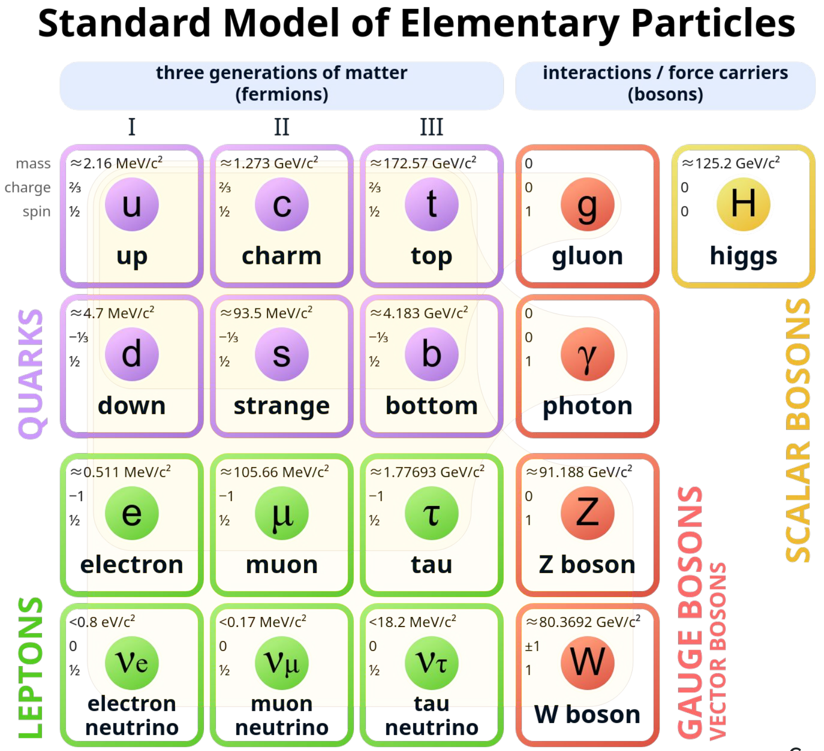
Lecture 1

Astrophysical Origins of Neutrinos

What are neutrinos ?

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

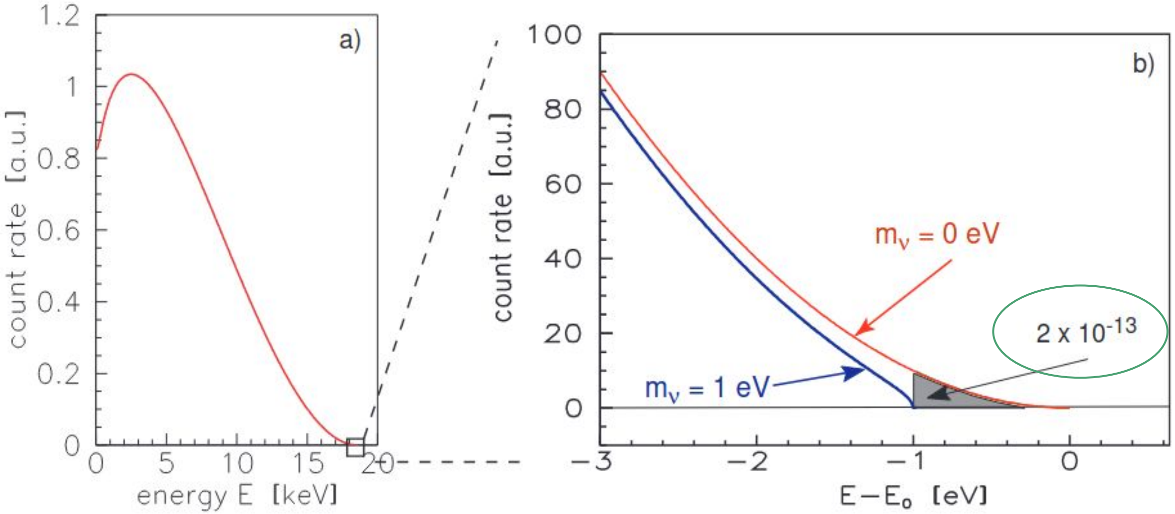
- **Elementary** particles predicted by the Standard Model
- Produced through **weak** interactions
- **Neutral** particles with **very low mass** compared to other leptons.
- Most stringent upper limit from lab experiments is $\mathbf{m_\nu < 0.45\ eV/c^2}$ (KATRIN Collaboration, 2025, Science, 388)
- Come in **three flavors**



Measuring neutrino mass

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_e$$

$$\frac{dN}{dE} = C \times F(Z,E)pE(E_0 - E)[(E_0 - E)^2 - m_\nu^2]^{\frac{1}{2}}\Theta(E_0 - E - m_\nu)$$



Experimental requirements:

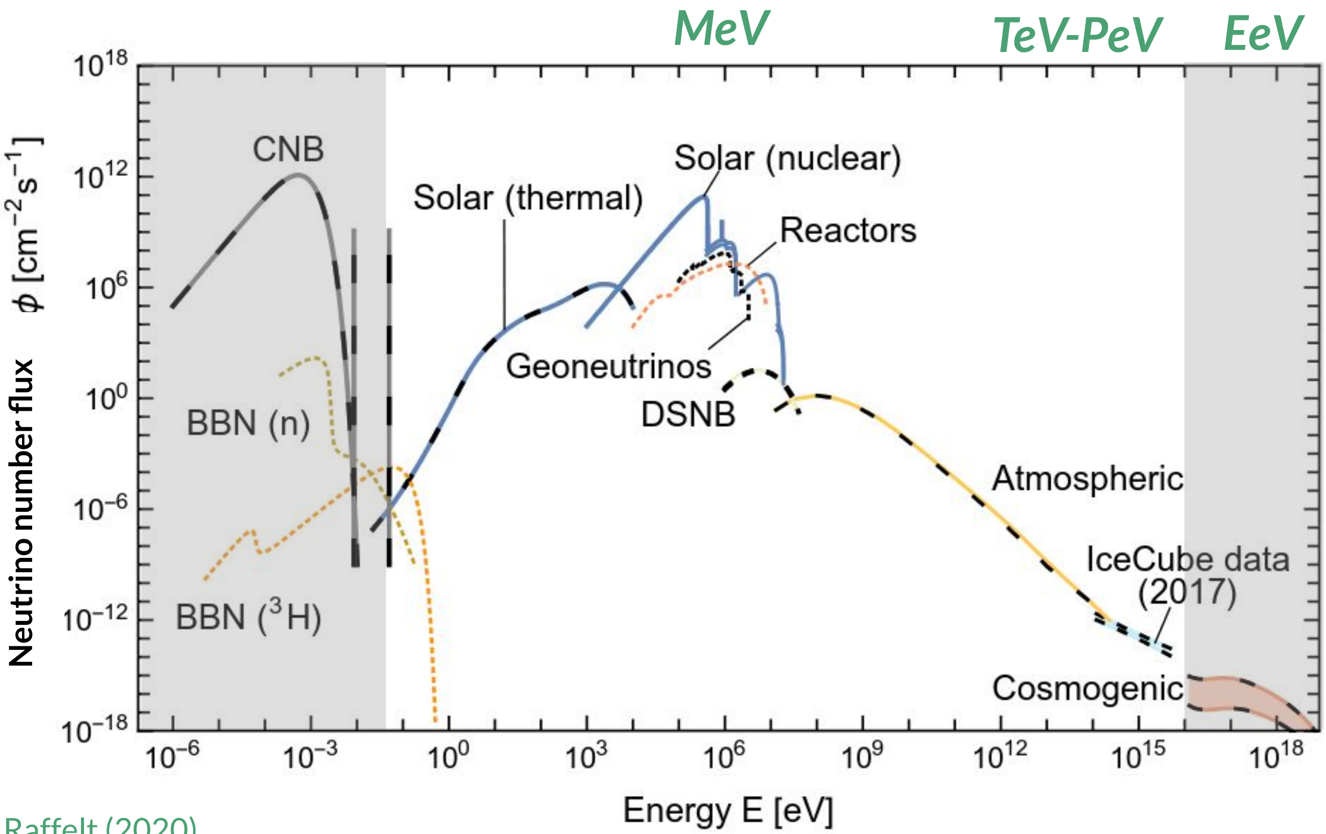
- High power source
- High energy resolution

Why Tritium?

- Low endpoint energy Eo ~ 18.6 keV
- Moderate half time of ~ 12.3 yr

https://www.katrin.kit.edu/publikationen/loi.pdf

The flux spectrum of neutrinos

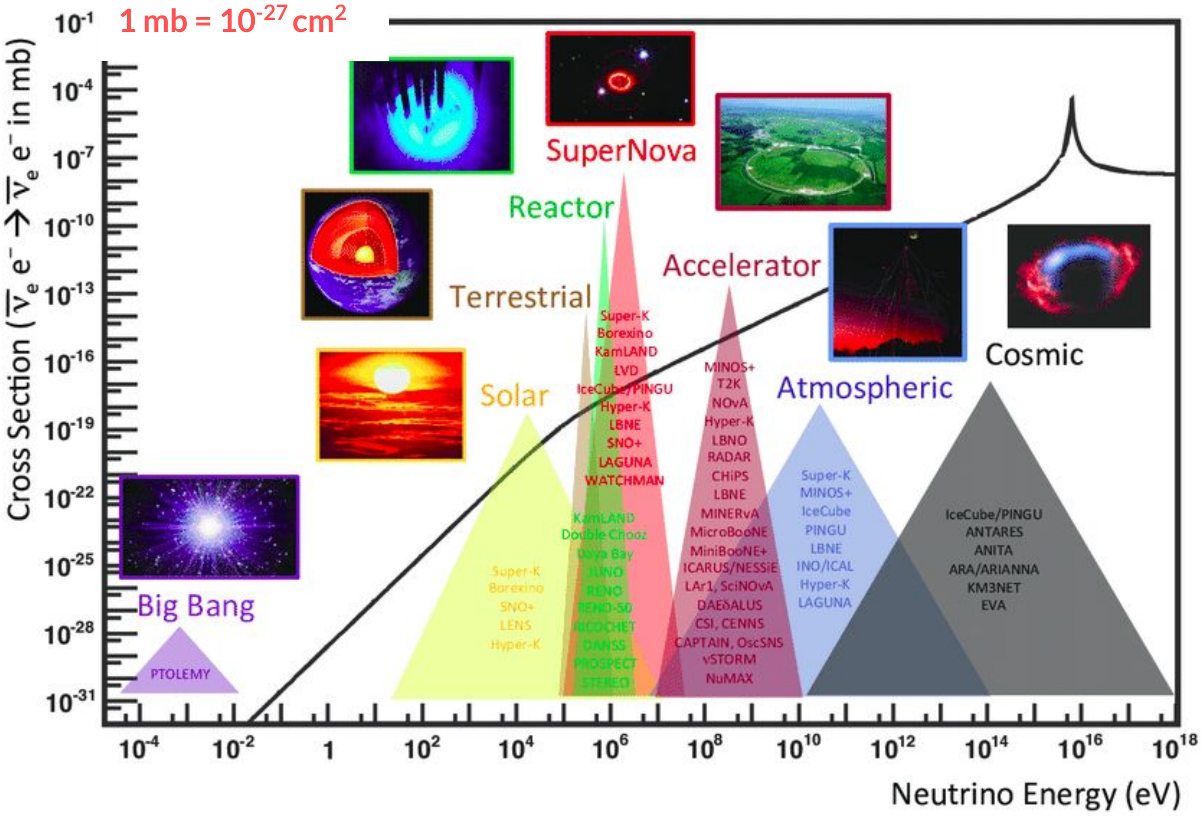


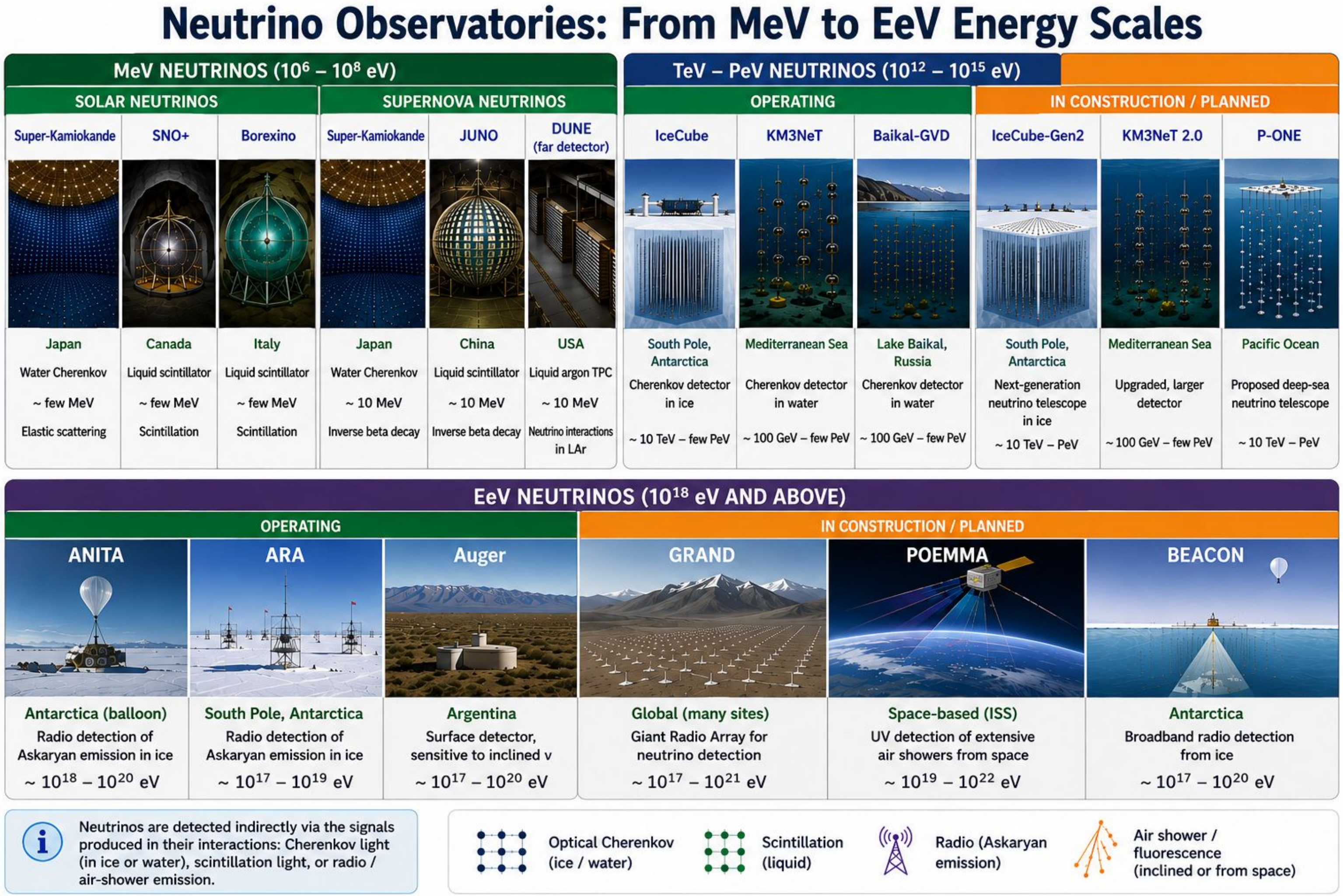
Vitagliano, Tamborra, Raffelt (2020)

Neutrino cross section

- The cross section of ν-e scattering for solar neutrinos (~0.1 MeV) is about **10^{22}** times smaller than electron Thomson cross section (γ-e scattering) !!!
- Extremely small cross sections → detection challenging

Check lectures by
E. Tzamariudaki





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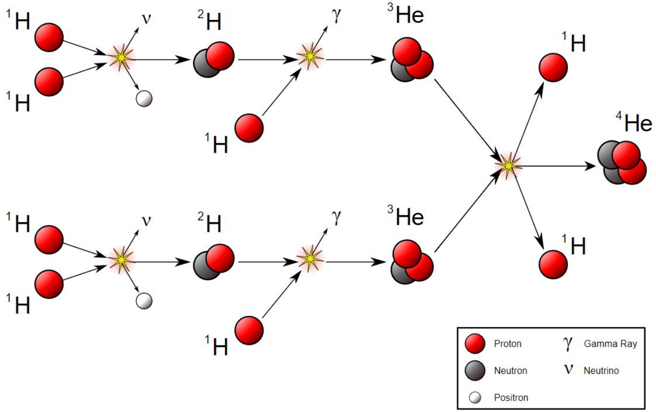
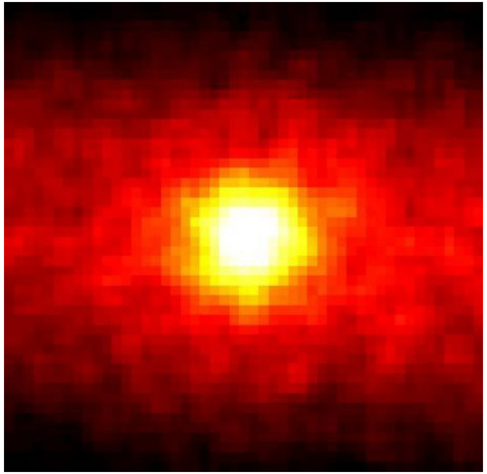
The Sun: the 1st astrophysical ν source

Artistic impression of the Sun

Nuclear Fusion H → He



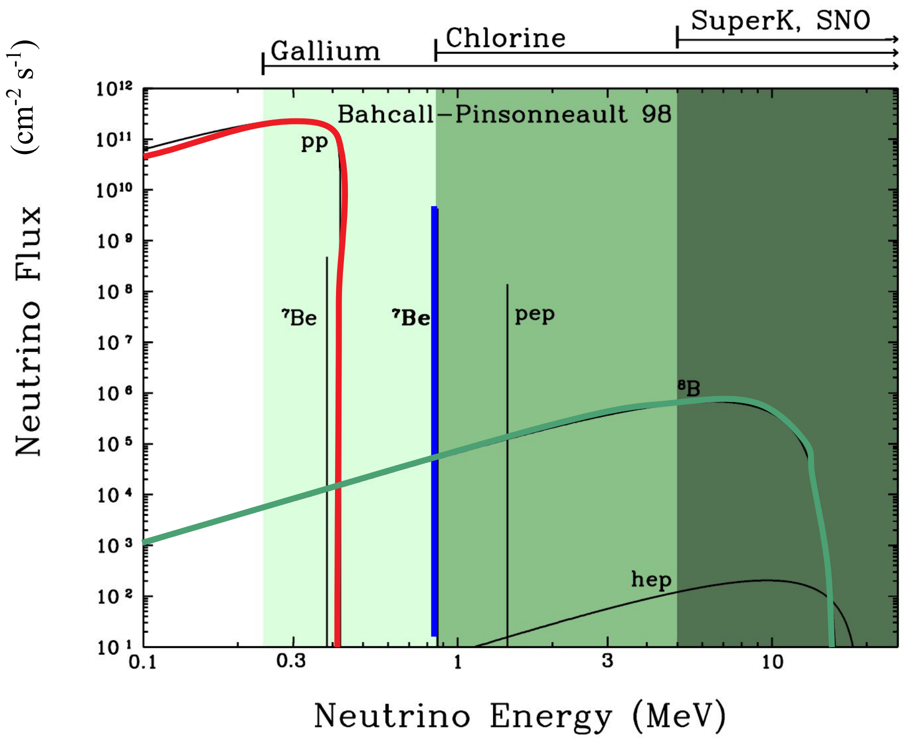


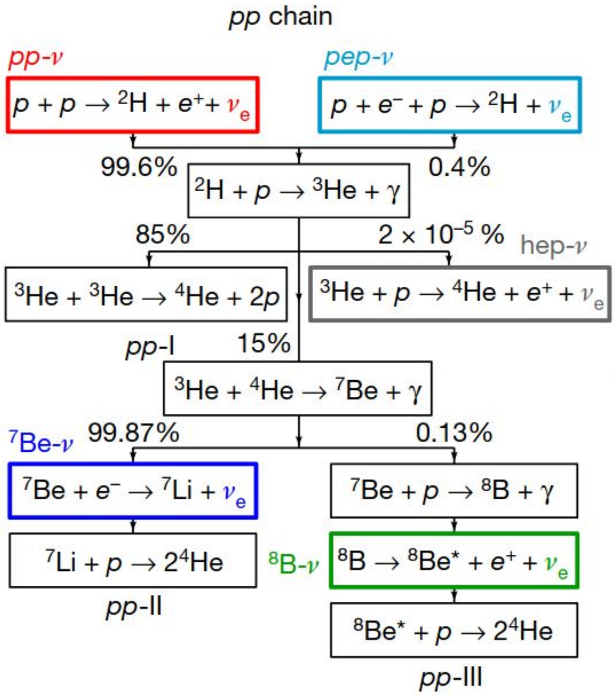
Neutrino image of the Sun using 500 days of data from Super-K

Credit: R. Svoboda and K. Gordan (LSU)

The solar ν spectrum

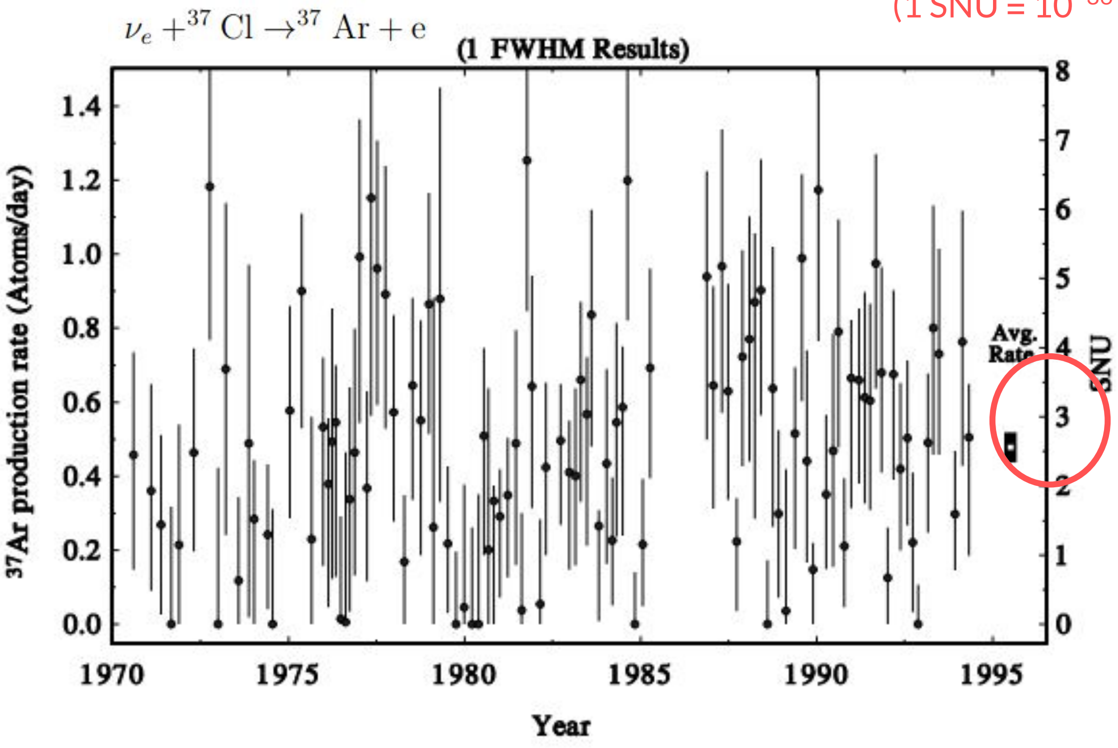
Detectors with different targets probe different ν production channels





The missing solar ν problem

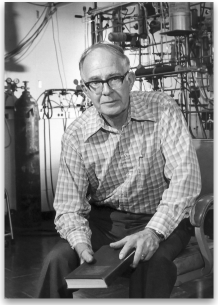
Solar Neutrino Unit or SNU
(1 SNU ≡ 10^{-36} interactions/atom/sec)



Cleveland et al. (1998)

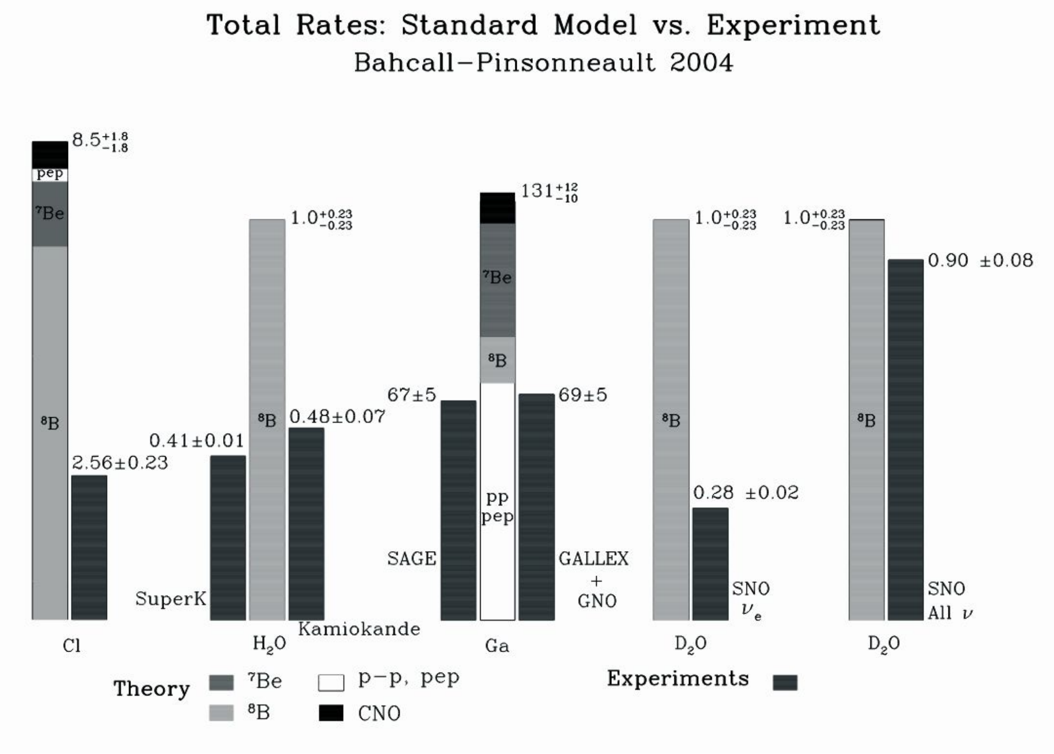
John Bahcall calculated **theoretically** the ν detection rate from Davis experiment based on the standard solar model and found **~7.9 SNU**

For the calculations on p-p → d, see Bahcall & May 1969



The 25-year average SNU from Davis experiment was **~ 3 times lower** than predicted!!

The missing solar ν problem … solved



4 experiments with different target material confirm the missing neutrino flux problem,
BUT …
the SNO experiment measured a flux consistent with the theory!

Neutrinos change flavor during their propagation!

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino Oscillations

Neutrinos change flavor during their propagation!

- Solar neutrinos, which are born in the Sun as electron neutrinos, ν_e, have a **non-zero probability** to transform into neutrinos with a different flavour (either ν_μ or ν_τ) as they propagate from the stellar core to Earth.
- Quantum mechanical effect.
- First proposed by Pontecorvo (1957) .
- 2 conditions must be met for oscillations to occur:
  - Flavor and mass eigenstates must not coincide
  - The mass of at least one neutrino must be non zero
- The **probability of flavor conversion** depends on the (1) neutrino energy and (2) density of medium

$$P_{\alpha\to\beta} = \left|\langle \nu_\beta | \nu_\alpha(L)\rangle\right|^2 = \left|\sum_j U^*_{\alpha j} U_{\beta j}\, e^{-i m_j^2 L/(2E)}\right|^2 .$$

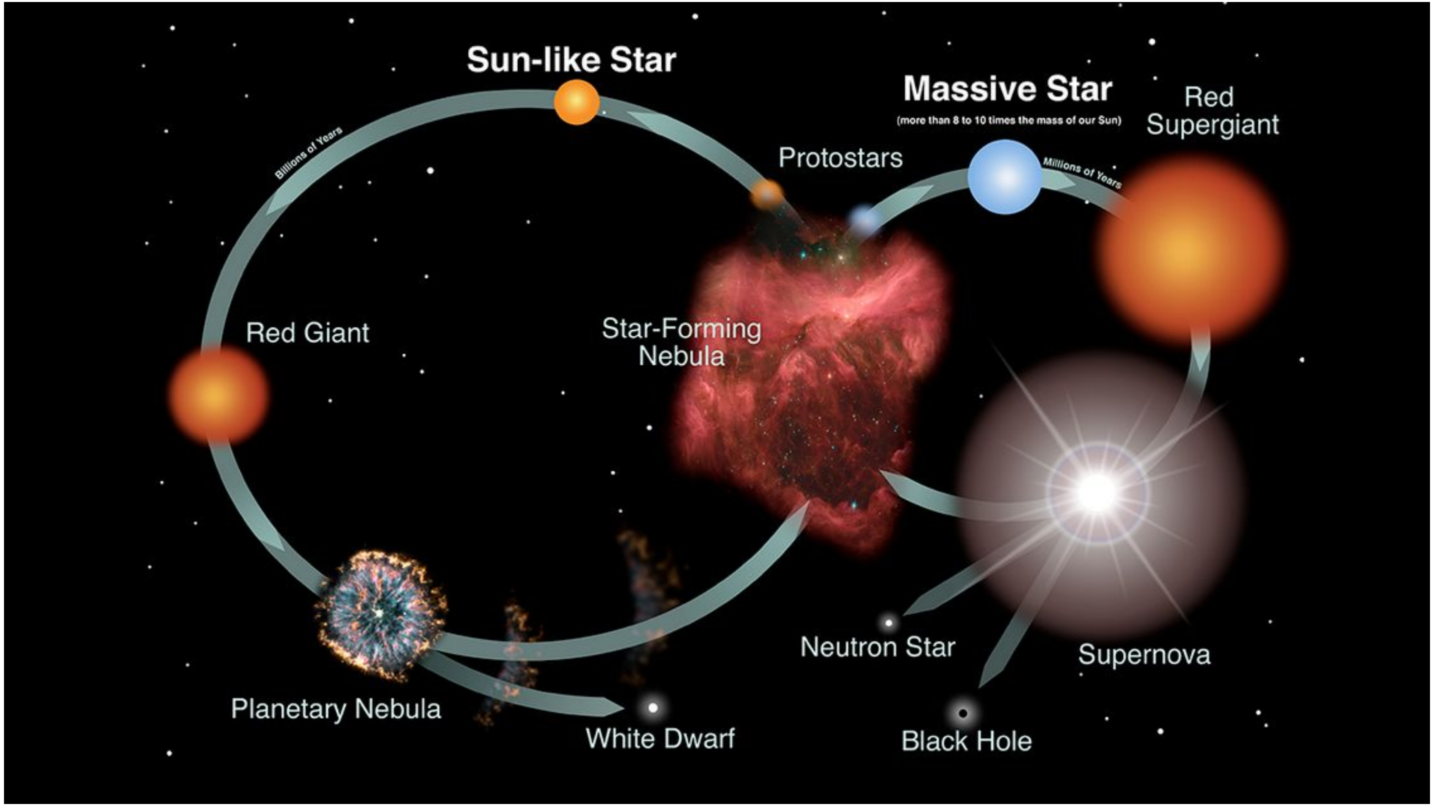
$$P_{ee} = \frac{1+\cos 2\theta_{12}\cos 2\theta_{12}^{M}}{2}\cos^4\theta_{13} + \sin^4\theta_{13}$$

$$\cos 2\theta_{12}^{M} = \frac{\cos 2\theta_{12} - \beta}{\sqrt{(\cos 2\theta_{12} - \beta)^2 + \sin^2 2\theta_{12}}}$$

$$\beta = \frac{2\sqrt{2}\, G_F \cos^2\theta_1\, n_e E_\nu}{\Delta m_{12}}$$

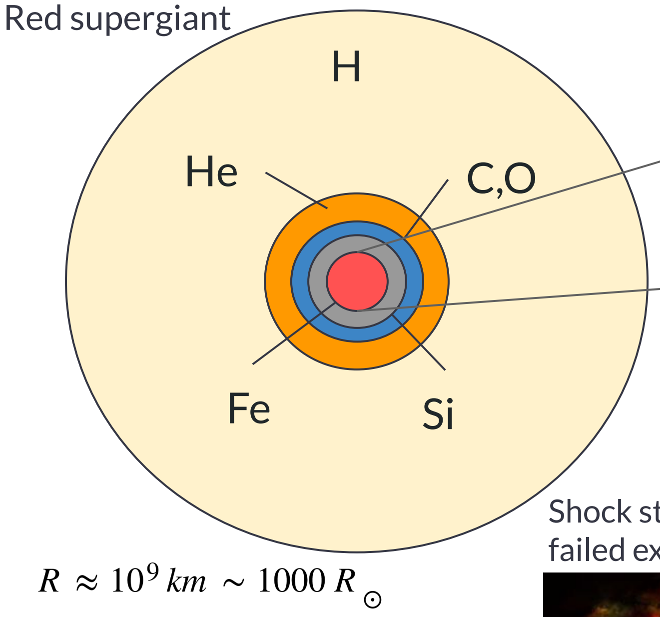
Recent review on theory of oscillations

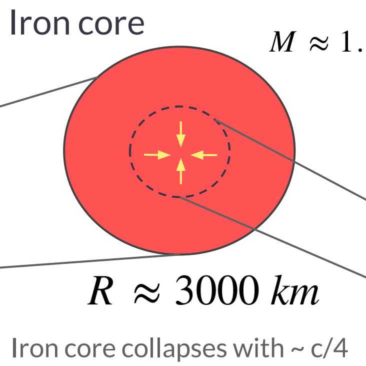
The life cycle of stars

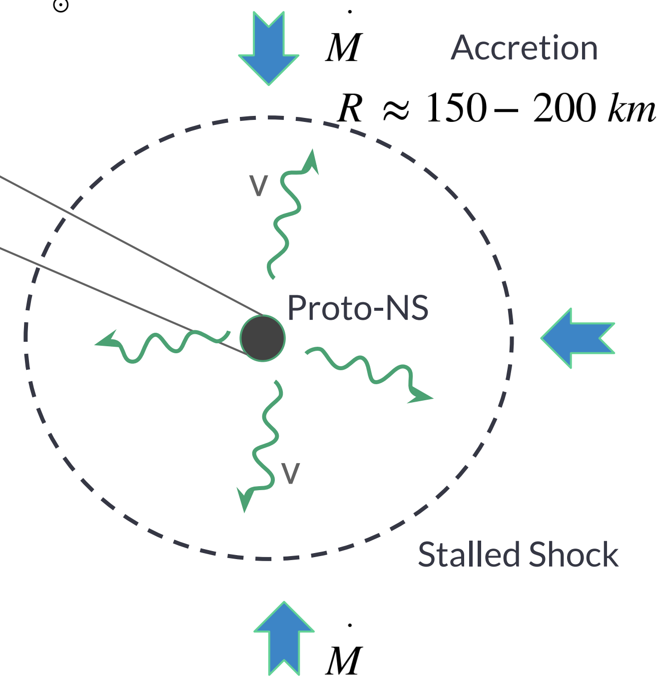


Credit: NASA, Night Sky Network

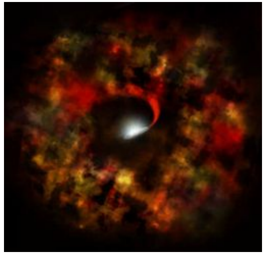
Core-collapse SNe: the explosive death of massive stars







Shock stalled → failed explosion



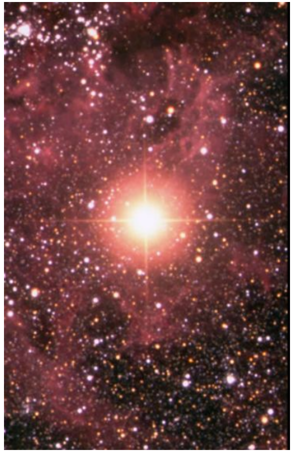
Shock revival → explosion

Theory of Core-Collapse Supernovae, Janka et al. (2007) *Physics Reports*

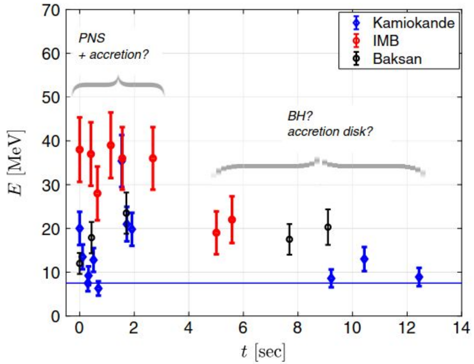
SN 1987A: the 1st extragalactic ν source

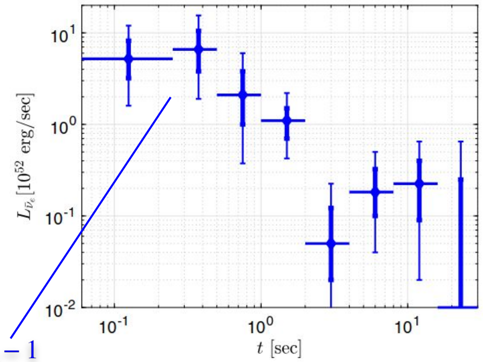
How does the ν luminosity compare with the photon luminosity in the visual band?

@ Large Magellanic Cloud (~51 kpc)



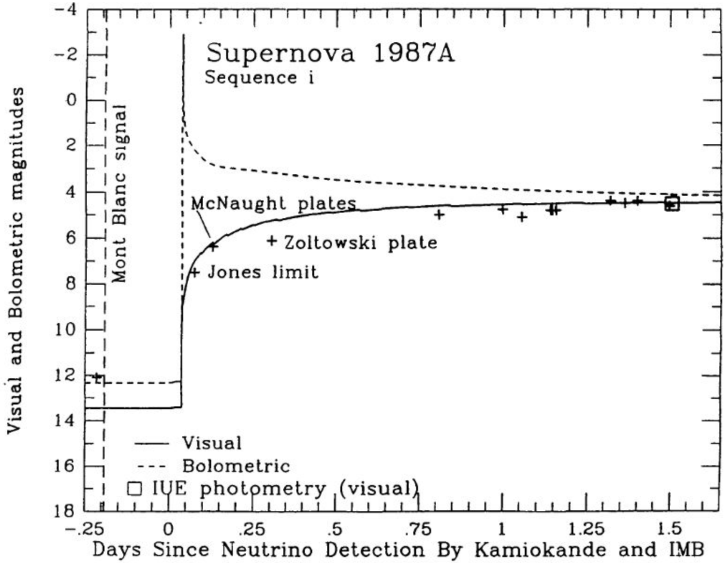
Credit: Anglo-Australian Observatory/David Malin





$L_{\nu,\ max} \approx 10^{53}\ erg\ s^{-1}$

Bar, Blum, D'Amico (2020)



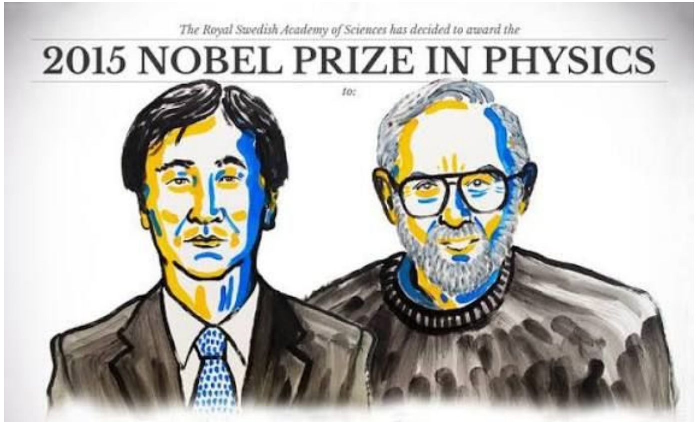
Arnett et al. (1989)

The Nobel Prize in Physics 2002

Raymond Davis Jr.	Masatoshi Koshiba	Riccardo Giacconi
Photo from the Nobel Foundation archive.	Photo from the Nobel Foundation archive.	Photo from the Nobel Foundation archive.
Prize share: 1/4	Prize share: 1/4	Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources."*

The Nobel Prize in Physics 2015



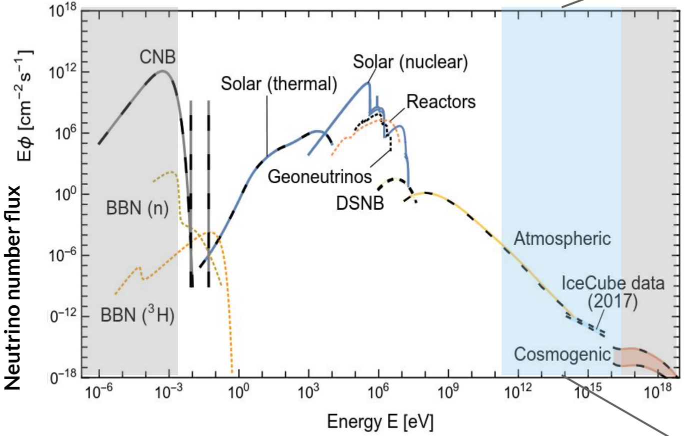
Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

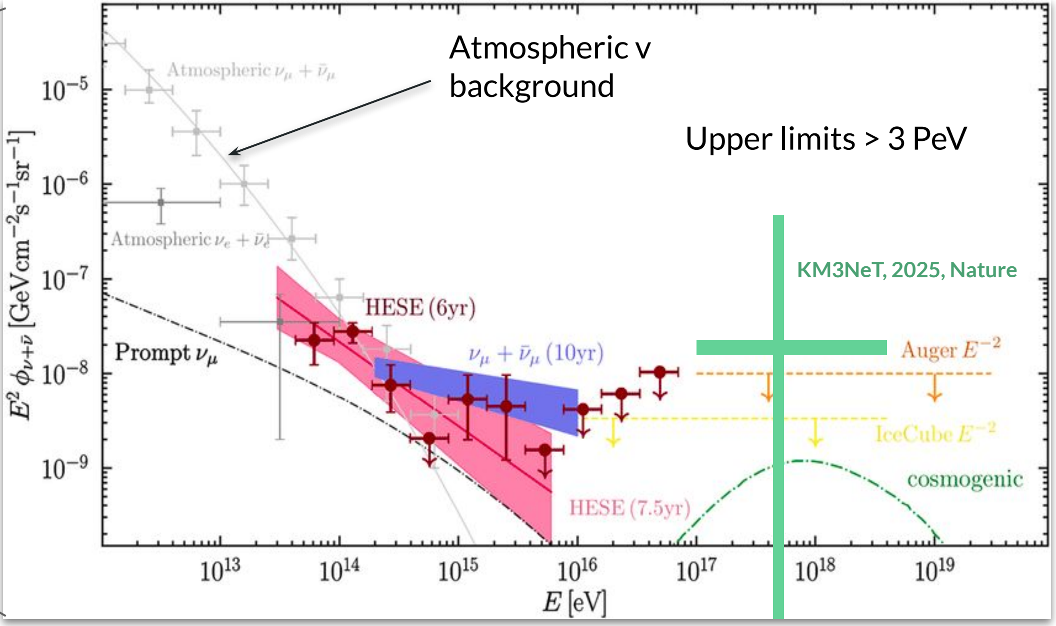
and

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Moving to higher energies …





Kheirandish, A. (2020) A&SS

High-energy ν production mechanisms

p-p collisions (Hadronuclear)

$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow p + n + \pi^+$$
$$p + p \rightarrow p + p + \pi^+ + \pi^-$$

p-γ collisions (Photohadronic)

Photo-pion production

$$p + \gamma \rightarrow p + \pi^0$$
$$p + \gamma \rightarrow n + \pi^+$$
$$p + \gamma \rightarrow p + a\pi^0 + b(\pi^+ + \pi^-)$$

Photo-pair production (Bethe-Heitler pair creation)**

$$p + \gamma \rightarrow p + e^- + e^+$$

Decays of pions/muons

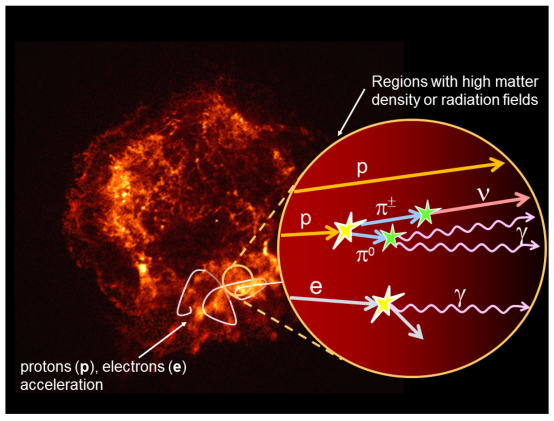
$$\begin{aligned} \pi^0 &\rightarrow \gamma + \gamma \\ \pi^+ &\rightarrow \mu^+ + \bar{\nu}_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ \pi^- &\rightarrow \mu^- + \nu_\mu \quad \text{and} \quad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \end{aligned}$$

**Bethe-Heitler is not a ν production mechanism, but is important for pair enrichment in astrophysical sources

Cosmic rays are the drivers of high-energy ν

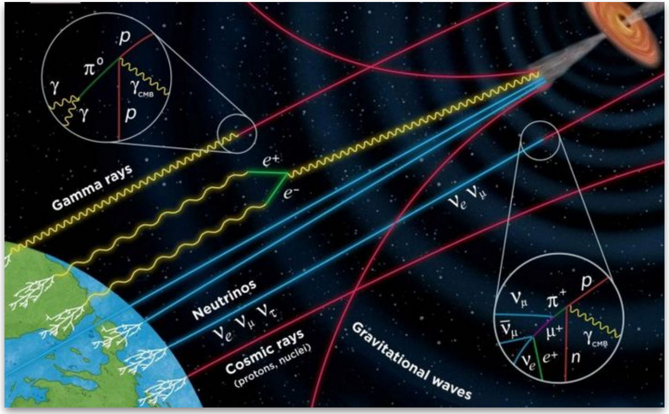
Check lectures by
F. Oikonomou on CRs

Astrophysical neutrinos



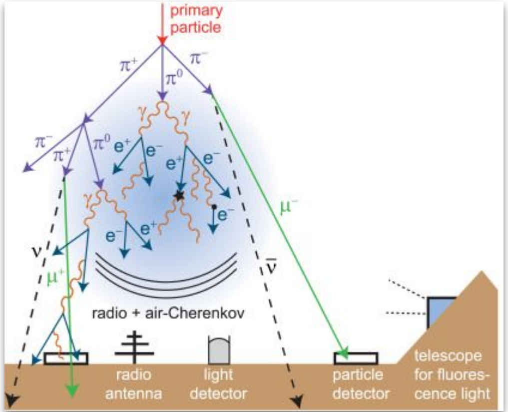
Hadronuclear + Photohadronic

Cosmogenic neutrinos



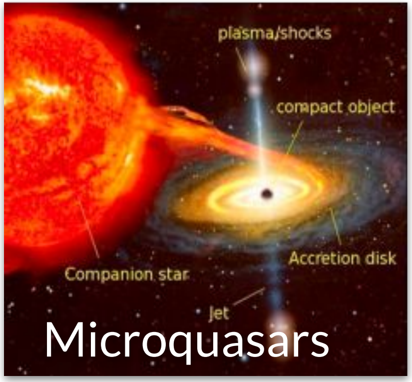
Mostly Photohadronic

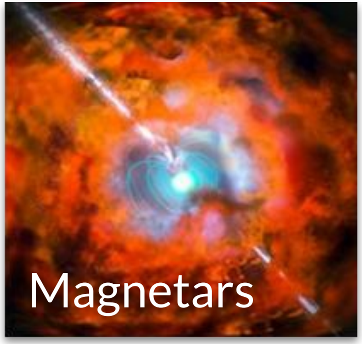
Atmospheric neutrinos

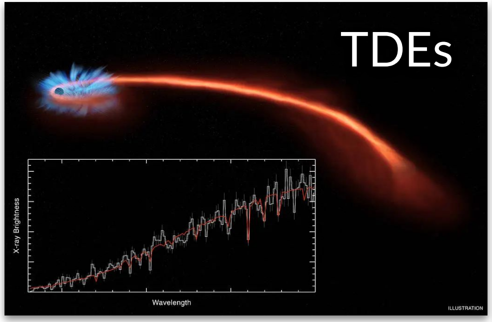


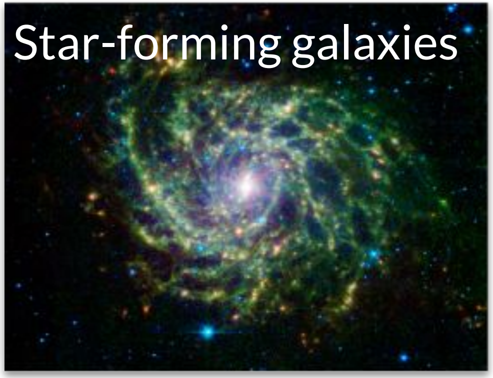
Mostly Hadronuclear

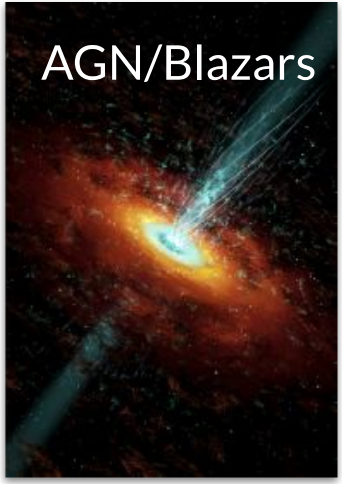
A “zoo” of astrophysical ν sources





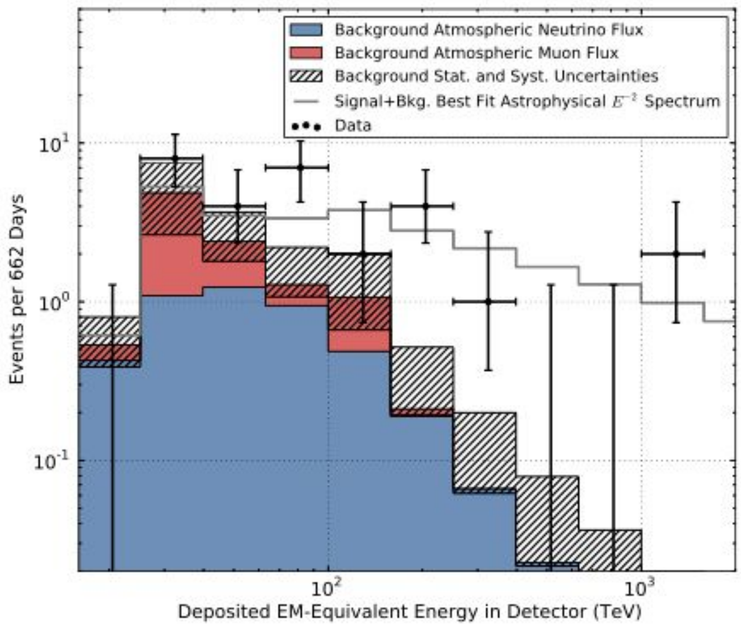


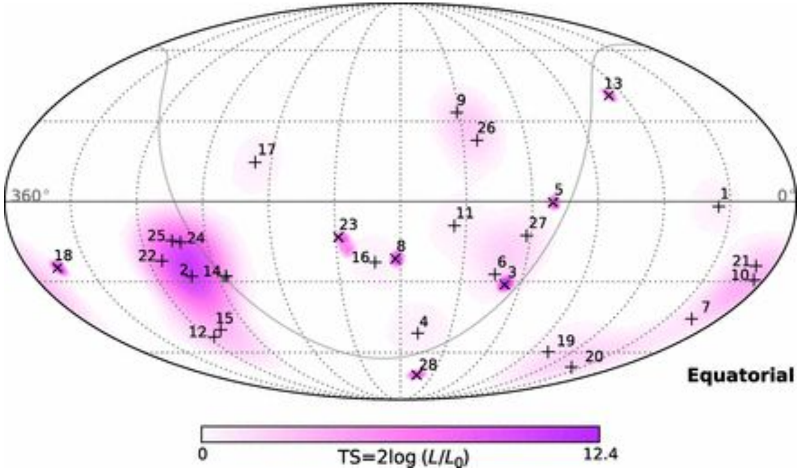


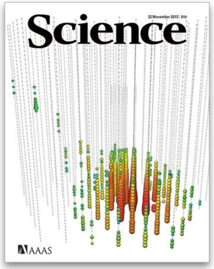


Reviews: Ahlers & Halzen (2015), Murase (2015), Fiorillo (2025)

Experimental Highlights 1:
Discovery of diffuse flux



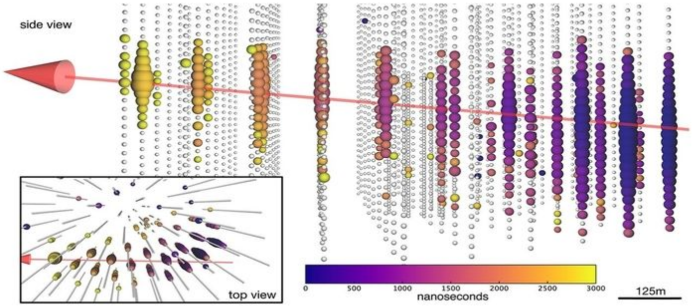


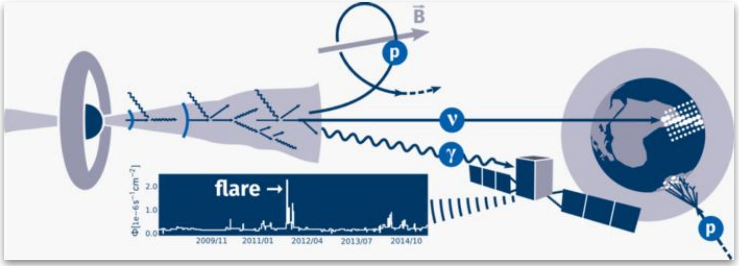


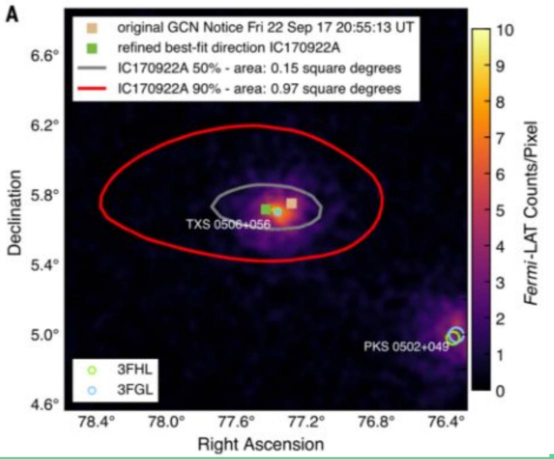
- **28 events** above atmospheric background with energies **> 30 TeV**
- Arrival directions consistent with isotropic distribution

IceCube Collaboration, Science (2013)

Experimental Highlights 2:
1st association with an astrophysical source







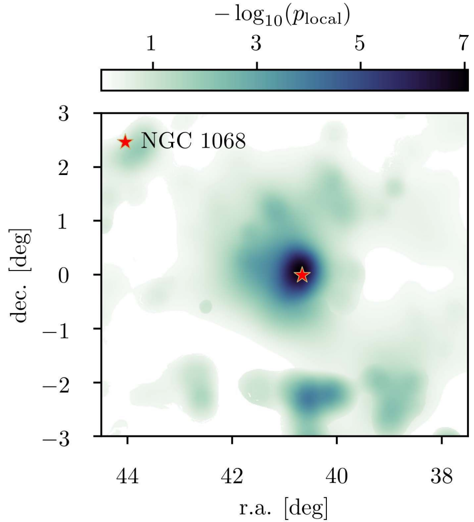
- High-energy neutrino (**~290 TeV**) detected during a **γ-ray flare from active galaxy** TXS 0506+056
- **1st spatial and temporal 3σ association** with an astrophysical source

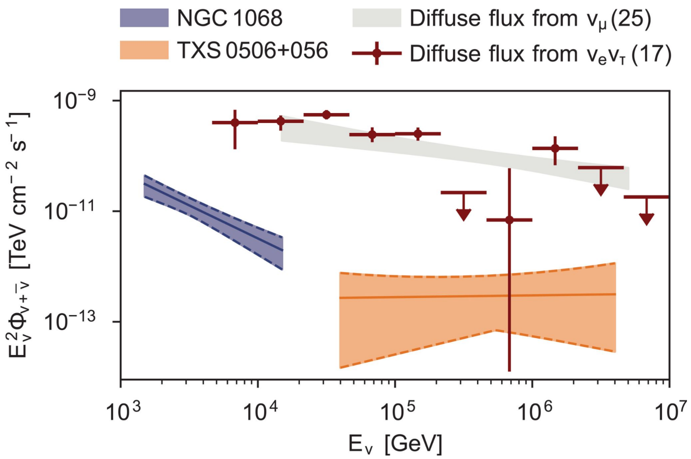
IceCube Collaboration, Science 361 (2018) no. 6398, eaat1378

Experimental Highlights 3:

“Hottest ν spot” in the sky

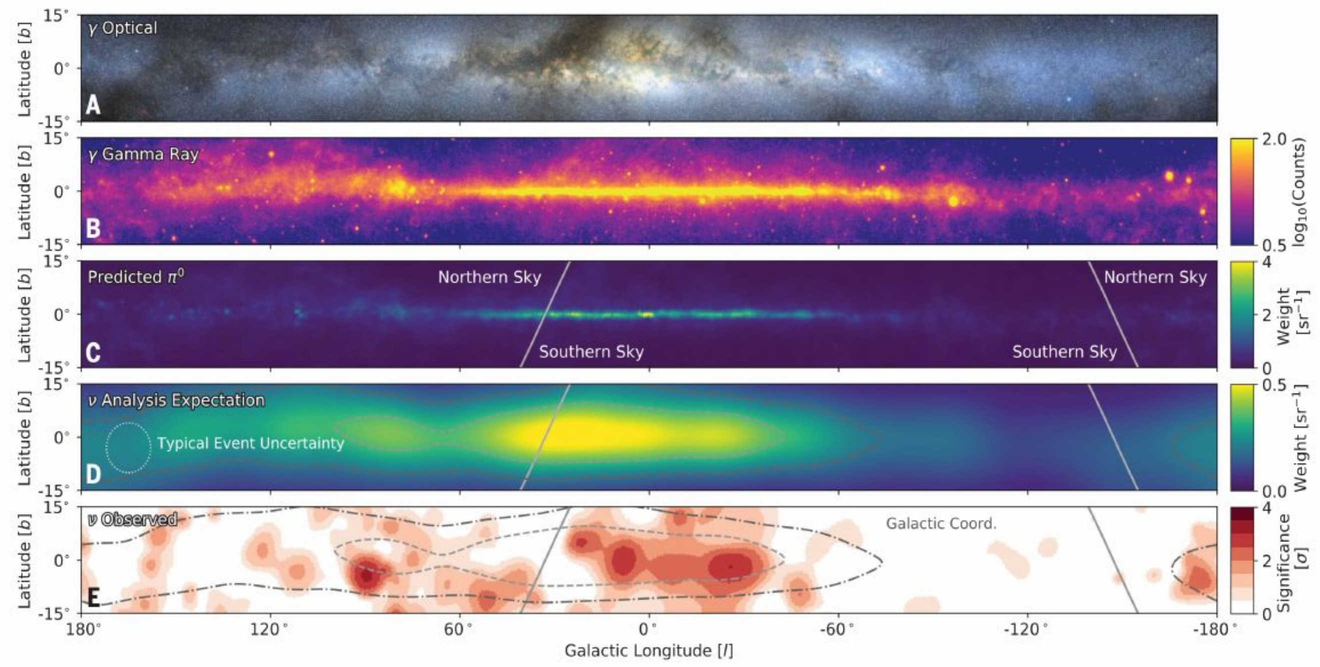
IceCube Collaboration, Science 378 (2022) , Issue 6619





- N=79 (+22,-20) with **E > 3 TeV** detected from the location of **active galaxy NGC 1068**
- Neutrino spectrum: dN/dE ~ E^-γ, γ=3.2 +/- 0.2
- **“Hottest spot”** on neutrino Northern Sky in time-integrated searches

Experimental Highlights 4:
1st observation of ν from the Milky Way

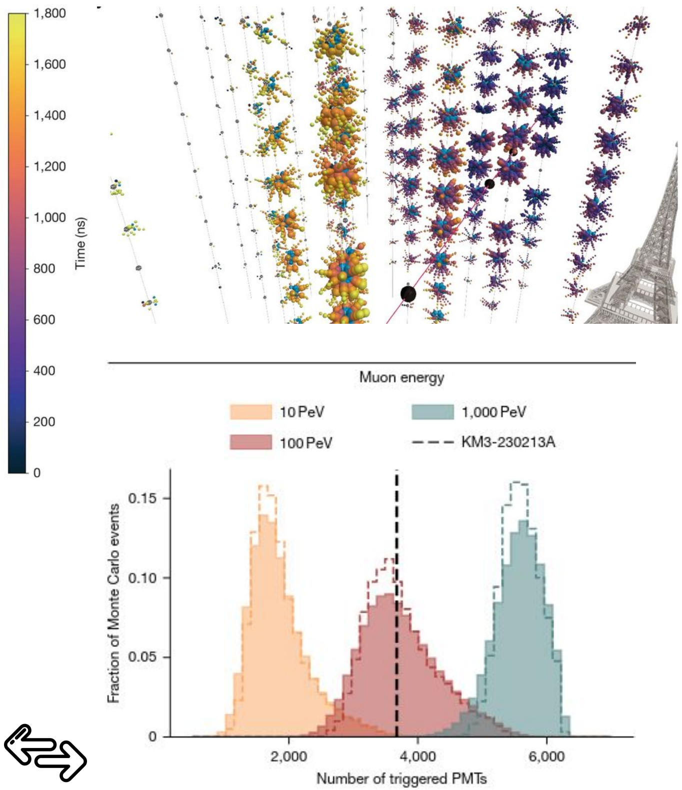


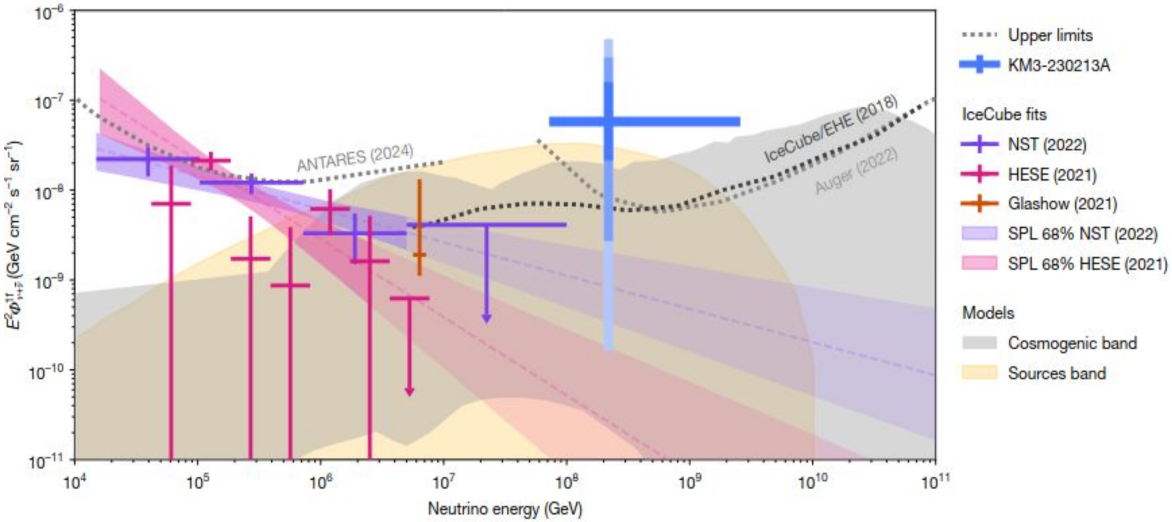
- 1st observation of the **Galactic plane** in neutrinos at **4.5σ**
- Truly diffuse emission or unresolved point sources (PeVatrons?)

IceCube Collaboration, Science 380 (2023) , Issue 1338

Experimental Highlights 5:
1st observation of an UHE ν

KM3NeT Collaboration, Nature 638 (2025)





- 1st observation of an **ultra-high-energy ν (>120 PeV)**
- Astrophysical source **not uniquely** identified

So, why do we study neutrinos?

Particle physics	Astroparticle physics
Why are neutrino masses so small?	What can neutrinos tell us about nuclear reactions in the core of the Sun and of dying massive stars?
What is the absolute neutrino mass scale?	Are the sources of high-energy cosmic rays the same as those of cosmic neutrinos ?
Are neutrinos Dirac or Majorana particles?	What types of sources make up the diffuse flux?
Are there additional ("sterile") neutrinos beyond the Standard Model?	Can neutrinos be used as cosmic messengers that probe extreme environments?

Neutrinos connect the physics of elementary particles with the physics of the Universe.

Summary - 1

- Astrophysical neutrinos observed from **MeV** energy scales (Sun, SN 1987A) to **TeV-PeV** energy scales (Galactic plane, AGN) to **EeV** scales.
- Different production mechanisms in low-energy (MeV) scales and high-energy (>TeV) scales (nuclear fusion/β decays *versus* p-p and p-γ inelastic collisions).
- Many open questions about the origin of the diffuse astrophysical flux and its connection to cosmic-ray sources.

Useful References - 1

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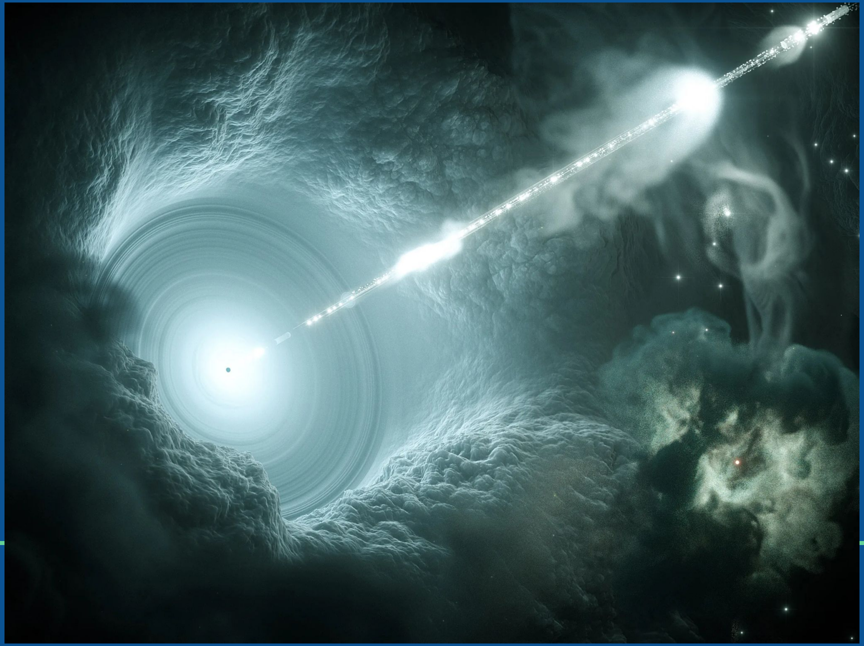
4. The Borexino Collaboration. *Comprehensive measurement of pp-chain solar neutrinos.* *Nature* **562**, 505–510 (2018).
5. Janka et al. (2007) *Theory of Core-Collapse Supernovae*, *Physics Reports*, Volume 442, Issues 1–6, 38–74
6. Gaisser T. K., 2019, arXiv, arXiv:1910.08851.
7. V. Vieregg, A., Ackermann, M., Ahlers et al. (2019). *Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos.* Bulletin of the AAS, 51(3).
8. Santander, M., Buson, S., Fang, K. et al. (2019). *A Unique Messenger to Probe Active Galactic Nuclei: High-Energy Neutrinos.* Bulletin of the AAS, 51(3).
9. Fiorillo D. F. G. (2024). *High-Energy and Ultra-High-Energy Neutrino Astrophysics.* Universe, 10, 149. doi:10.3390/universe10030149
10. Ahlers M., Halzen F., 2015, RPPh, 78, 126901. doi:10.1088/0034-4885/78/12/126901

Check also: Meszaros et al. 2019, Nature Physics Review, Astro2020 Decadal Survey white papers

Lecture 2

Neutrinos from AGN



Credit: DESY

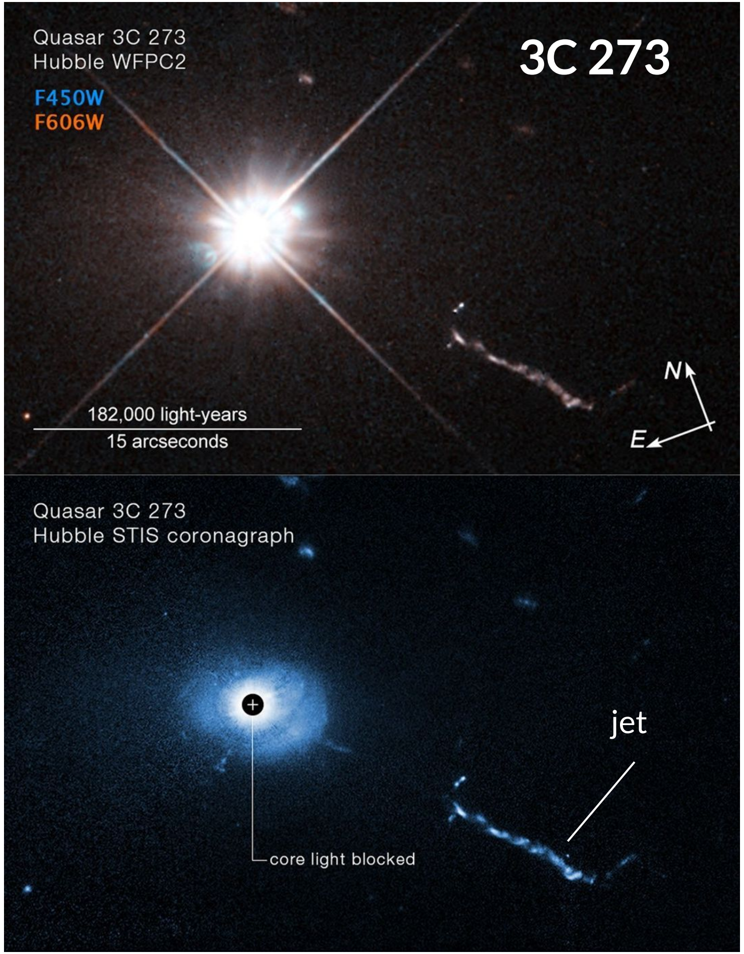
Active galactic nuclei (AGN)

- **Very high luminosity** ($L \gtrsim 10^{43}$ erg/s) often outshining the stellar emission of the host galaxy. The radiation originates from a **very compact** nuclear region.

- **Only about 5–10% of galaxies** in the local Universe host an active galactic nucleus (AGN).

- AGN were initially identified in optical observations as **star-like objects** (see Hubble image), but their spectra exhibited unusual broad emission lines that could not be explained by ordinary stellar atmospheres.

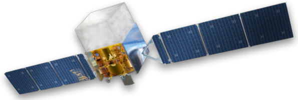
- A fraction of AGN produces **relativistic jets**: highly collimated plasma outflows that can extend far beyond the host galaxy (see Hubble image).



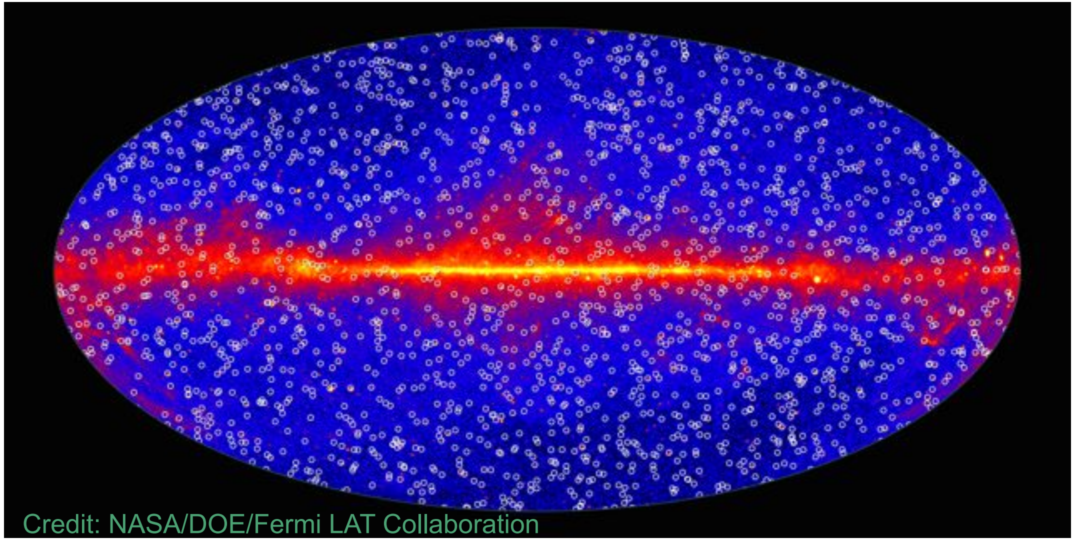
Credit: NASA, ESA, Bin Ren (Université Côte d'Azur/CNRS)

AGN dominate the GeV γ-ray sky

Check lecture by
S. Buson



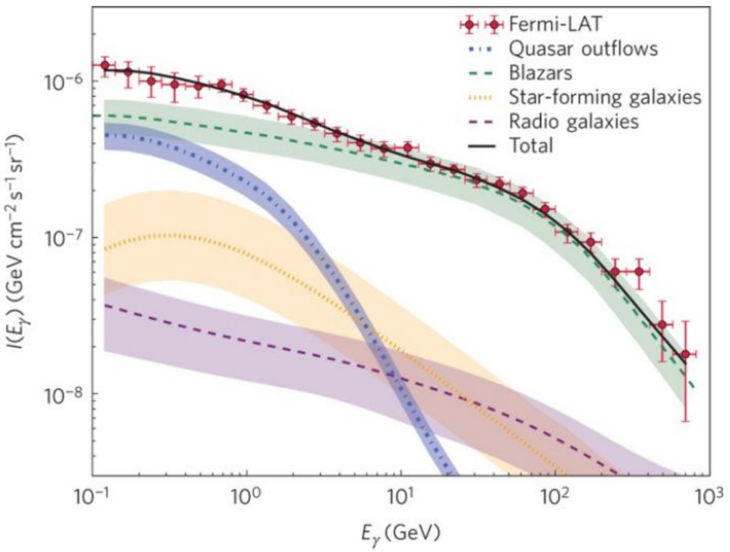
Sky map E_γ > 100 MeV



4th Fermi-LAT point-source catalog (4FGL)

- 8 yr science data
- 5,064 sources
- ~60% AGN (~56% of AGN are blazars)

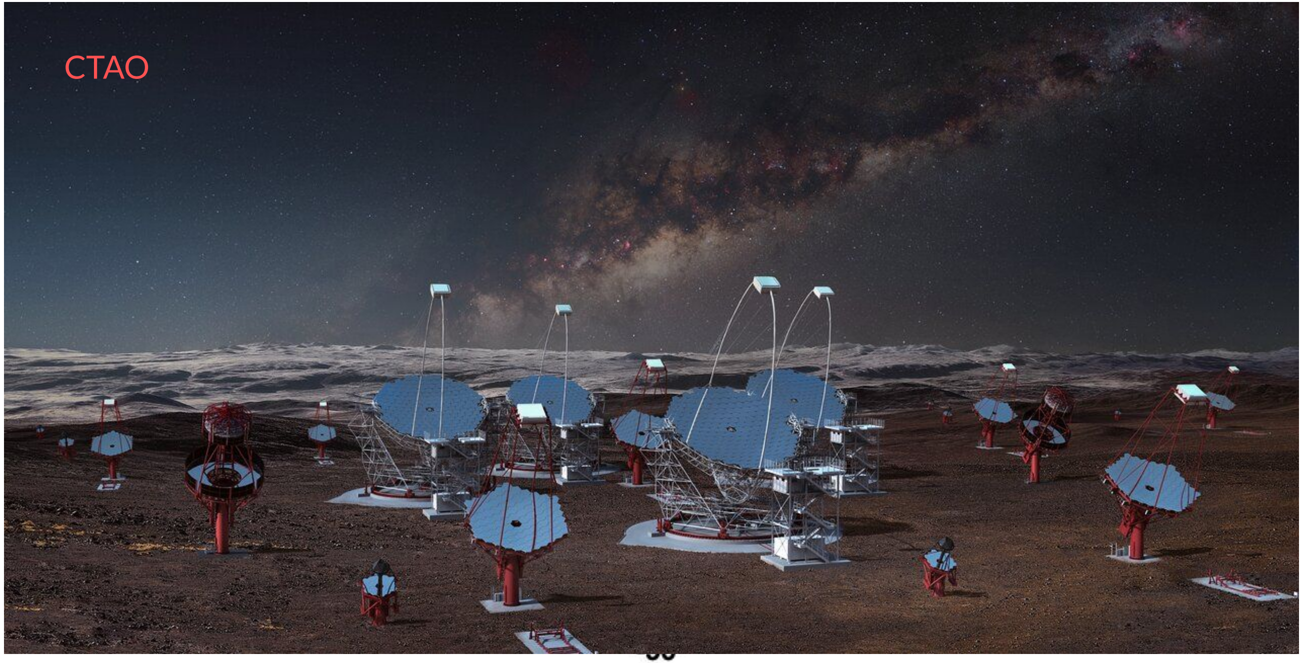
Extragalactic γ-ray background (EGB)



Wang & Loeb (2016) - see also: Ackermann et al. (2015), Ajello et al. (2016)

Check lecture by
M. Cerruti

Blazars dominate the TeV γ - ray sky

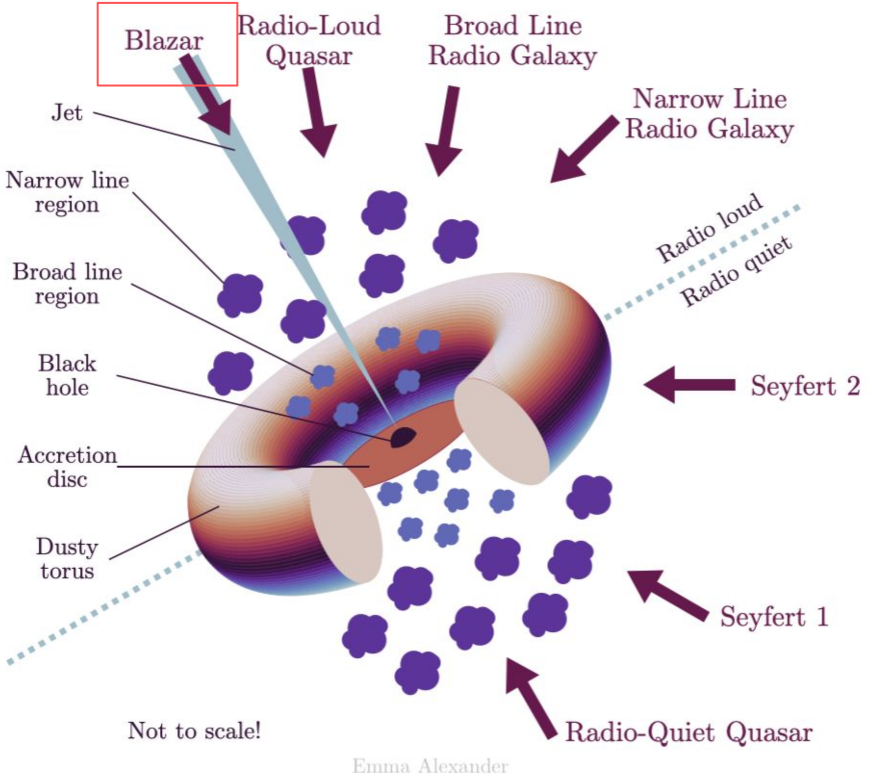


Source Types

- SNR SNR/Molec. Cloud Superbubble Shell Giant Molecular Cloud Composite SNR
- Binary PSR Gamma BIN Nova XRB
- TeV Halo TeV Halo Candidate PWN PWN/TeV Halo
- IBL Blazar FRI GRB HBL AGN (unknown type) LLAGN LBL FSRQ
- UNID DARK Other
- Starburst
- Globular Cluster WR Microquasar BIN Cat. Var. Massive Star Cluster Star Forming Region BL Lac (class unclear)

The AGN paradigm

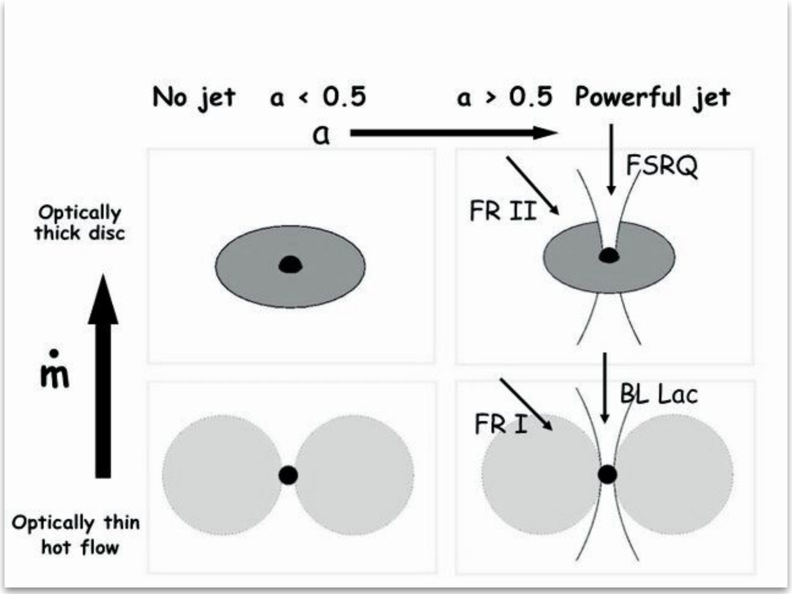
Urry and Padovani (1995)



Check also: [Padovani et al. (2017), A&A Review, 25]

AGN unification based on 3 quantities:

1. Viewing orientation (Urry & Padovani 1995)
2. Mass accretion rate
3. Black hole spin

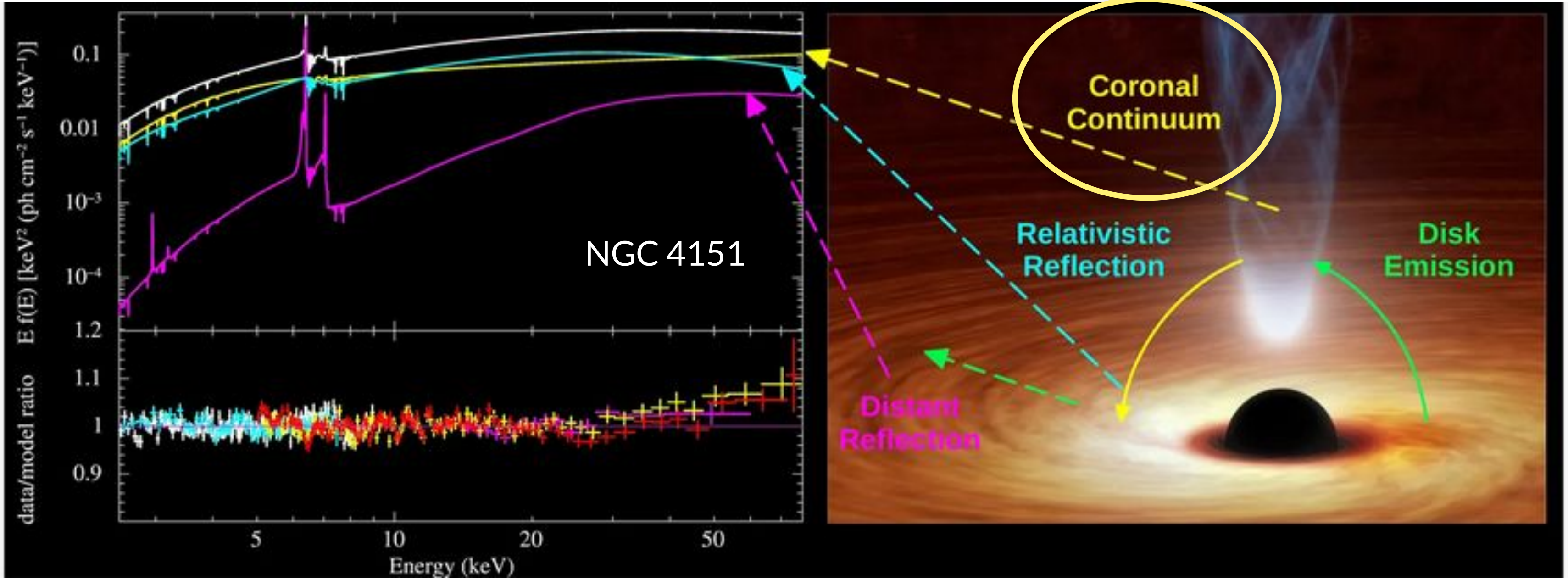


Laura Maraschi et al 2012 J. Phys.

Measuring black hole spin in AGN

Check lecture by
G. Vasilopoulos

Modeling X-ray spectra from non-jetted AGN



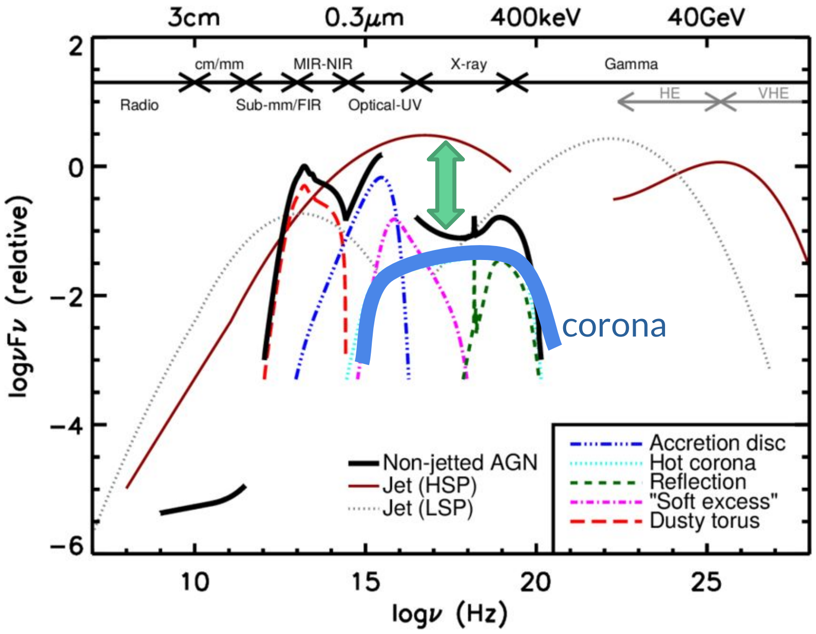
Danekhar (2024), Front. Astron. Space Sci.

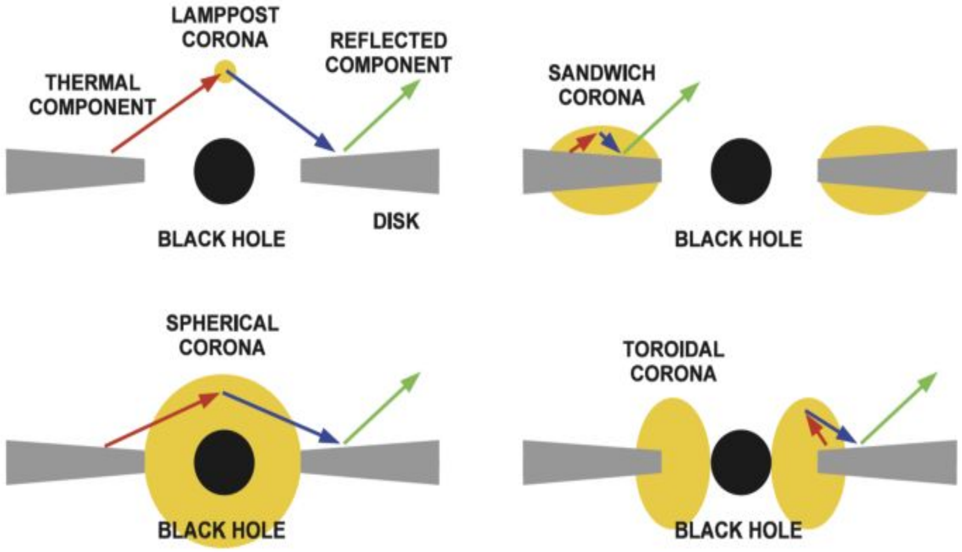
AGN Corona

Scale unit: black hole gravitational radius

$$R_g = \frac{GM}{c^2} \simeq 3 \cdot 10^9 \left(\frac{M}{10^8 M_\odot}\right) cm$$

Typical physical parameters:
Distance ~ 10 R_G
kT_e ~ 1 - 100 keV
Magnetic field ~$10^2 - 10^5$ G
optical depth τ ~ 0.2 – 1



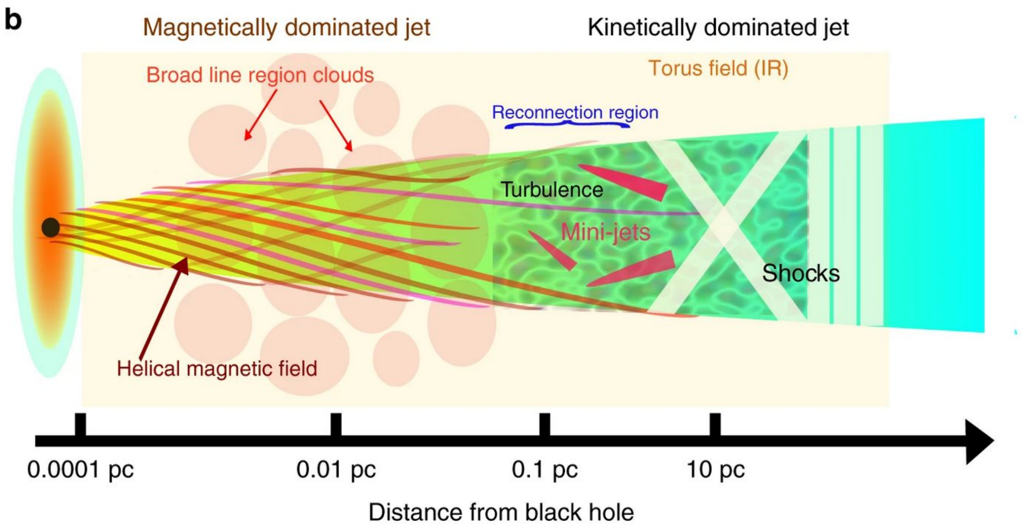


Check student talk by M. Kouzis

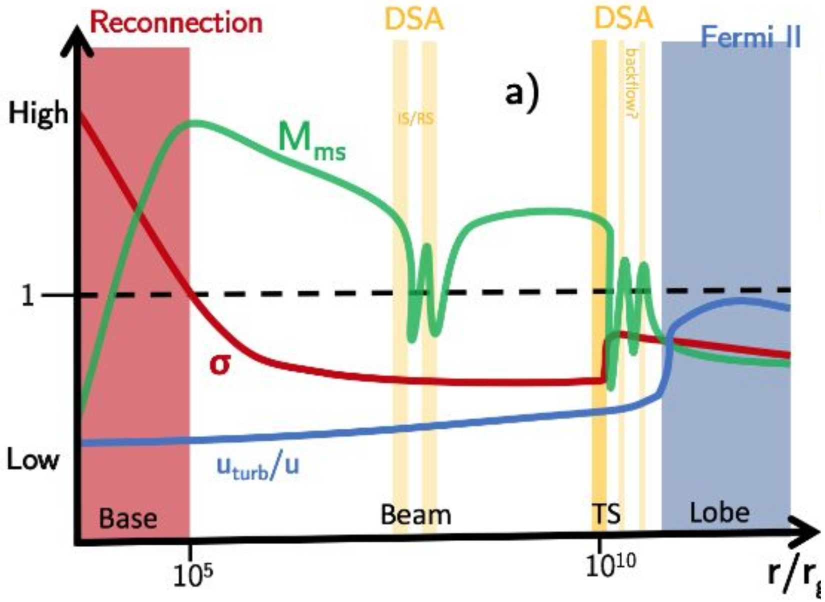
Recent review on X-ray coronae: Laha et al. (2025)

AGN: a multi-scale physical problem

- Many potential sites for energy dissipation, with different jet plasma properties
- Various particle acceleration mechanisms, with impact on photon & neutrino emission



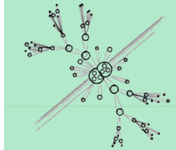
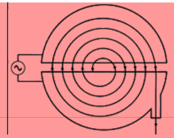
Shukla & Mannheim, 2020, Nat. Comm.



Matthews et al. 2020, NewAR

Basic theoretical elements

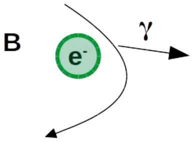
Ingredients of an astrophysical neutrino model

 **Particle Physics**	 **Particle Acceleration**	 **Astrophysics**
Neutrino production channels	Plasma conditions	Matter & photon fields
Interaction thresholds	Acceleration mechanism	Magnetic fields
Cross sections , reaction rates, emissivities	Maximum energy	Source size & opacity
Secondary-particle spectra	Particle distribution	Source evolution

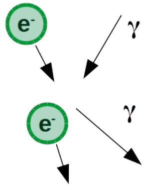
Common non-thermal radiative processes

Leptonic

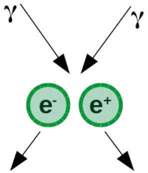
Synchrotron



Inverse Compton scattering

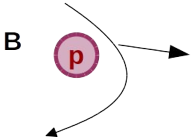


Photon-photon pair production

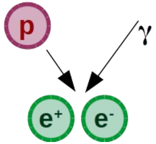


Hadronic

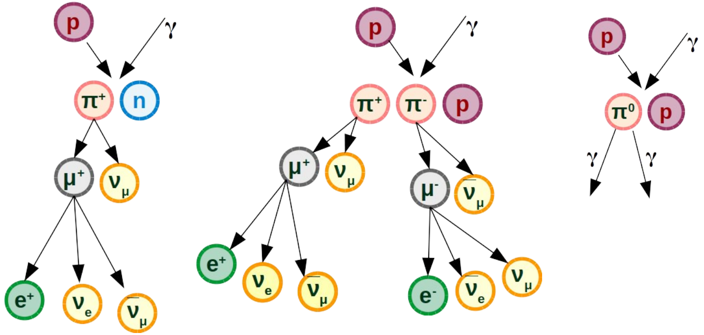
Synchrotron



Proton-photon pair production



pγ pion production

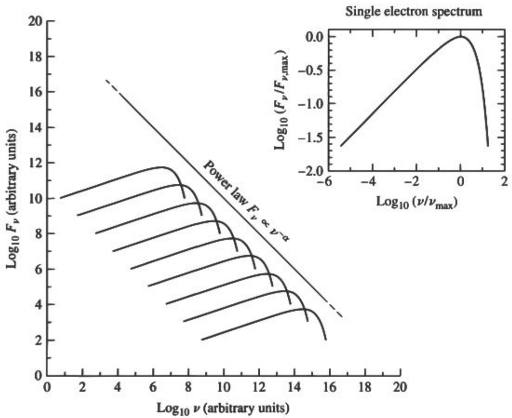


Basics of non-thermal radiative processes

Synchrotron

Emitted Power $$P_{syn} \propto B^2 \gamma^2 \left(\frac{m_e}{m}\right)^2$$

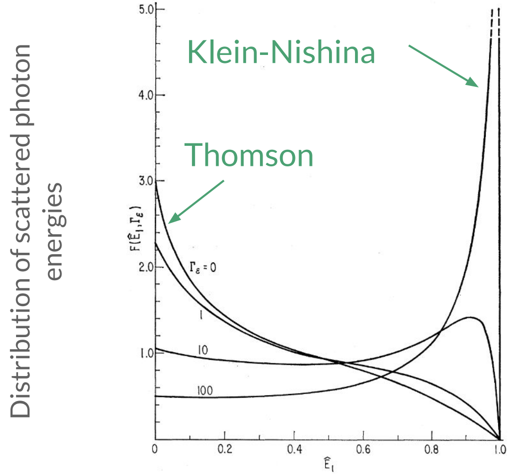
Photon Energy $$E_{syn} = \left(\frac{B}{4.4 \times 10^{13}\, G}\right) \gamma^2 \left(\frac{m_e}{m}\right) m_e c^2$$



Inverse Compton Scattering

Emitted Power $$P_{ICS} \propto U_{ph} \gamma^2 \left(\frac{m_e}{m}\right)^2$$

Photon Energy $$E_{ICS} \propto \begin{cases} \varepsilon_0 \gamma^2, & \gamma \cdot \varepsilon_0 < m c^2 \quad \text{Thomson} \\ \gamma m c^2, & \gamma \cdot \varepsilon_0 > m c^2 \quad \text{Klein-Nishina} \end{cases}$$



Interaction threshold*

$$a + b \rightarrow c + d$$

4-momentum vectors

$P_i = \left(\frac{E_i}{c}, \vec{p}_i \right)$ LAB frame

$P'_i = \left(\frac{E'_i}{c}, \vec{p'}_i \right)$ CM frame

Lorentz invariant $P \cdot P = \|P\|^2$

Known variables: $P_{a+b} = \left(e_a + e_b, \vec{p}_a + \vec{p}_b \right)$

$$\Delta m = m_c + m_d - \left(m_a + m_b \right)$$

$$e_a e_b - \vec{p}_a \cdot \vec{p}_b \geq m_a m_b c^2 + \Delta m\, c^2 \left(m_a + m_b + \frac{\Delta m}{2} \right)$$

*The minimum energy that a pair of colliding particles must have to create new particles at rest in CM frame

Examples

$p + p \rightarrow p + p + \pi^0$

Collision of a cosmic-ray proton (γ > 1) with a proton from the ISM (at rest)

$$\gamma \geq 1 + \frac{m_\pi}{m_p}\left(2 + \frac{m_\pi}{2m_p}\right) \approx 1.298$$

Very easily satisfied!

$p + \gamma \rightarrow p + \pi^0$

Collision of a cosmic-ray proton (γ > 1) with AGN coronal photons $E_X \sim 1\ keV$

$$\gamma E(1 - \beta\cos\theta) \geq m_\pi c^2 \left(1 + \frac{m_\pi}{2m_p}\right) \approx 145\ MeV \quad \theta = \pi,\ \beta \approx 1:\ \gamma \geq \frac{145\ MeV}{2E_X} \approx 7.2 \cdot 10^4\ !$$

Requires ~ 70 TeV protons!

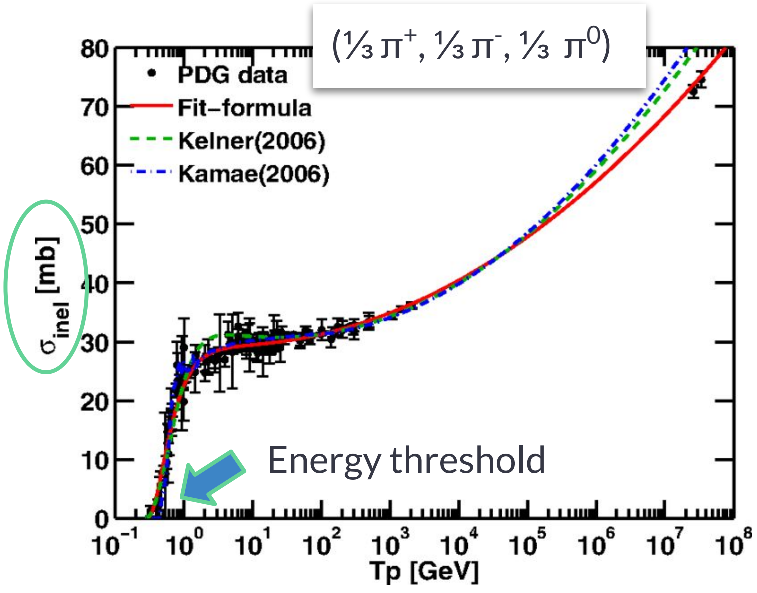
$\gamma + \gamma \rightarrow e^- + e^+$

Collision of a γ-ray photon with AGN coronal photons $E_X \sim 1\ keV$

$$E_\gamma E_X(1 - \cos\theta) \geq 2\left(m_e c^2\right)^2 \xrightarrow{\theta = \frac{\pi}{2}} E_\gamma \geq 0.5\ GeV \left(\frac{1\ keV}{E_X}\right)$$

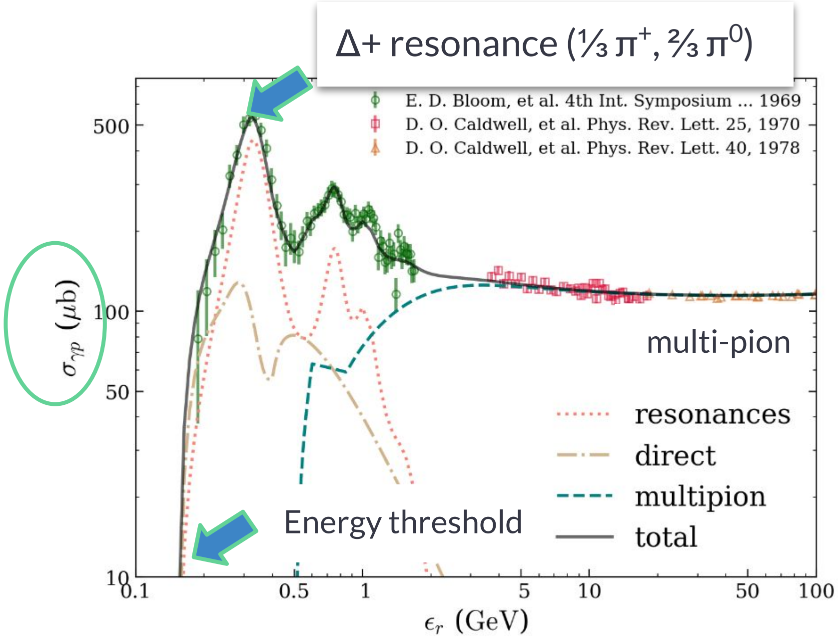
Cross sections

p-p collisions



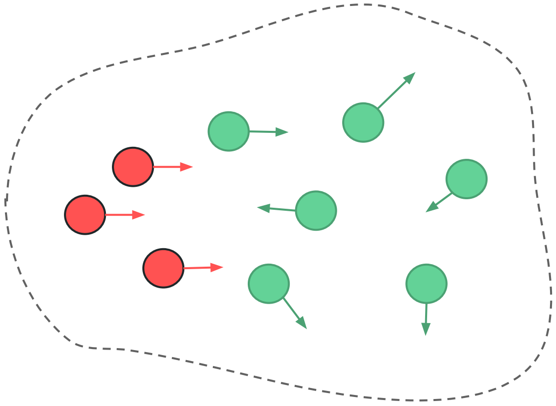
Kafexhiu et al. (2014)

p-γ pion production



Morejon et al. (2019)

Rate of interactions



Volumetric rate = cross section * density^2 * speed

$$\dot{n}_{sc} \equiv \frac{\mathrm{d}N_{sc}}{\mathrm{d}t\ \mathrm{d}V} = \sigma(\gamma_{rel})\, c\, \beta_{rel}\left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right) n_1 n_2$$

Cross section

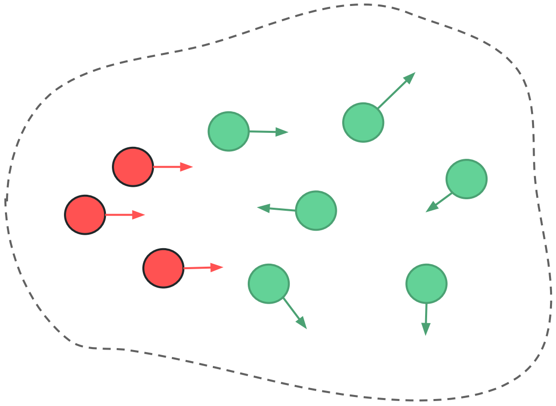
Relative velocity of two particles

Number density of particle "1"

Number density of particle "2"

Note. Applies also to interactions of massive particles with photons (replacing γ with $E/m_e c^2$ and $\beta_{rel} \rightarrow 1$)

Rate of interactions



$$\dot{n}_{sc} \equiv \frac{dN_{sc}}{dt\, dV} = \sigma(\gamma_{rel})\, c\, \beta_{rel} \left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right) n_1 n_2$$

$$\dot{n}_{sc} = \int dn_1 \int dn_2\, \sigma(\gamma_{rel})\, c\, \beta_{rel} \left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right) = c \int d\Omega_1 \int dp_1\, n_1(p_1, \Omega_1) \int d\Omega_2 \int dp_2\, n_2(p_2, \Omega_2)\, \sigma(\gamma_{rel})\, \beta_{rel} \left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right)$$

Differential number density (dN / dV dp dΩ)

Energy loss rate of particle "1" due to interactions with particle "2" :

"Effective" cross section

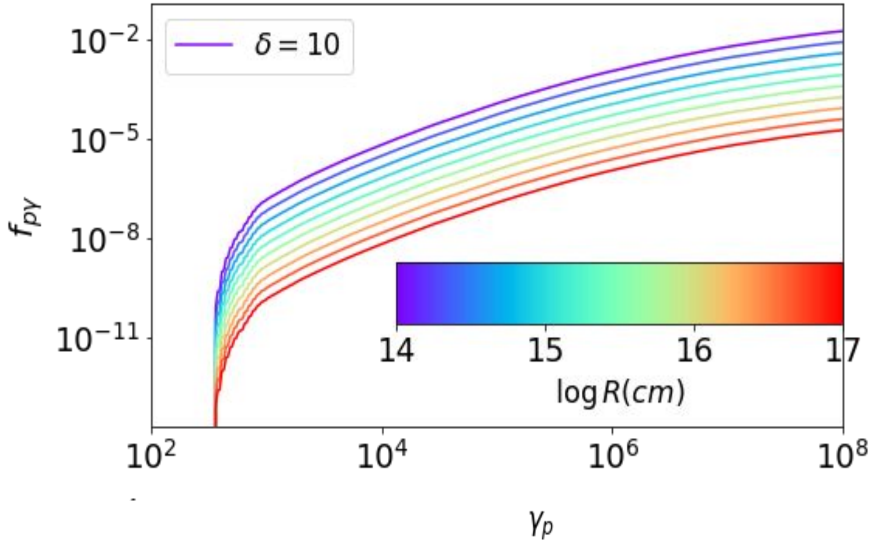
$$-\frac{dE_1}{dt} = \frac{1}{n_1}\, c \int d\Omega_1 \int dp_1\, n_1(p_1, \Omega_1) \int d\Omega_2 \int dp_2\, n_2(p_2, \Omega_2)\, \kappa(\gamma_{rel})\, \sigma(\gamma_{rel})\, \beta_{rel} \left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right)$$

Secondary production efficiency

$$f_i(\gamma_p) = \frac{1}{1 + \frac{t_i(\gamma_p)}{t_{p,esc}(\gamma_p)}}, \quad i = pp,\ p\gamma$$

Energy loss timescale $$t_i(\gamma_p) = \frac{(\gamma_p - 1)\, m_p c^2}{-\left.\frac{dE_p}{dt}\right|_i}$$

Example for pγ interactions in a blazar jet



- Compares the timescales for particle escape - interactions

- **Calorimetric limit:** $f \rightarrow 1$

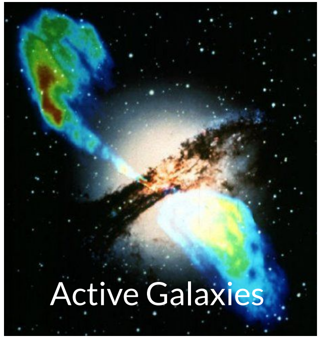
Opacity ~ Efficiency

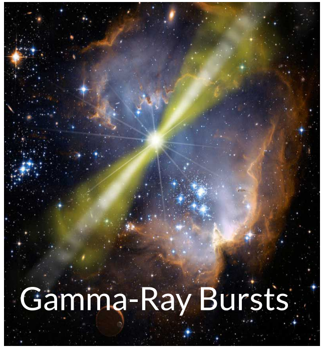
Opacity = cross section * target density * length

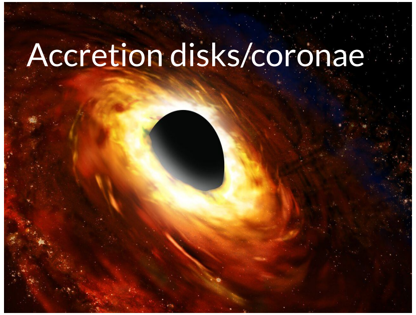
$$\tau = \int dl \int d\Omega \int d\varepsilon \, n_t(\varepsilon, \Omega) \; \sigma(\gamma_{rel}) \; c \, \beta_{rel} \left(1 - \vec{\beta}_p \cdot \vec{\beta}_t\right) \; \sim L \, \sigma \, n_t$$

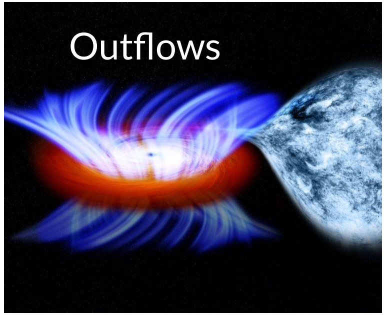
← More photon content

More gas content →









Comparing the opacity for pγ and γγ processes

$$f_{p\gamma} \approx \eta_{p\gamma} \cdot L \cdot \hat{\sigma}_{p\gamma} \cdot \left(\varepsilon'_t \cdot n_{\varepsilon'_t}\right)\Big|_{\varepsilon'_t = \frac{m_p c^2 \bar{\varepsilon}_\Delta}{2E'_p}}$$

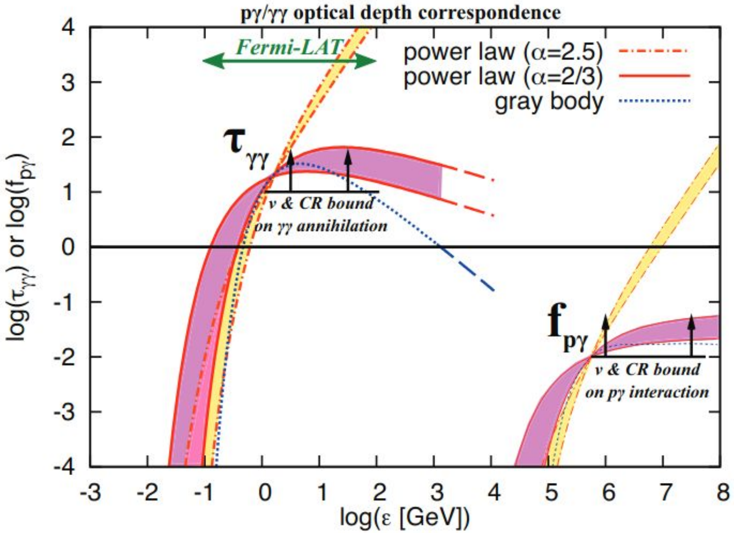
$$\varepsilon_t \approx \delta\, \varepsilon'_t \approx 70\, keV \left(\frac{\delta}{10}\right)^2 \left(\frac{E_\nu}{10\, TeV}\right)^{-1}$$

$$\tau_{\gamma\gamma} \approx \eta_{\gamma\gamma} \cdot L \cdot \hat{\sigma}_{\gamma\gamma} \cdot \left(\varepsilon'_t \cdot n_{\varepsilon'_t}\right)\Big|_{\varepsilon'_t = \frac{\left(m_e c^2\right)^2}{2E'_\gamma}}$$

$$E_\gamma = \delta\, E'_\gamma \approx \delta^2 \frac{\left(m_e c^2\right)^2}{\varepsilon_t} \approx 0.4\, GeV \left(\frac{E_\nu}{10\, TeV}\right)$$

Independent of beaming effects

$$\frac{f_{p\gamma}}{\tau_{\gamma\gamma}} \approx \frac{\eta_{p\gamma}}{\eta_{\gamma\gamma}} \frac{\hat{\sigma}_{p\gamma}}{\sigma_{\gamma\gamma}} \approx \frac{1}{300} \frac{\eta_{p\gamma}}{\eta_{\gamma\gamma}}$$



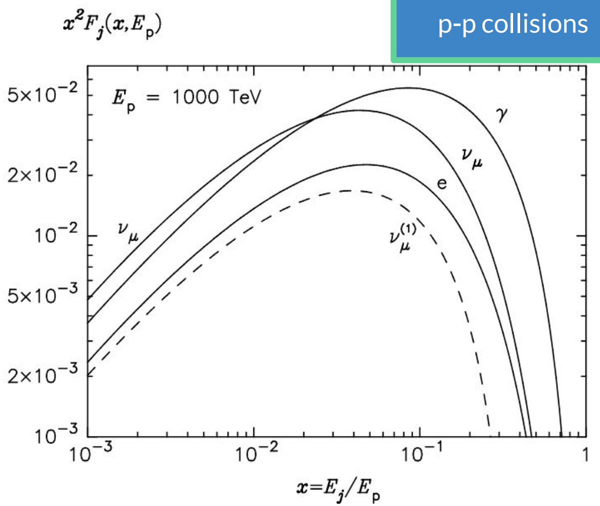
Murase, Guetta, Ahlers (2016)

Secondary particle spectrum (exact)

Production rate spectrum of secondary particles per unit volume:

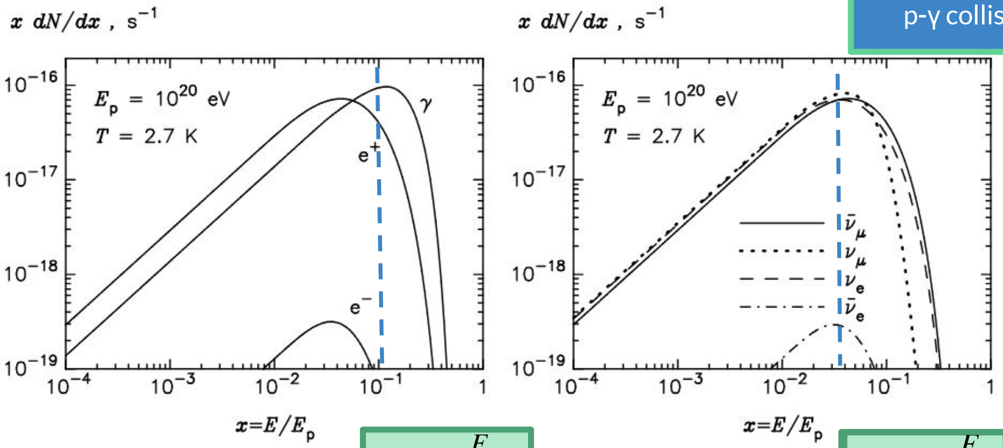
$$\dot{n}_{sc}(p_s) = c\int d\Omega_1 \int dp_1\, n_1(p_1, \Omega_1) \int d\Omega_2 \int dp_2\, n_2(p_2, \Omega_2)\, \beta_{rel}\left(1-\vec{\beta}_1\cdot\vec{\beta}_2\right) \int d\Omega_s \frac{d\sigma(\gamma_{rel})}{dp_s\, d\Omega_s}$$

p-p collisions



Kelner et al. (2006)

p-γ collisions

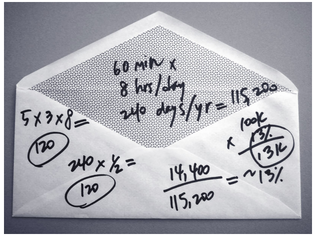


Kelner et al. (2008)

$$\langle E_\gamma\rangle \approx \frac{E_p}{10}$$

$$\langle E_\nu\rangle \approx \frac{E_p}{20}$$

Secondary particle spectrum (approximate)

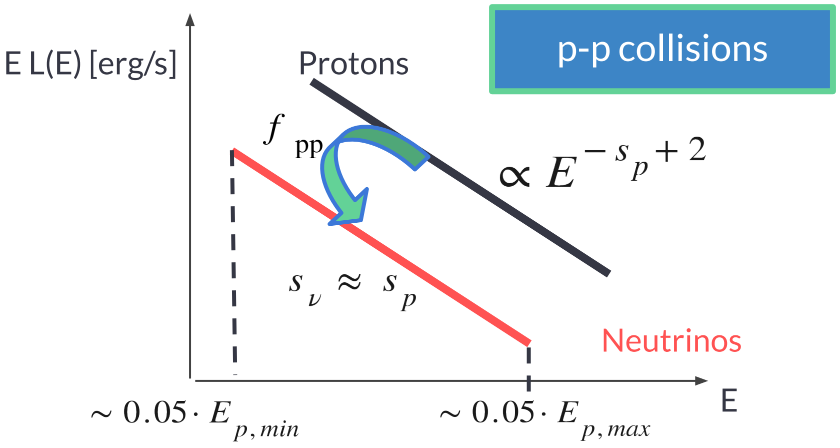


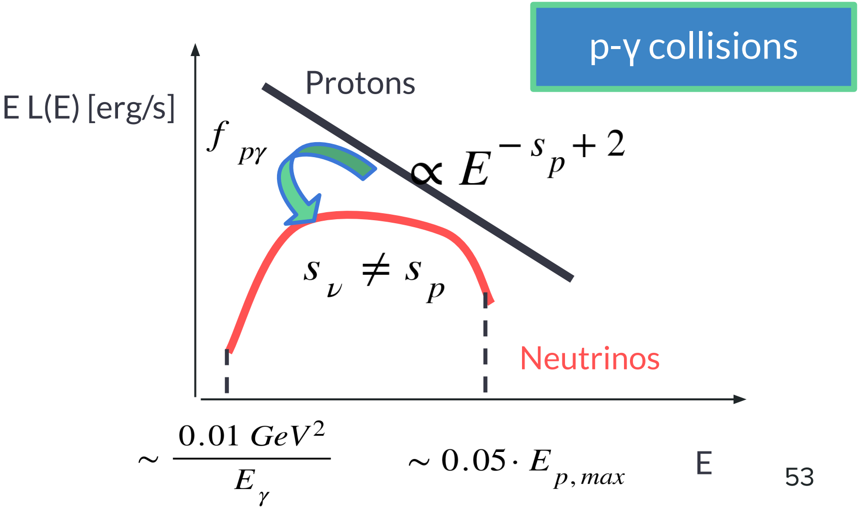
$$E_\nu L_{\nu+\bar{\nu}}(E_\nu) \approx \eta \, f_i(E_p) \cdot E_p L_p(E_p) \Big|_{E_p \approx 20\,E_\nu}$$

Interaction physics (branching ratio + typical energy)

Interaction physics + Source properties

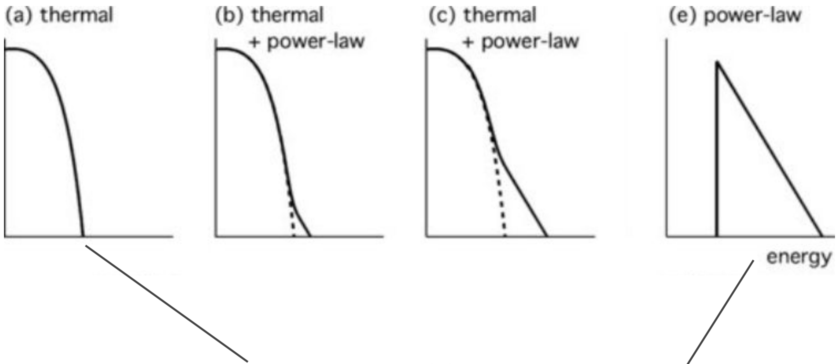
Acceleration physics





Particle acceleration

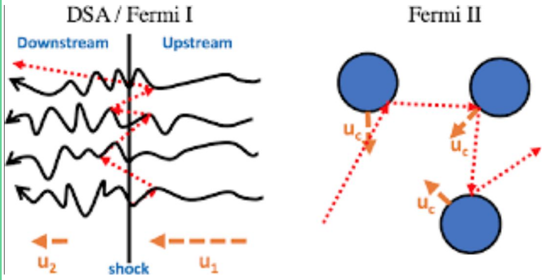
Heating → Acceleration



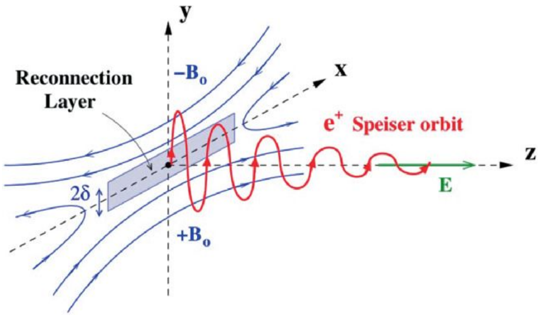
$$f(\mathbf{p}) = \frac{1}{4\pi m^3 c^3 \theta K_2(1/\theta)} \exp\left(-\frac{\gamma(p)}{\theta}\right)$$

$$f(x) = ax^{-k}$$

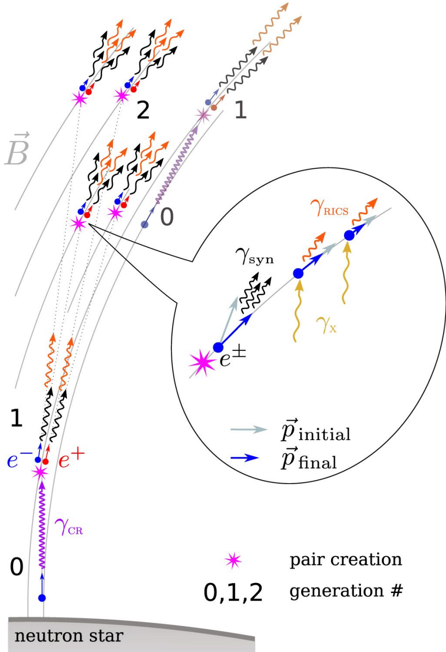
Shocks/turbulence



Magnetic reconnection



Electrostatic gaps

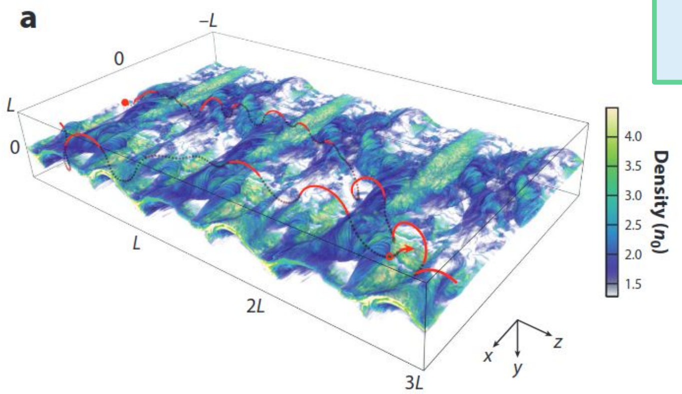


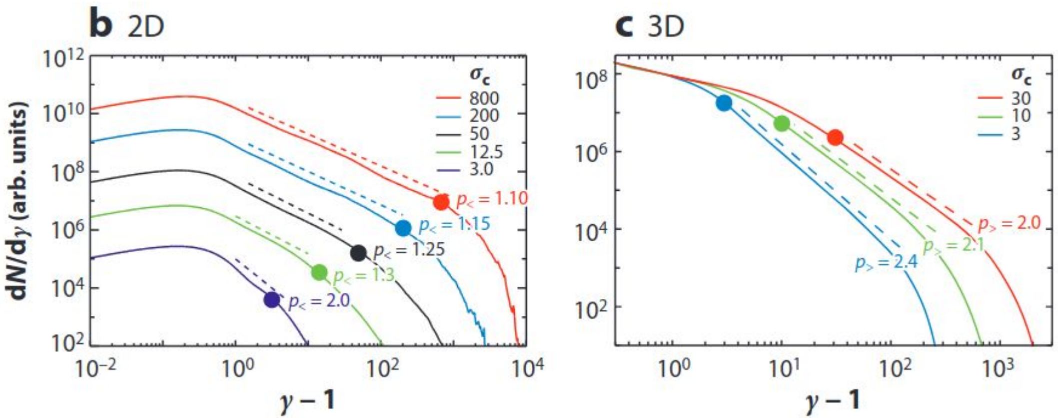
Relativistic magnetic reconnection

Key Parameter:
Plasma Magnetization

$$\sigma = \frac{B^2}{4\pi \rho c^2}$$

- Dissipation of magnetic energy → internal energy, non-thermal particle energy
- **E-field acceleration** → particles gain energy as the move along non-ideal E-fields and motional E-fields
- Reconnection can efficiently accelerate particles with (**broken**) **power-law** distributions

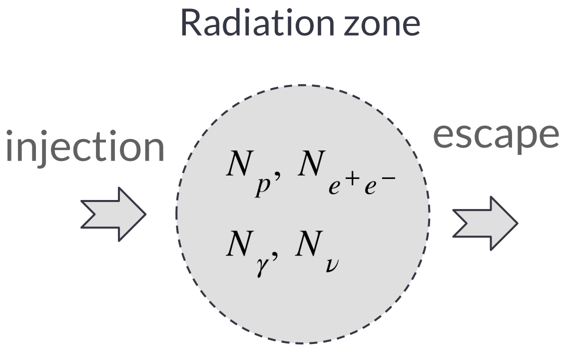




Check student talks by D. Karavola , G. Konstantis, K. X. Argyropoulos

Recent review:
[Sironi, Uzdensky, Giannios (2025), ARA&A, Vol. 63]

Numerical approach



$$\frac{\partial N_i(E,t)}{\partial t} + \frac{\partial}{\partial E}\left(b(E)N_i(E,t)\right) + \frac{N_i(E,t)}{t_{esc}(E,t)} = Q_{inj}(E,t) + Q_{ext}(E,t)$$

Evolution in time — Energy losses — Escape term — Injection terms

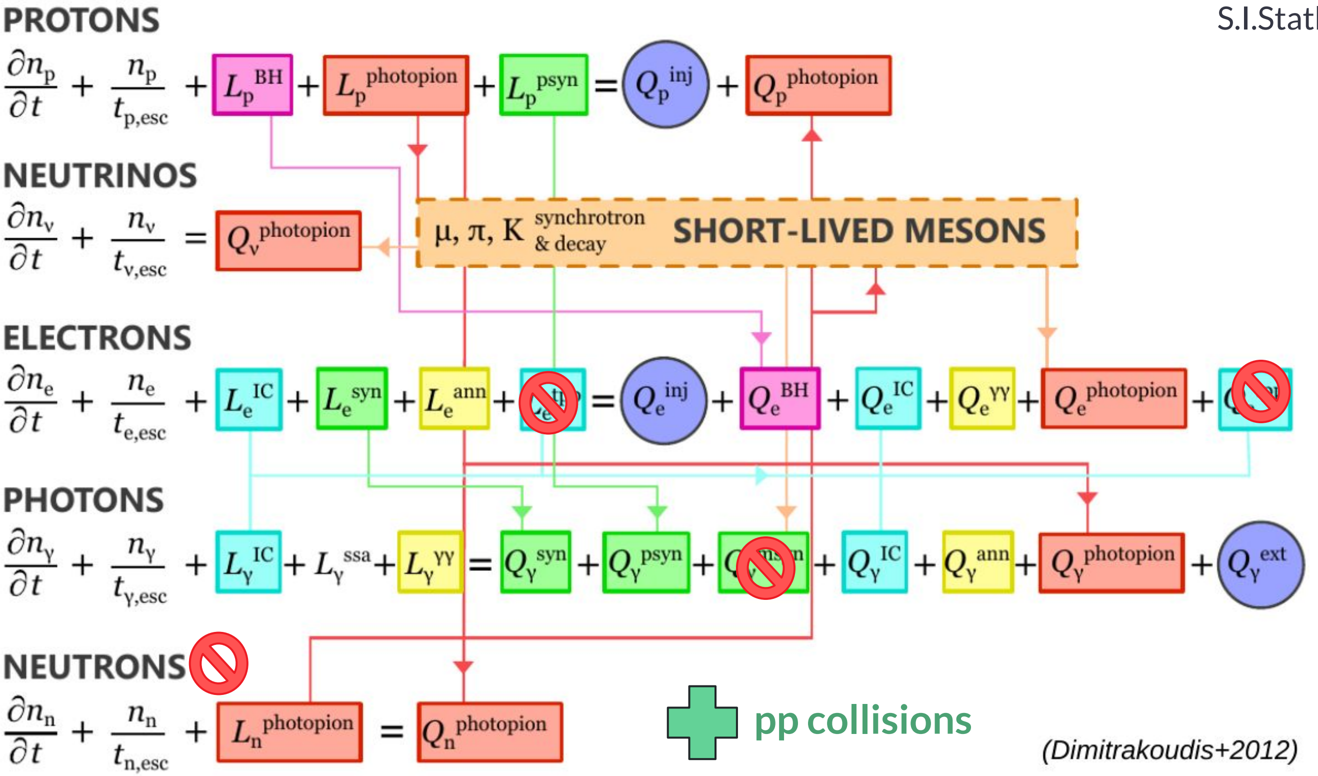
- Partial differential equation for particle species *i* distribution
- Key difference with CR propagation models: feedback between primary and secondary particles can be important!

Numerical codes - 2

LeHaMoC (2024 -)

S.I.Stathopoulos

https://github.com/Stamatis-Ilias/LeHaMoC-V2/tree/new-version/LeHaMoC%20V2



(Dimitrakoudis+2012)

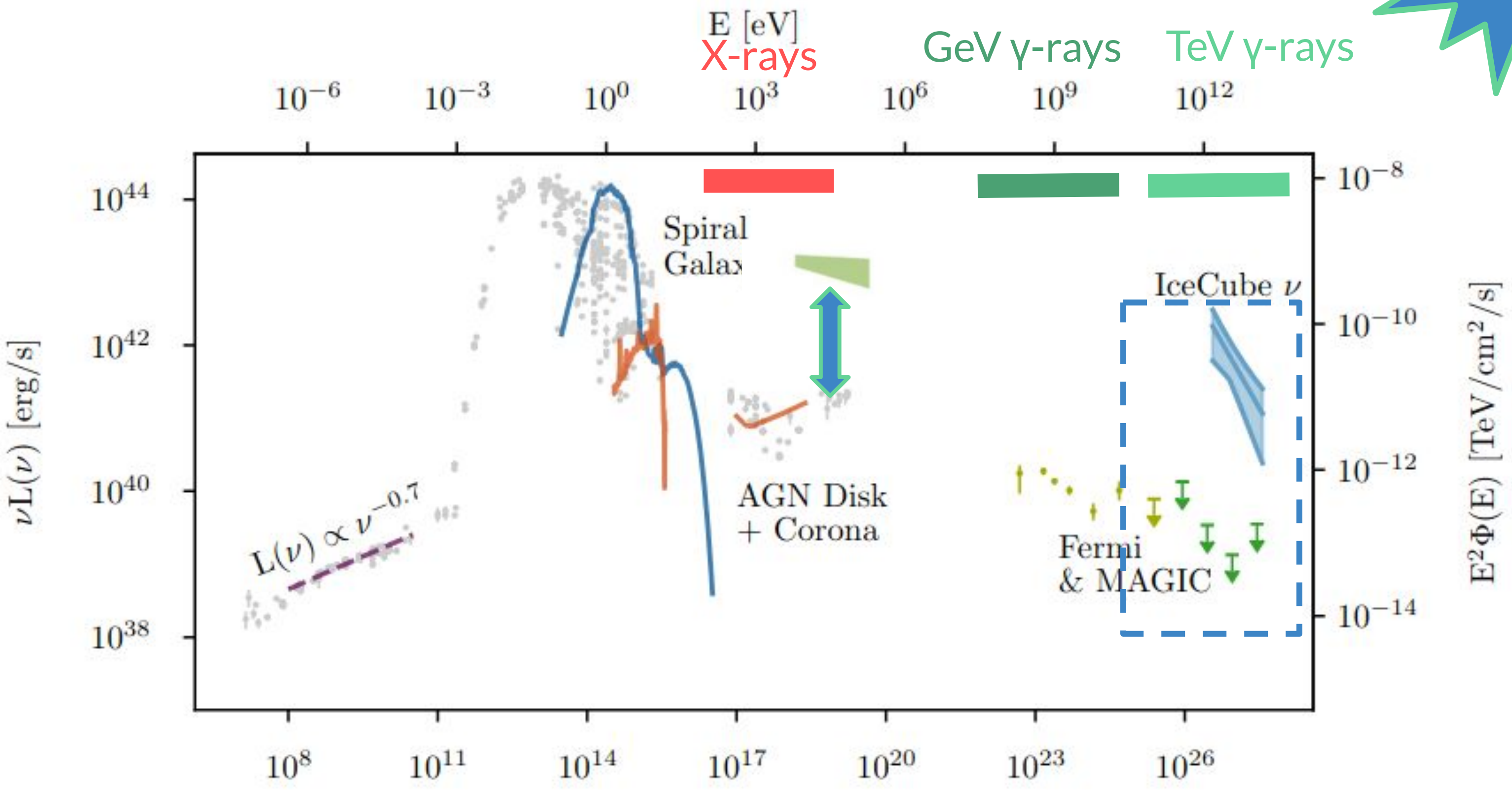
Stathopoulos et al. 2024

PROs

- Time-dependent
- Feedback of secondaries on primaries is included
- Modeling of optically thick sources and non-linear electromagnetic cascades
- Public code in Python
- Short execution times (~1 sec for leptonic, ~20 sec for hadronic)
- MCMC fitting

Building an AGN ν-coronal model

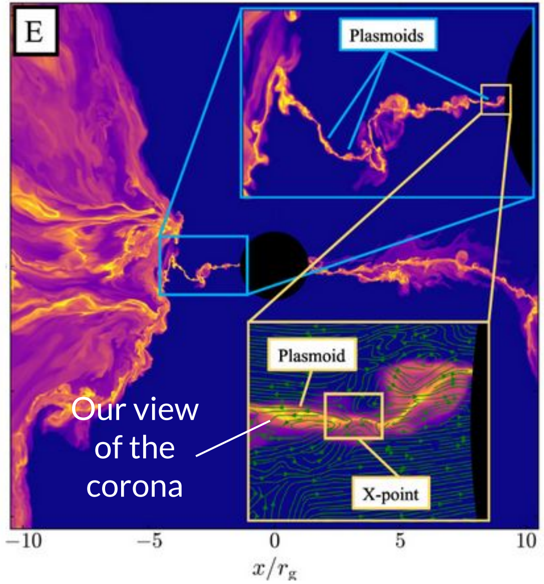
A multi-wavelength view of NGC 1068



Padovani et al., 2024, Nat. Astronomy

Corona powered by reconnection

Fiorillo et al., 2024a, ApJL



Ripperda et al. (2022)

Poynting flux

Comptonized X-ray luminosity

$$L_X = \eta_X S_P A$$

+

Corona spectrum

Relativistic proton luminosity

$$L_p = \eta_p S_P A = \frac{\eta_p}{\eta_X} L_X.$$

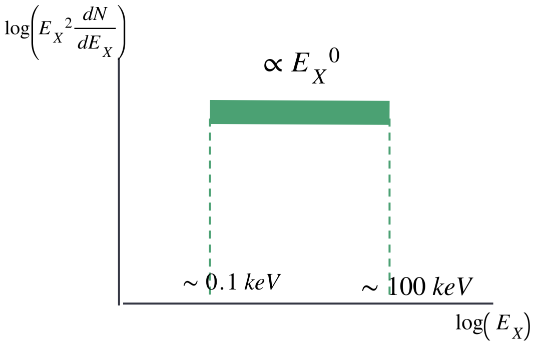
+

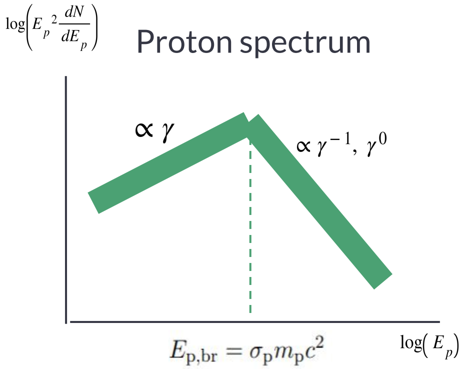
Proton spectrum

p-γ collisions

Neutrino spectrum

Corona spectrum

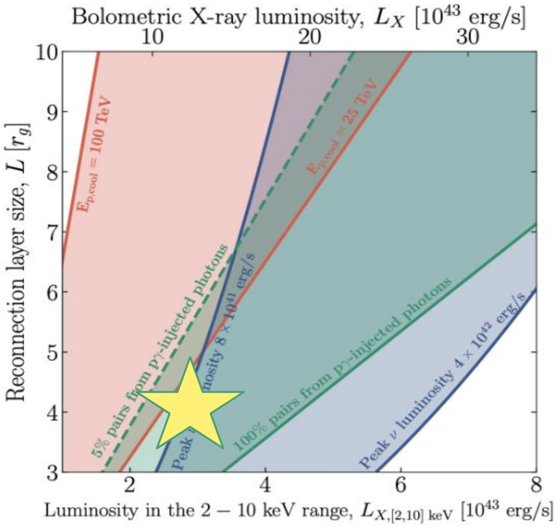


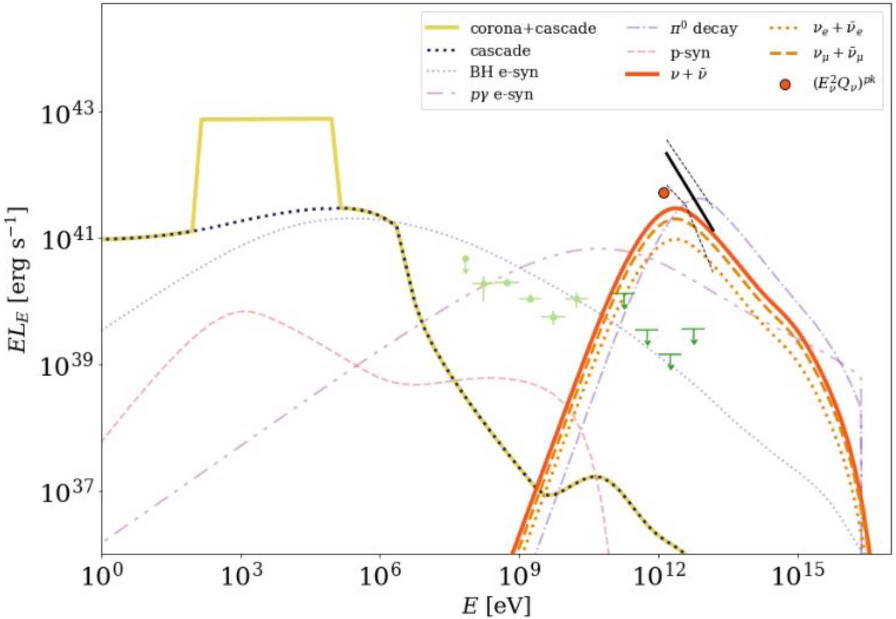


For particle acceleration check : Werner & Uzdensky 2017, Chernoglazov et al. 2023, Zhang et al. 2021, 2023

Results for NGC 1068

Fiorillo et al., 2024, ApJL





- Compact corona: L ~ (3-10)*R_g
- Pair dominated corona: n_{ee}/ n_p~10^{6-7}

- Highly magnetized corona: σ_e ~ 10^2 and σ_p~ 10^5
- Non-thermal-to-thermal proton fraction: ~1
- Not an UHECR accelerator

What about AGN corona with different X-ray luminosities and black hole masses?

Extending to other AGN

Karavola et al., 2025, JCAP

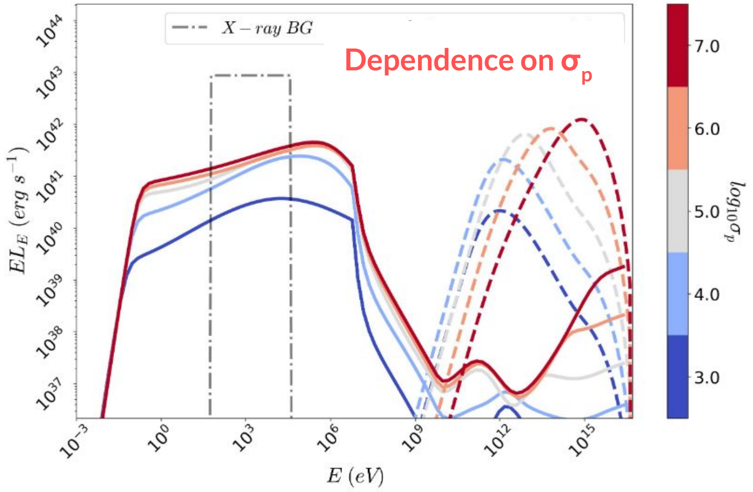
Key Parameters:

$$\lambda = \frac{L_X}{L_{Edd}} \propto \frac{L_X}{M_{BH}}$$

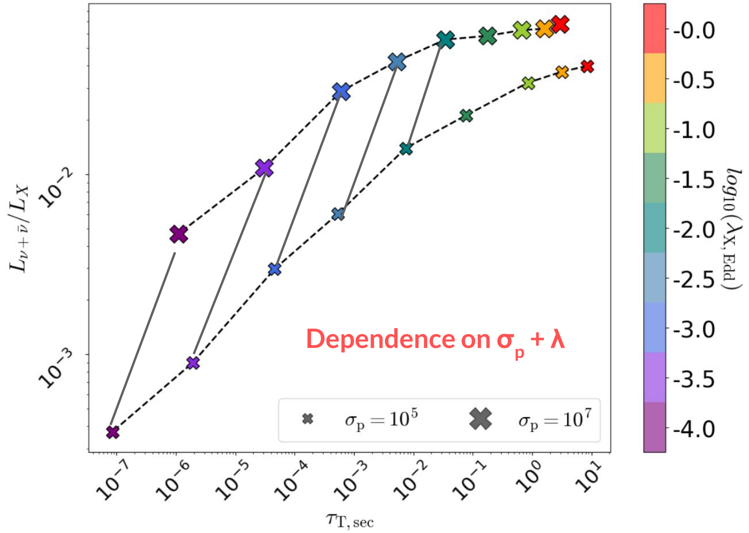
$$\sigma_p = \frac{B^2}{4\pi n_p m_p c^2}$$

Parametric study showed that the neutrino emission depends on 2 parameters:

Photon & Neutrino SEDs



Neutrino-to-X ray Luminosity ratio vs. Thomson optical depth

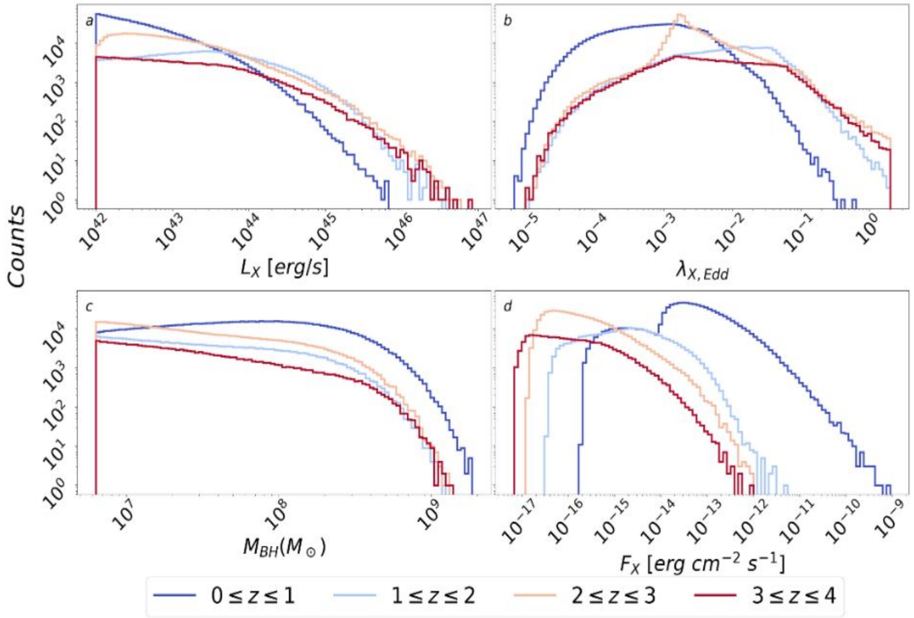


Diffuse ν emission from non-jetted AGN

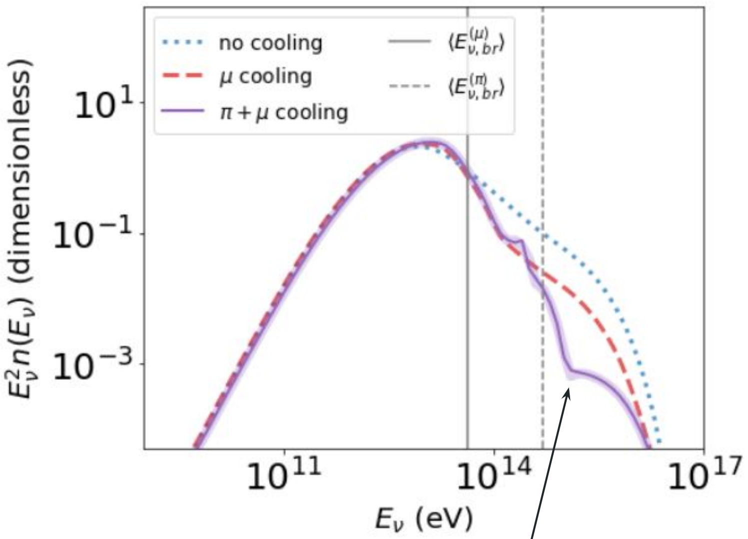
Karavola et al., 2026, A&A

https://github.com/Des0053/Coronal_neutrinos

Mock AGN catalog
(Georgakakis, Ruiz, LaMassa 2020)



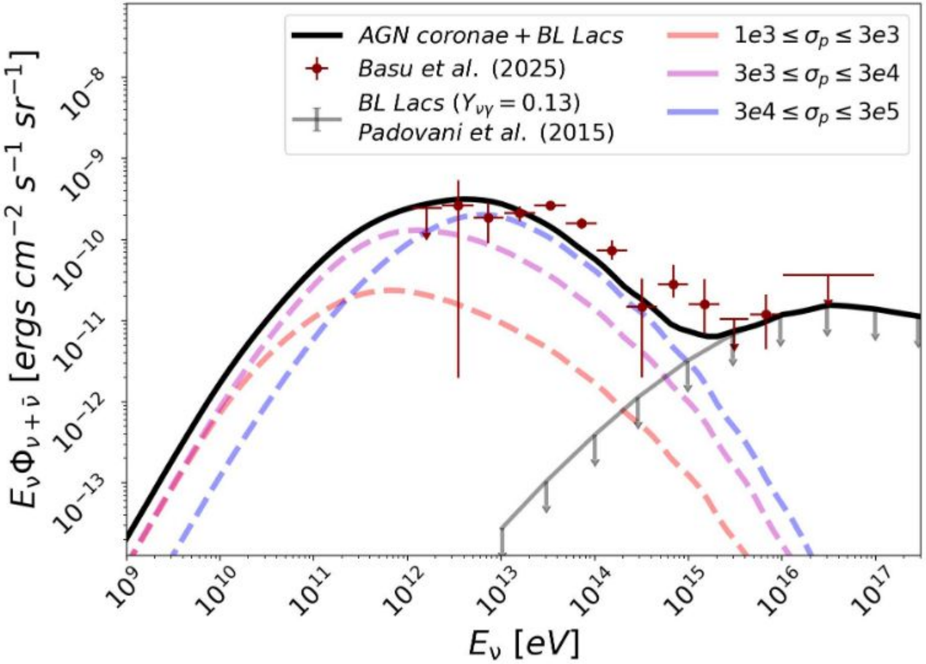
AGN Neutrino Spectral Template



Suppression due to synchrotron cooling of pions/muons

Diffuse ν emission from non-jetted AGN

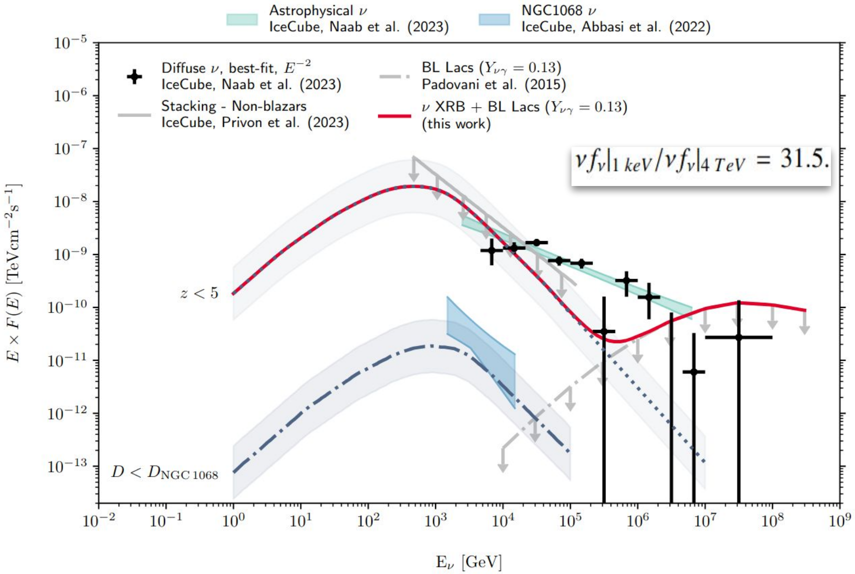
Karavola et al., 2026, A&A



- ~10 % of non-jetted AGN should have coronae with $\sigma_p \sim 10^5$ (like NGC 1068)
- The majority of AGN coronae should have lower magnetizations (10^3-10^4)
- Pion & muon synchrotron cooling suppress PeV flux, leaving room for jetted AGN

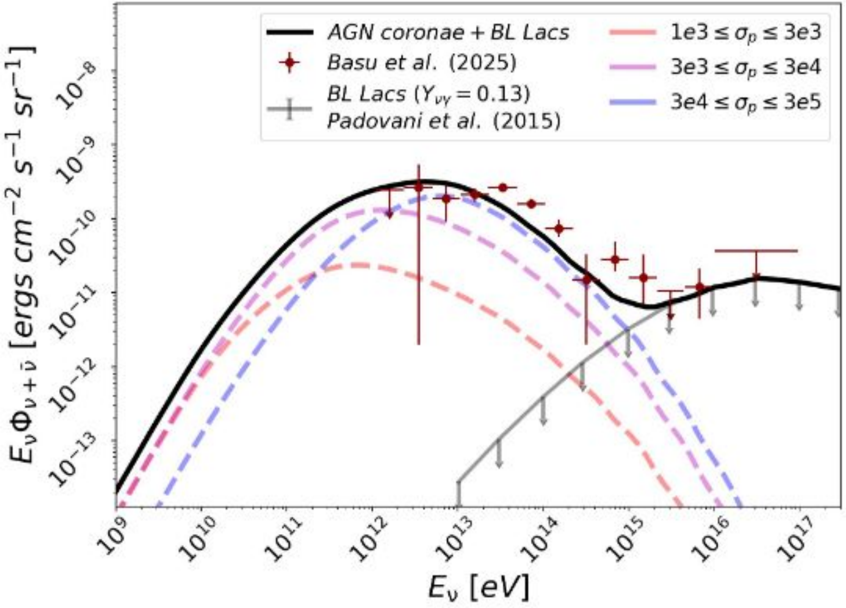
Diffuse emission from AGN

Data driven approach



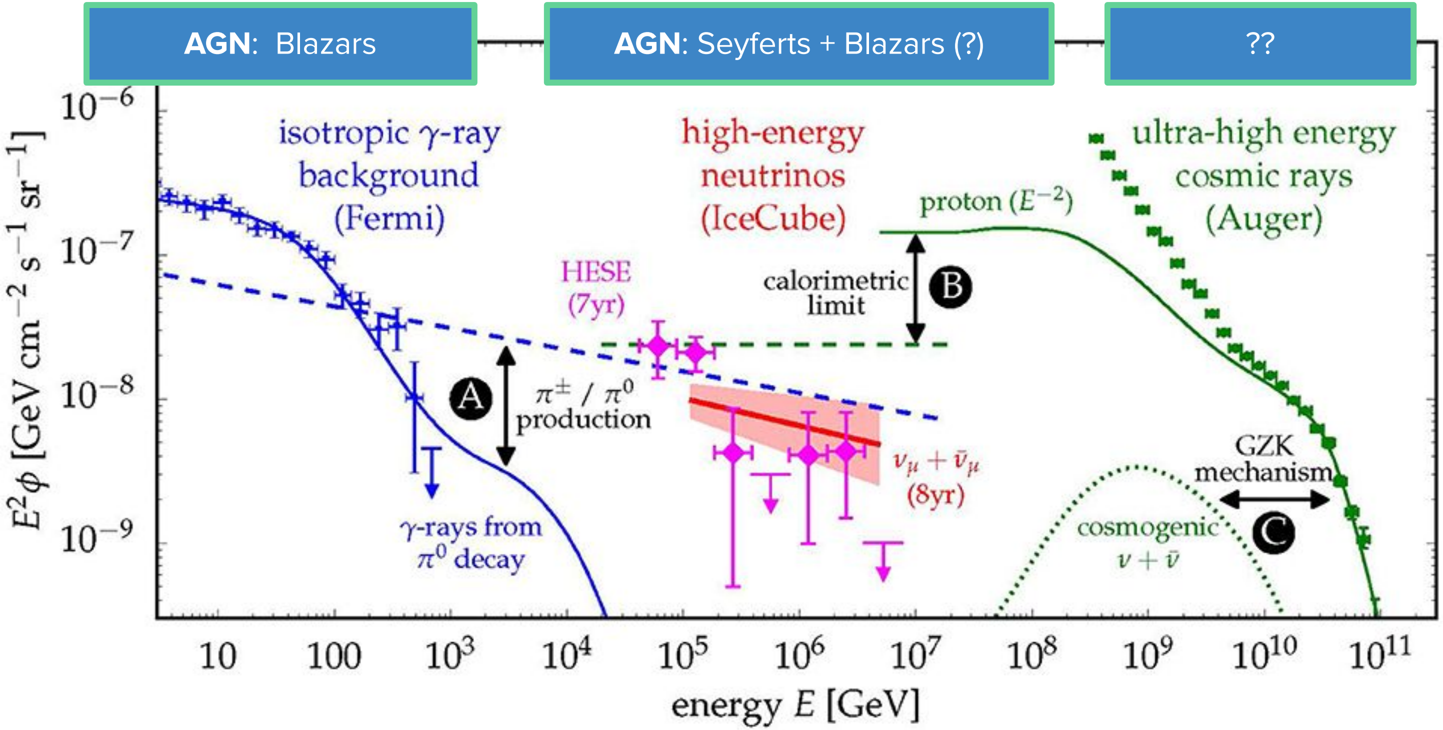
Padovani et al. (2024) MRNAS

Physically driven approach



Karavola et al., 2026, A&A

The multi-messenger picture: γ - ν - CRs



Halzen & Kheirandish, 2019, Frontiers

Summary - 2

- Many astrophysical sources are plausible cosmic-ray accelerators and neutrino emitters as they have *sufficient energetics and interacting targets*.
- The neutrino output of an astrophysical sources depends critically on two quantities: *the opacity to pp/pγ interactions and the relativistic proton power*.
- Both quantities may vary significantly across astrophysical sources and across scales in the same source (*multi-scale problem*) making the problem extremely complex.
- Sources of diffuse neutrino flux are likely AGN, but sources of UHECRs remain unknown.

Useful References - 2

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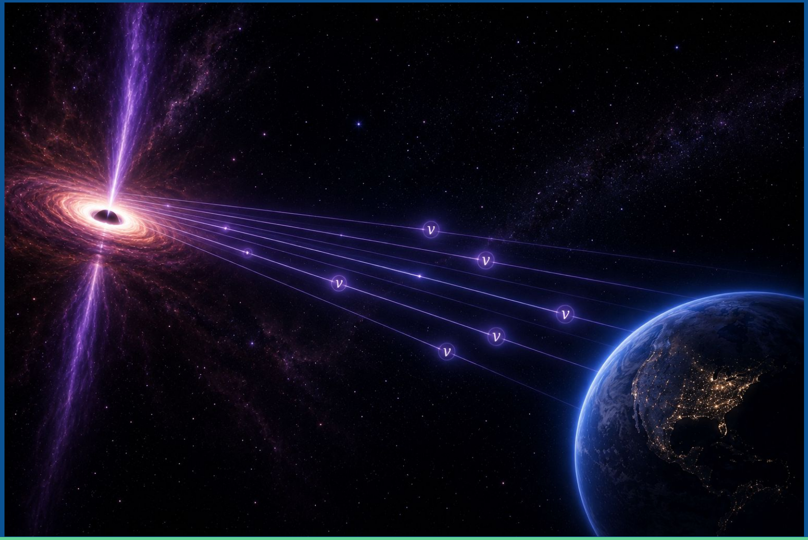
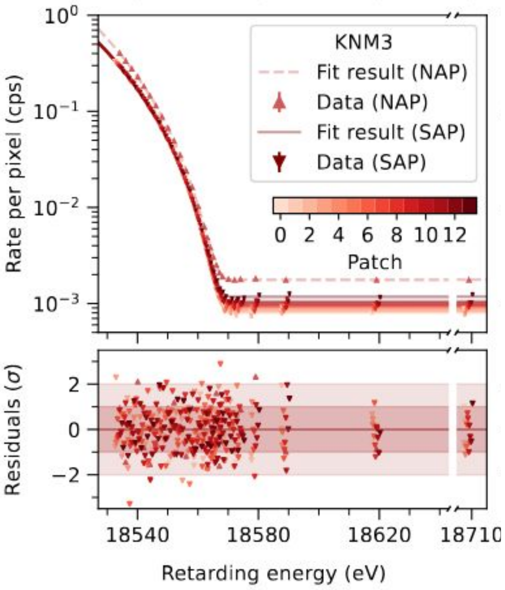
11. Palladino A., Fedynitch A., Rasmussen R.~W., Taylor A.~M., 2019, JCAP, 2019, 004. doi:10.1088/1475-7516/2019/09/004
12. Laha S., Ricci C., Mather J. C., Behar E., Gallo L., Marin F., Mbarek R., et al., 2025, FrASS, 11, 1530392. doi:10.3389/fspas.2024.1530392

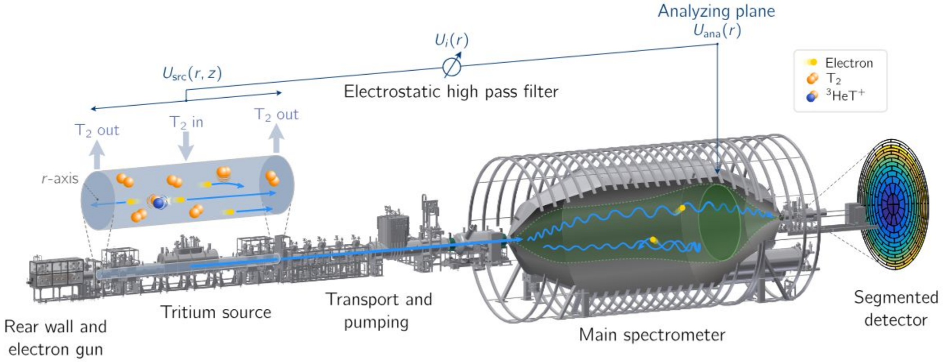


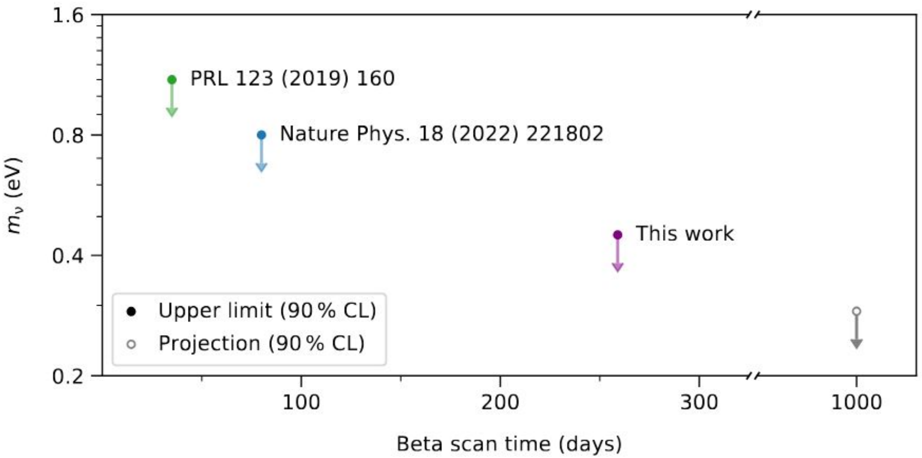
Thank you!

Backup

KATRIN experiment







KATRIN Collaboration, 2025, Science, 388

How big should be a detector of 0.1 MeV solar neutrinos?

Neutrino number flux @ 0.1 MeV:

$$E\varphi_E\big|_{E=0.1MeV} \approx 10^{10}\ cm^{-2}\ s^{-1}$$

v-e scattering cross section @ 0.1 MeV:

$$\sigma_{\nu e}\big|_{E=0.1MeV} \approx 10^{-18}\ mb = 10^{-45}\ cm^2$$

Event rate:

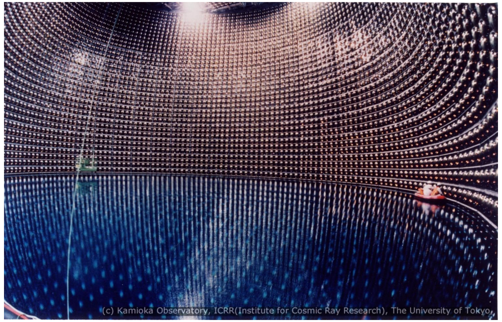
$$R = N_t \cdot \sigma_{\nu e} \cdot E\varphi_E\big|_{E=0.1MeV}$$

Number of target e-:

$$N_t \approx 10^{31} \left(\frac{R}{10\ d^{-1}} \right)$$

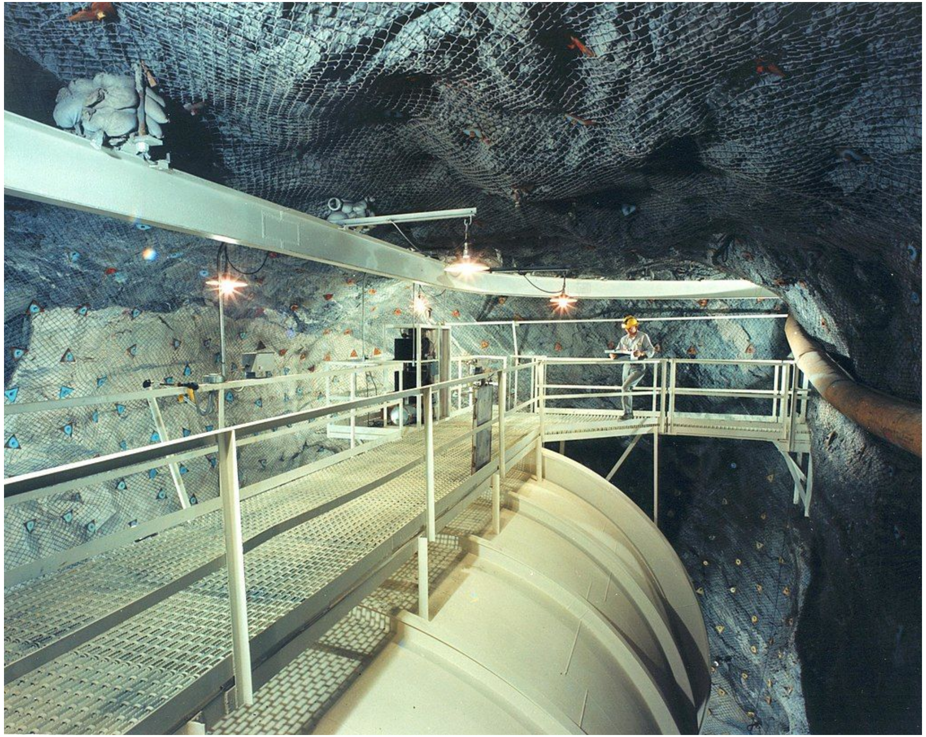
For water detector (1 ton → 3e29 e-):

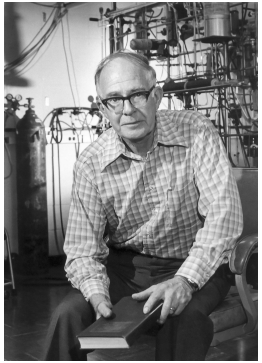
$$M \approx \frac{N_t}{3 \cdot 10^{29}}\ tons \approx 30\ tons \left(\frac{R}{10\ d^{-1}} \right)$$



Davis experiment (1970-1994)

Video link

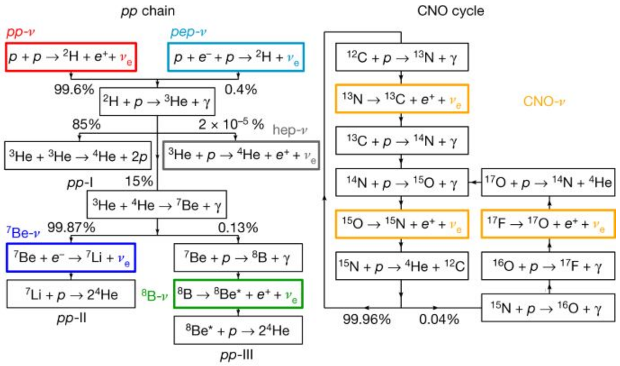


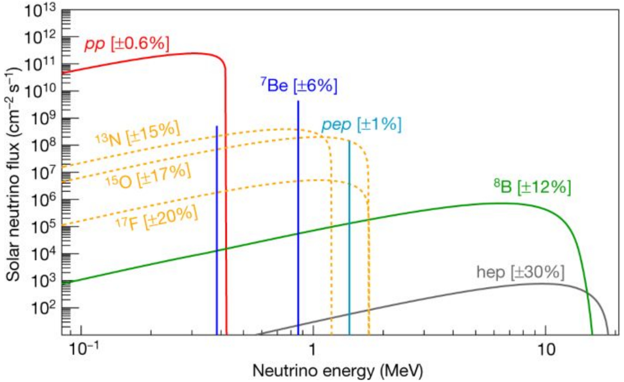


- 1st experiment for solar neutrino detection
- Designed by R. Davis (1965)
- Mining site (~1.5 km depth), South Dakota, USA
- Detection method: $\nu_e + {}^{37}_{17}Cl \rightarrow e^- + {}^{37}_{18}Ar$
- Radiochemical experiment

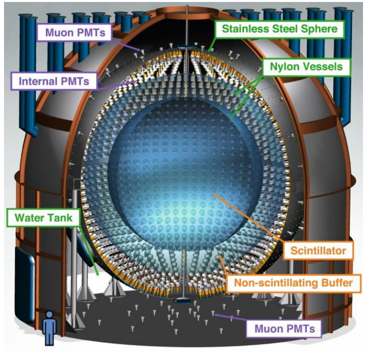
- Tank with 610 tons liquid $C_2Cl_4 \rightarrow$ **$2.2\ 10^{30}$** atoms of ^{37}Cl
- Energy threshold: ~ 0.814 MeV
- Half time of ^{37}Ar ~ 35 days
- Measure number of ^{37}Ar every several months → estimate ν capture rate from ^{37}Cl

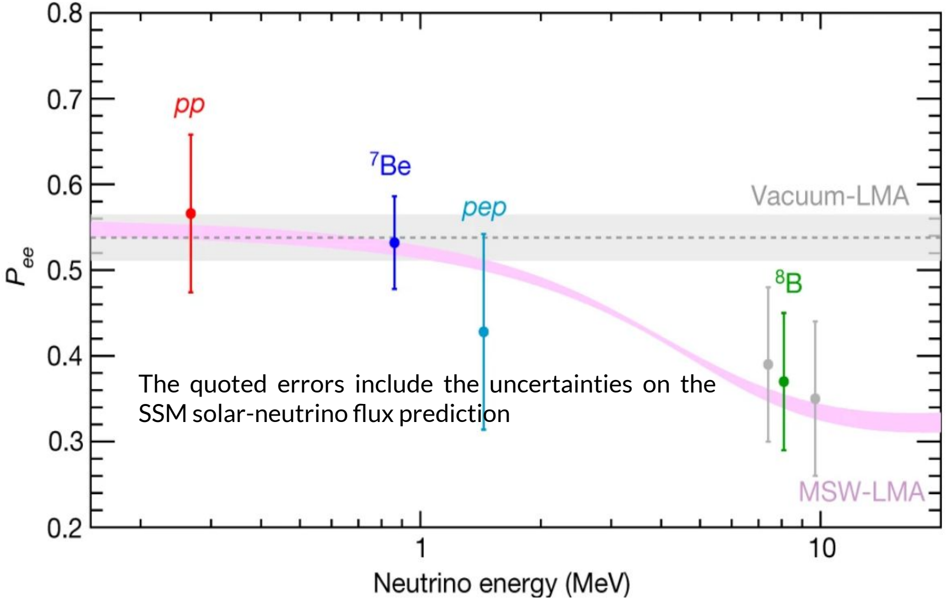
Solar neutrino oscillations





The Borexino Collaboration (2018) Nature

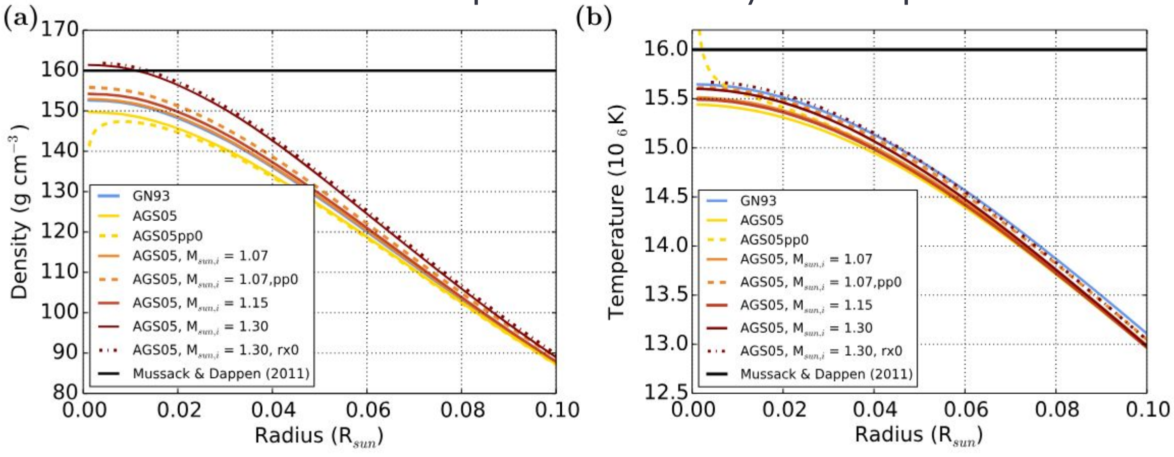




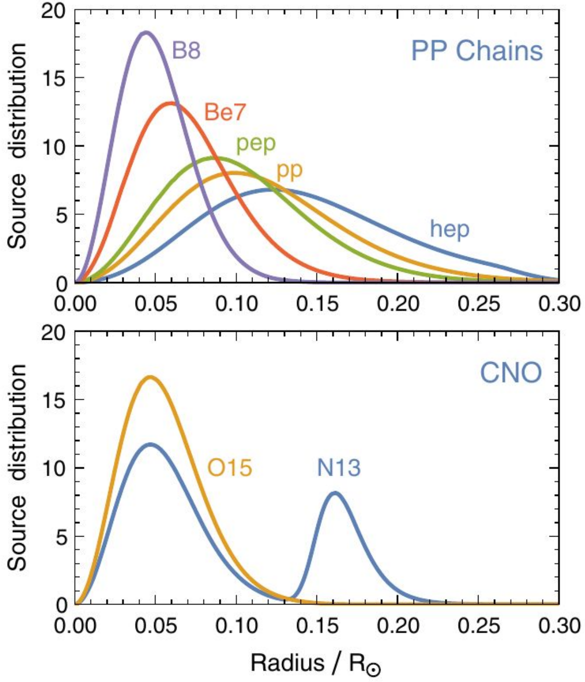
The quoted errors include the uncertainties on the SSM solar-neutrino flux prediction

Radial dependence of ν production

Solar models: radial profiles of density and temperature



Radial profiles of ν production rate



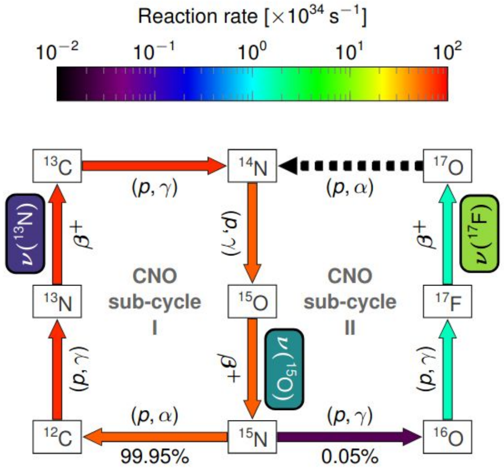
Blue-yellow: standard solar models
Orange-maroon: non-standard solar models (with mass loss)

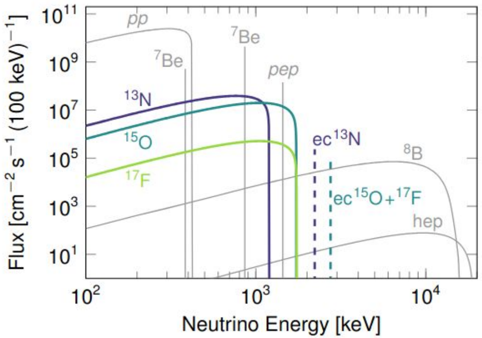
Wood, S. R. (2018)

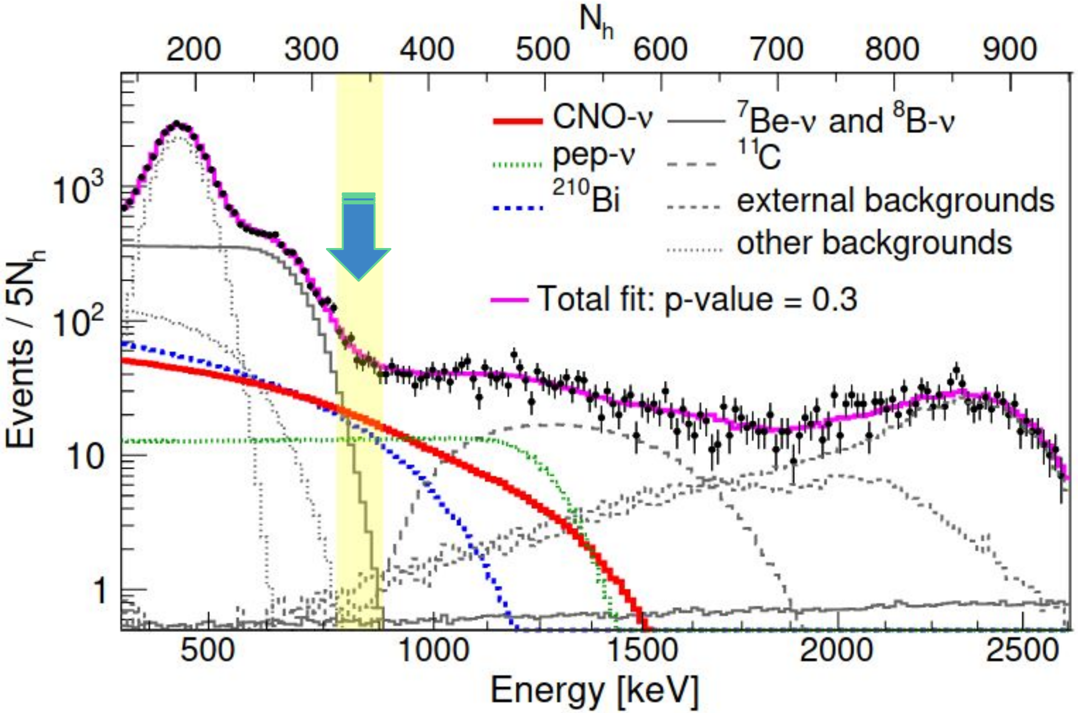
At smaller radii, temperature increases and neutrino production rates due to CNO peak

Vitagliano, Tamborra, Raffelt (2020)

Experimental evidence of ν_e from CNO cycle



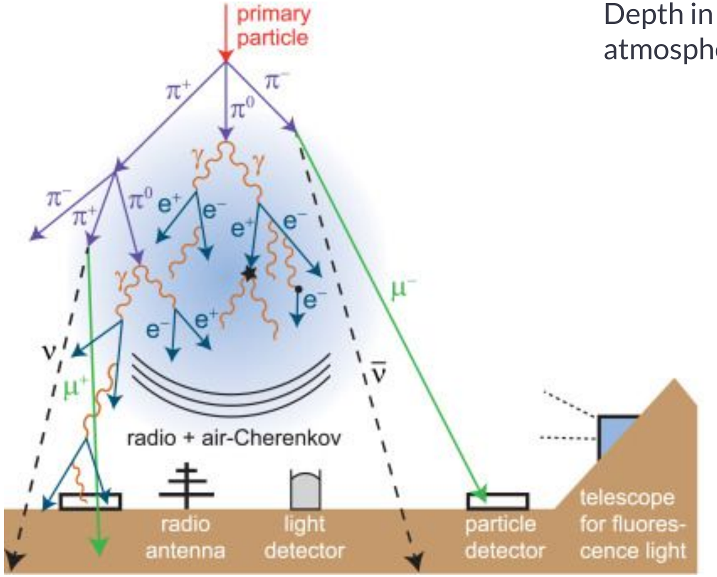




The Borexino Collaboration (2020)

Atmospheric neutrinos

- Atmospheric neutrinos produced by cosmic-ray showers
- Steep spectrum $\varphi_{\nu+\bar{\nu}} \propto E_{\nu}^{-3.7}$
- Background for astrophysical neutrinos



Cascade equation

$$\lambda_N = A_{\rm air}\, m_p \,/\, \sigma^{\rm inel}_{p-air}$$

$$d_i(X) = \rho(X)\, \gamma\, c\, \tau_i$$

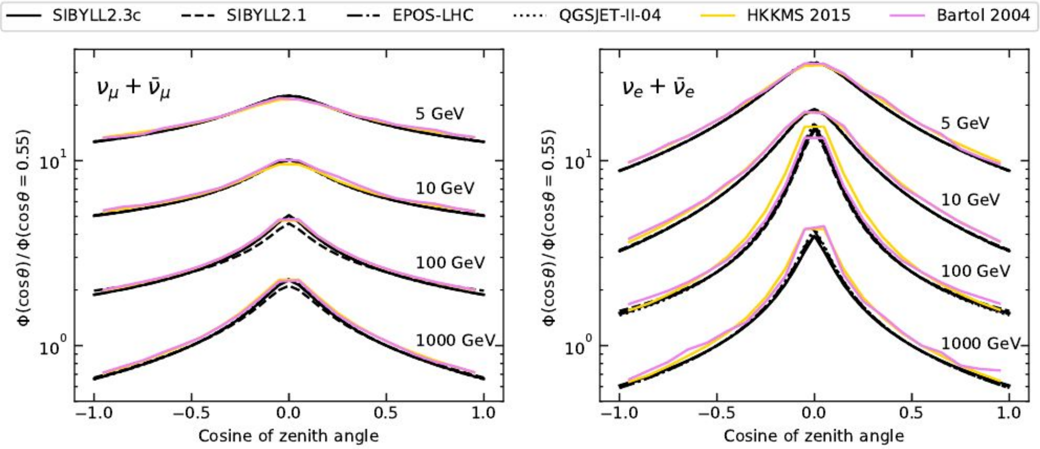
Depth in atmosphere (g/cm^2)

$$\frac{\mathrm{d}N_i(E_i,X)}{\mathrm{d}X} = -\frac{N_i(E_i,X)}{\lambda_i} - \frac{N_i(E_i,X)}{d_i} + \sum_{j=i}^{J} \int_E^{\infty} \frac{F_{ji}(E_i,E_j)}{E_i} \frac{N_j(E_j,X)}{\lambda_j}\, \mathrm{d}E_j .$$

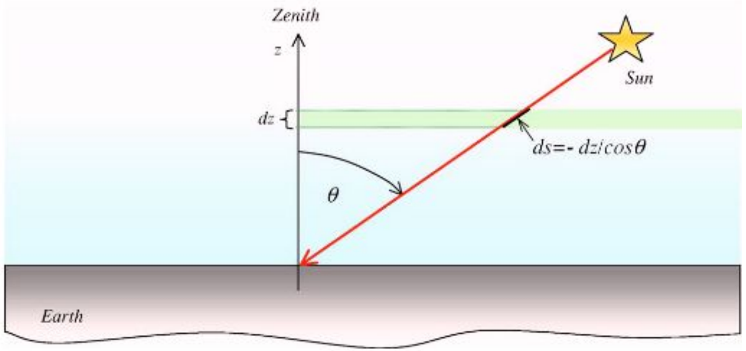
$$F_{ji}(E_i,E_j) \equiv E_i \frac{1}{\sigma_j^{\rm air}} \frac{\mathrm{d}\sigma_{j\,{\rm air}\to i}}{\mathrm{d}E_i}$$

Gaisser T. (2019)

Atmospheric neutrino spectra



Fedynitch et al. (2018)



Analytical approximate spectrum (without μ decays)

$$\frac{dN_\nu}{dE_\nu} \simeq \frac{N_0(E_\nu)}{1 - Z_{NN}} \left\{ \frac{\mathcal{A}_{\pi\nu}}{1 + \mathcal{B}_{\pi\nu} \cos\theta\, E_\nu/\epsilon_\pi} + 0.635 \frac{\mathcal{A}_{K\nu}}{1 + \mathcal{B}_{K\nu} \cos\theta\, E_\nu/\epsilon_K} + \sum_i B_{D_i} \frac{\mathcal{A}_{D\nu}}{1 + \mathcal{B}_{D\nu} \cos\theta\, E_\nu/\epsilon_D} \right\}$$

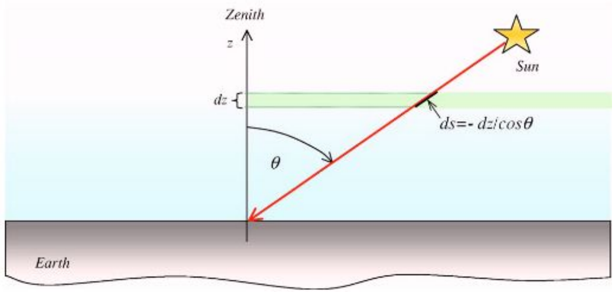
μ	$\pi^\pm$	$K^\pm$	$D^\pm$	D^0
1.	115.	850.	3.9×10^7	9.9×10^7

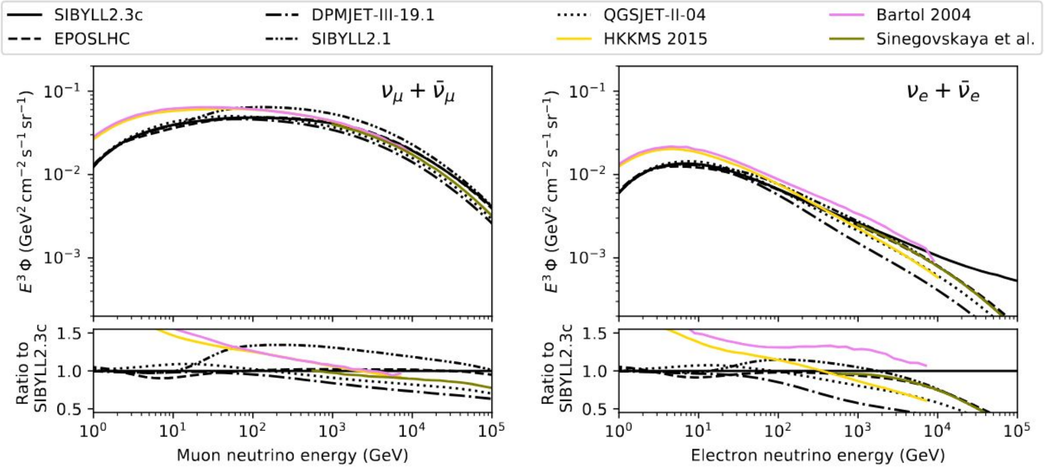
(GeV)

- For $\cos\theta\, E_\nu \ll \epsilon_i$: parent mesons decay before interacting → lepton spectrum reflects the primary spectrum + isotropic flux
- For $\cos\theta\, E_\nu \gg \epsilon_i$: interaction rate higher than decay rate → lepton spectrum steeper than primary spectrum + anisotropic flux

See also T. K. Gaisser, R. Engel and E. Resconi (2016)

Atmospheric neutrino spectra





Fedynitch et al. (2018)

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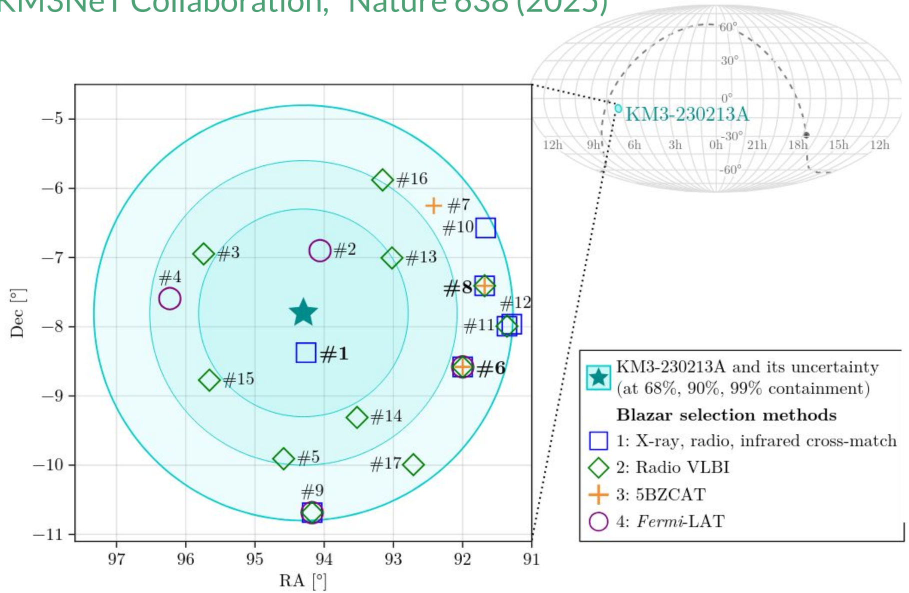
μ	$\pi^\pm$	$K^\pm$	$D^\pm$	D^0
1.	115.	850.	3.9×10^7	9.9×10^7

(GeV)

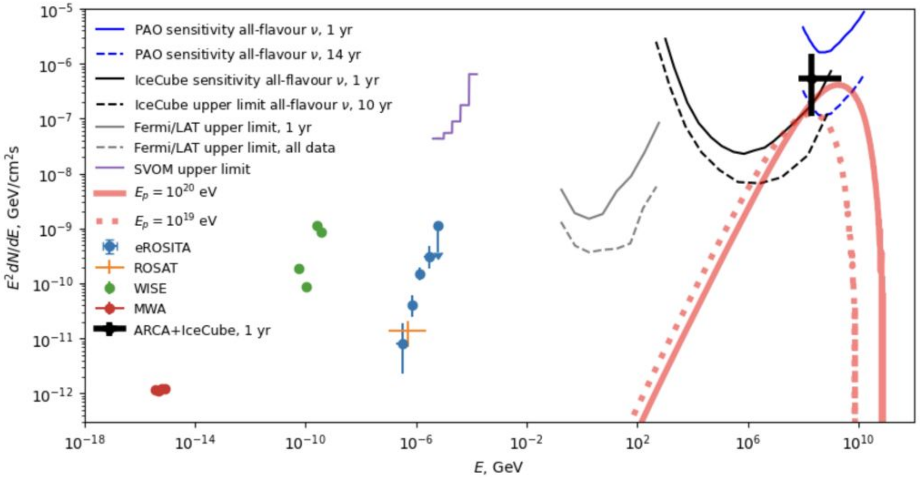
- The angle-averaged spectrum steepens progressively due to:
  - Energy dependence of angular distribution (see previous slide)
  - Steepening of (primary) cosmic-ray spectrum at higher energies

High-energy astrophysical neutrinos -
Experimental Highlights 5

KM3NeT Collaboration, Nature 638 (2025)



Neronov, Oikonomou, Semikoz (arXiv:250212986N)



- First observation of an ultra-high-energy neutrino (>120 PeV)
- Astrophysical source not uniquely identified

- Compatible with a 2 yr transient ν source ?
- What would be the EM emission of the associated source ?

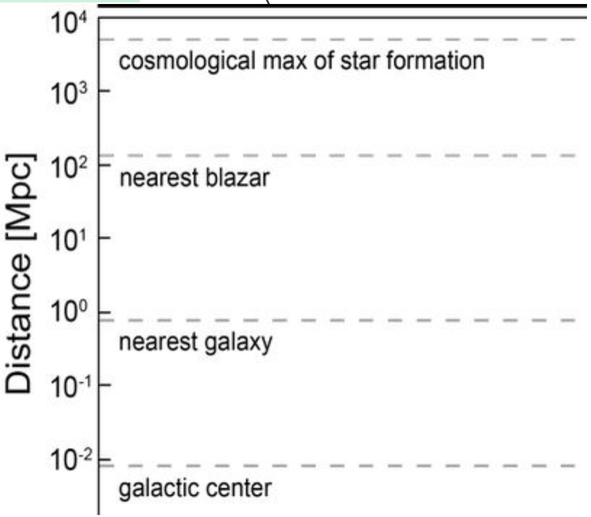
Energy loss timescale / Mean free path

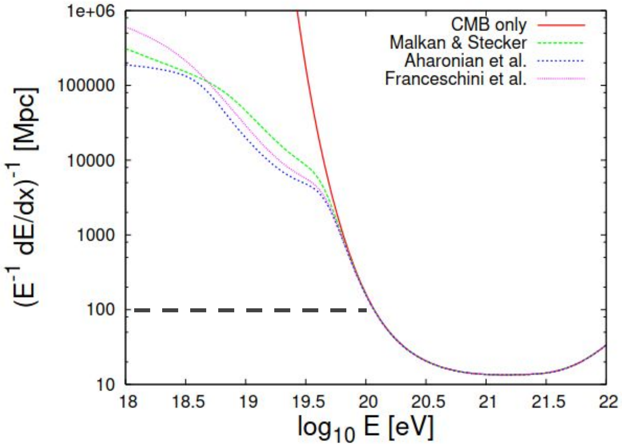
Stecker 1968; Begelman et al. 1990

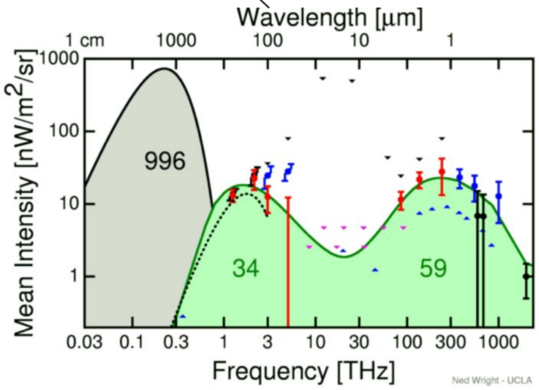
p-γ interactions with isotropic radiation field:

$$\left(t_{p\gamma}\right)^{-1} = -\frac{1}{E_p}\frac{dE_p}{dt} = \frac{c}{2}\int_0^\infty d\varepsilon\, n_\gamma(\varepsilon)\int_0^\pi d\theta\,\sin\theta\,\kappa(\varepsilon_r)\sigma(\varepsilon_r)\left(1-\beta_p\cos\theta\right) = \frac{c}{2\gamma_p^{\,2}}\int_0^\infty d\varepsilon\,\frac{n_\gamma(\varepsilon)}{\varepsilon^2}\int_{\varepsilon_{th}}^{2\gamma_p\varepsilon} d\varepsilon_r\,\kappa(\varepsilon_r)\sigma(\varepsilon_r)\,\varepsilon_r$$

Example





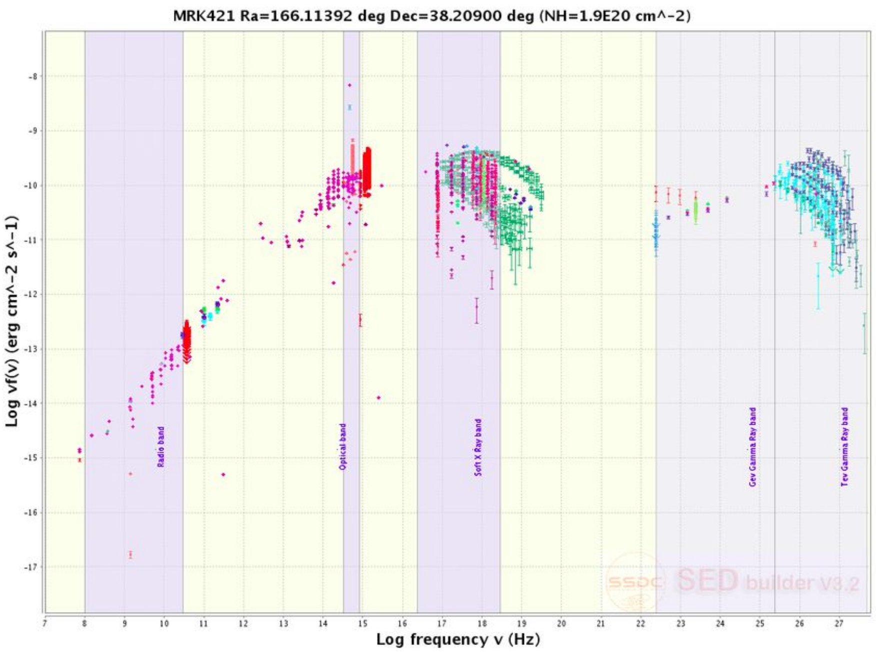


Hooper et al. (2007)

Credit: Ned Wright (UCLA)

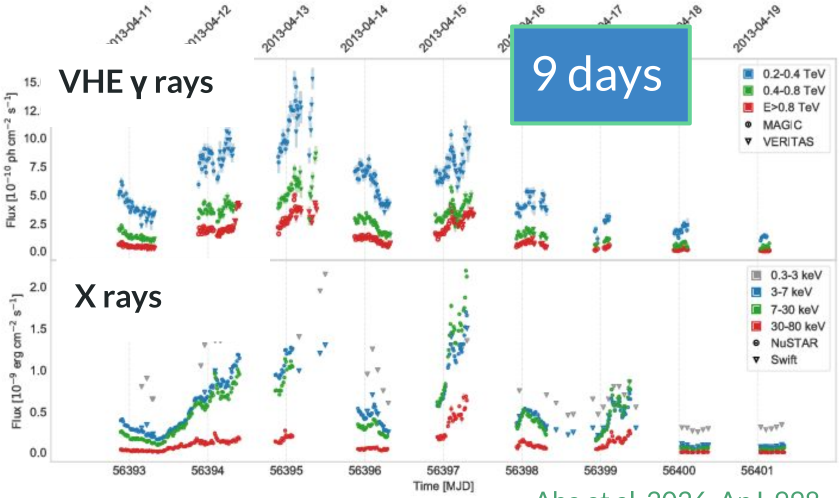
AGN Blazar

Spectral Energy Distribution (SED)

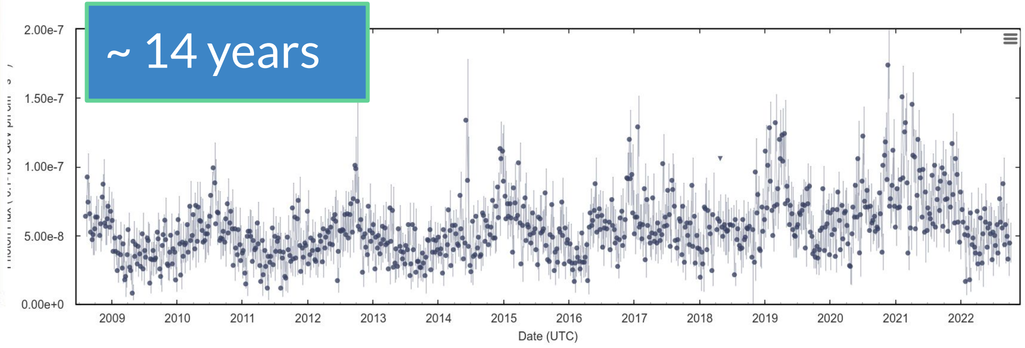


Credit: SED Builder

Light curves



Abe et al. 2026, ApJ, 998



Fermi Lightcurve Repository

Blazar subclasses

Narrowband spectral classification

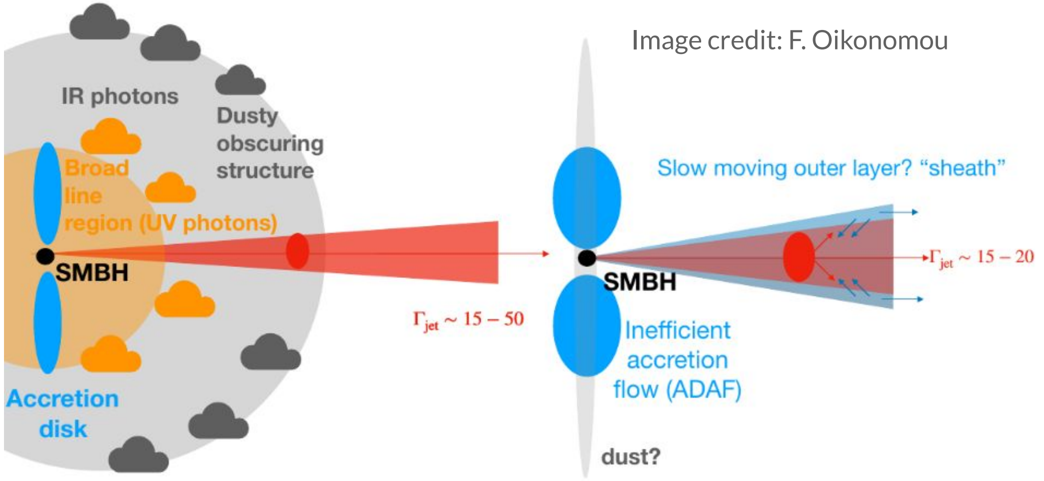
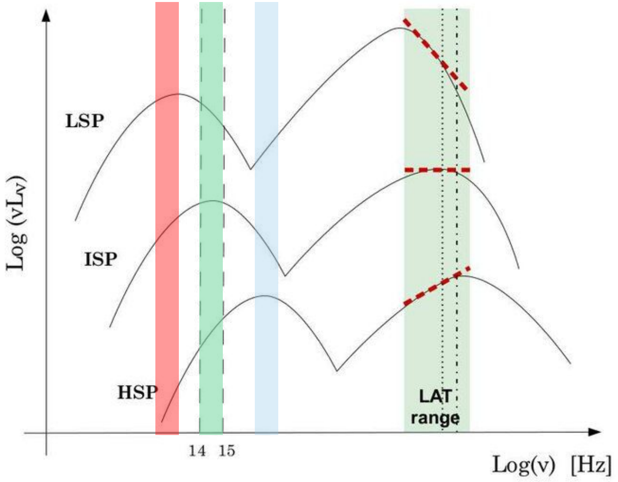


Image credit: F. Oikonomou

Broadband Spectral classification



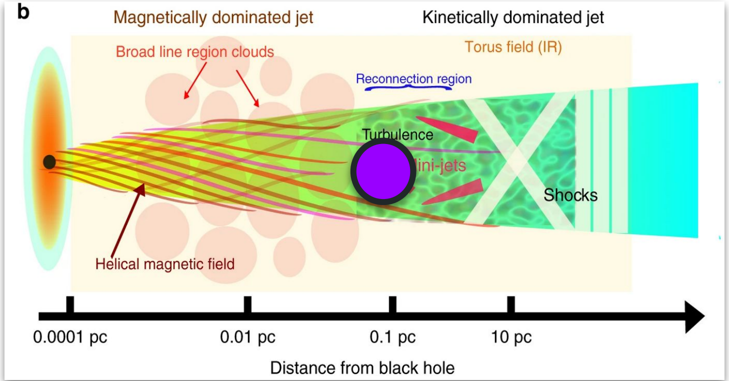
Lico et al. (2017) A&A

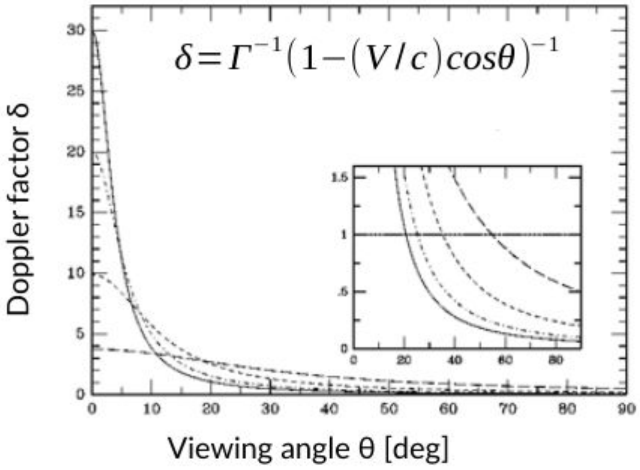
- Broad emission lines in optical spectra
- Radiatively efficient disks
- Accretion at Eddington rates
- High jet power & γ-ray luminosity

- Weak/absent broad emission lines in optical spectra
- Radiatively inefficient disks
- Accretion at sub-Eddington rates
- Low jet power & γ-ray luminosity

Recipe for radiative transfer in jets

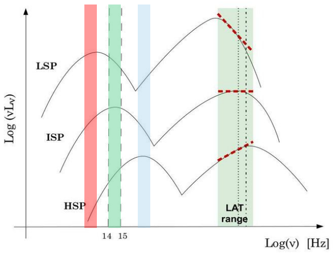
1. Specify emissivity and absorption coefficients for all relevant processes
2. Specify geometry (blob or slab)
3. Solve radiative transfer equation in jet rest frame
4. Apply Doppler boosting to calculate observed quantities





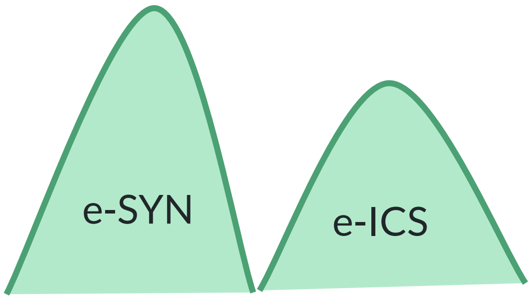
	Jet frame	Observer's frame
Emission pattern		
Luminosity	L'	$L=\delta^4 L'$
Frequency	ν'	$\nu=\delta\nu'$

One-zone emission models

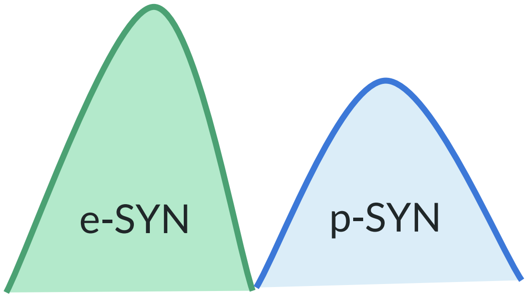


Lico et al. (2017) A&A

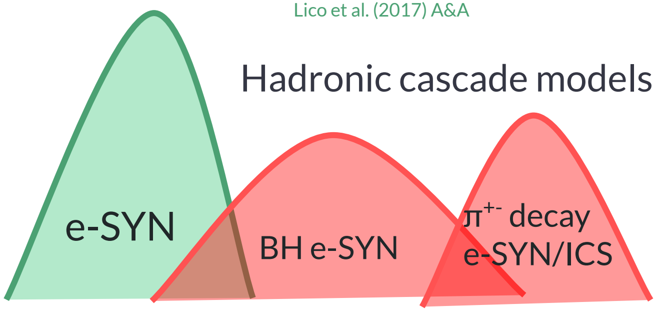
Leptonic synchro-Compton models



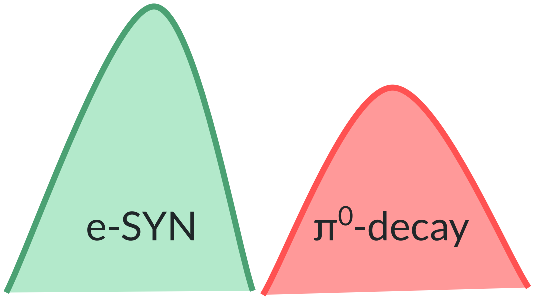
Proton synchrotron models



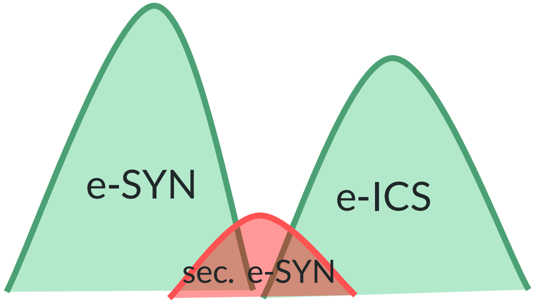
Hadronic cascade models



Neutral pion models



Hybrid leptonic models*

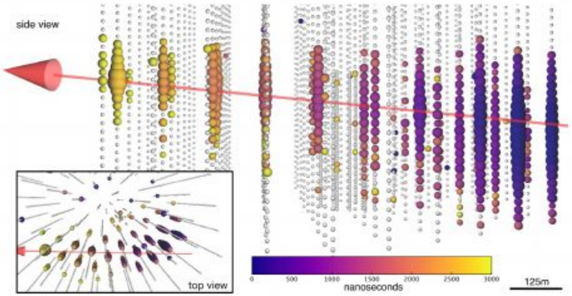


Bibliography

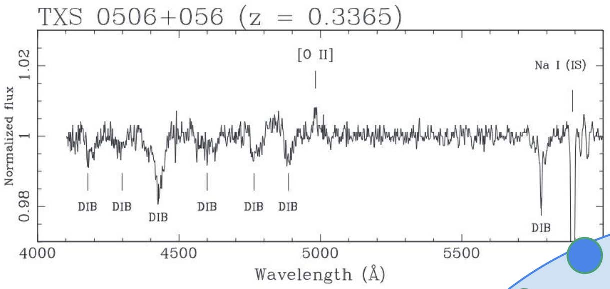
- **Leptonic:** Maraschi+1992, Dermer, Schlickeiser, Mastichiadis 1992, Sikora + 1994, Mastichiadis & Kirk 1995, Tavecchio+1998, Boettcher & Dermer 1998 ….
- **Hadronic**: Mannheim & Biermann 1992, Mannheim 1993, Aharonian 2000, Muecke & Protheroe 2001, Boettcher+2013, Petropoulou+2015a,b …

TXS 0506+056 / IC 170922A

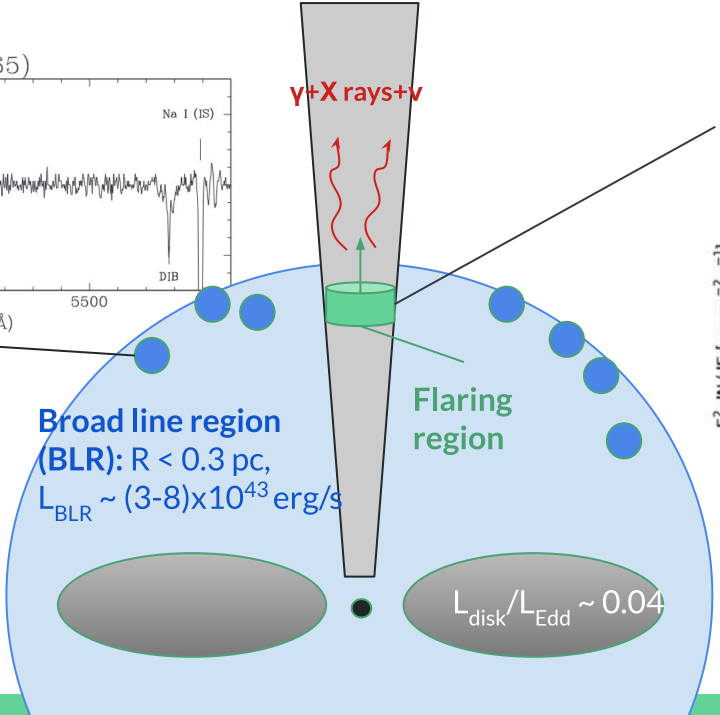
- IC 170922A (~ 290 TeV) detected during a 6 month-long flare
- Blazar at z = 0.3365 from weak emission lines
- Masquerading BL Lac with Esyn, pk < 4 eV [IBL] → hidden broad line region
  (Padovani et al. 2019, MNRAS; Georganopoulos & Marscher 1998; Giommi & Padovani 2013)

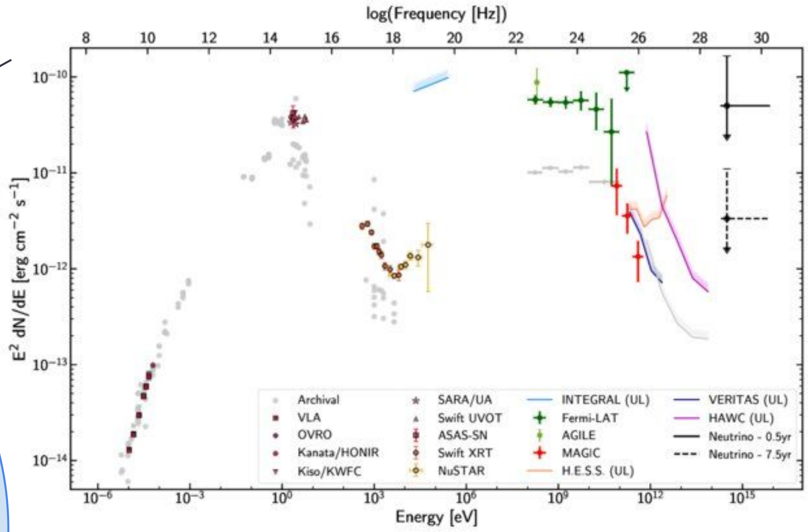


IceCube collaboration 2018, Science



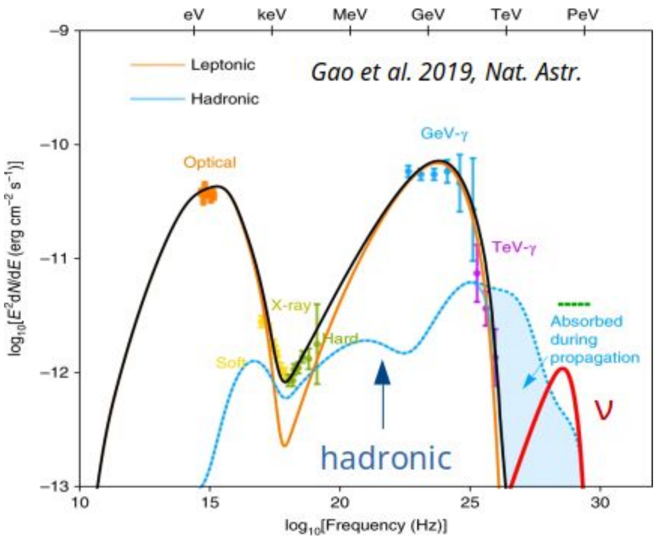
Paiano et al. 2018, ApJL

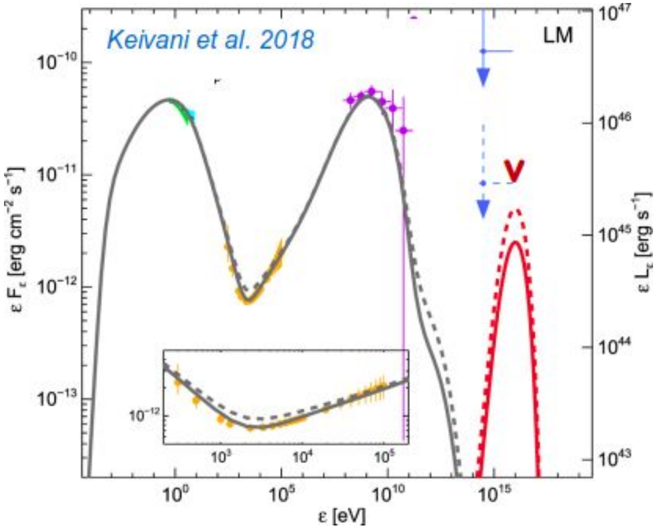




Modeling of the 2017 flare

Ansoldi et al. 2018, Keivani et al. 2018, Murase, Oikonomou, Petropoulou 2018, Cerruti et al. 2019, Gao et al. 2019

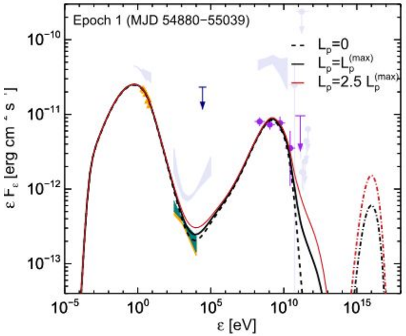




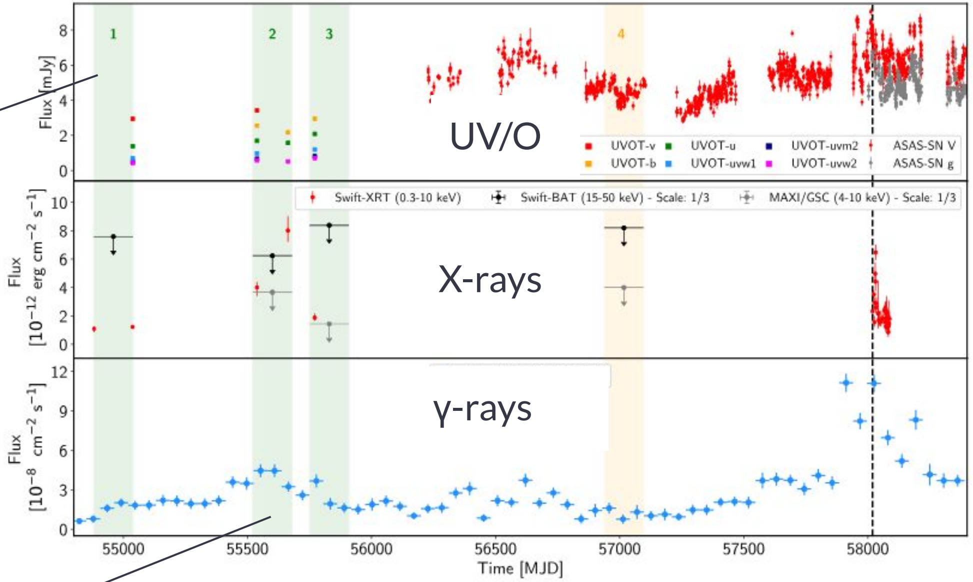
- Leptonic γ-rays → inverse Compton scat. radiation of accelerated electrons
- “Hidden” hadronic emission → **Hybrid model**
- Max. neutrino flux is set by the X-ray flux
- Max. ratio of neutrino-to-γ ray flux **Y ~ 0.03**
- Max. proton energies below EeV → **not an UHECR accelerator**

Check slide 106

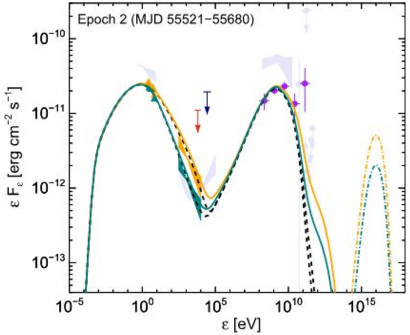
How many ν are expected from other epochs ?



Petropoulou, Murase, Santander et al. (2020) ApJ

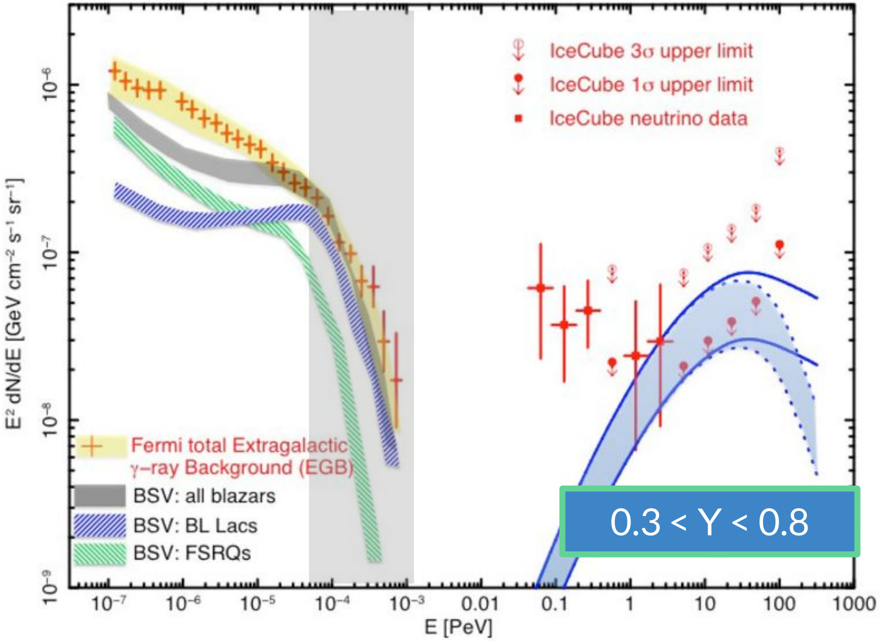


Epoch	$\dot{N}_{\nu_\mu+\bar{\nu}_\mu}$ (yr^{-1})
1	0.04
2[a]	0.2
2[b]	0.1
3	0.2
4	0.1
2017	0.1



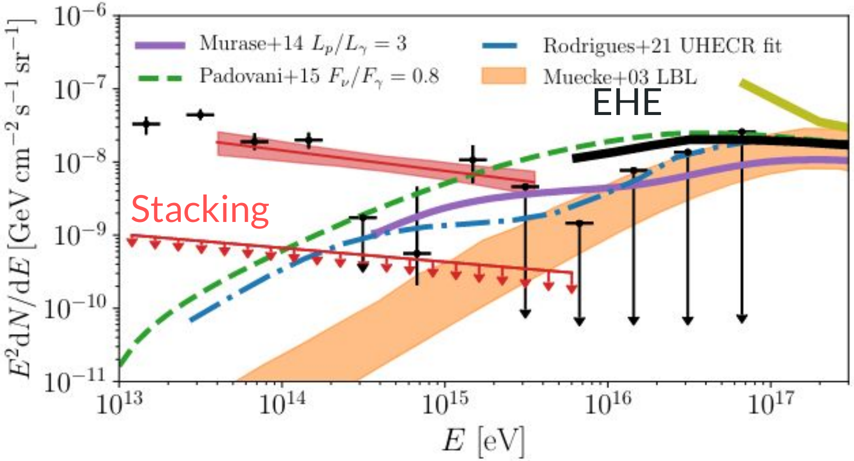
- Synchro-Compton model for all epochs (small changes in power-law index, power of e-)
- Model fails to explain the ν excess in Ep. 4
- Upper limit of **~ 0.4 - 2 muon ν in 10 yr** IceCube obs, **Y < 0.1**
- IceCube-170922A → **upper fluctuation** from average ν rate ?

Diffuse neutrino emission from blazars



Padovani, Petropoulou et al. (2016) MNRAS

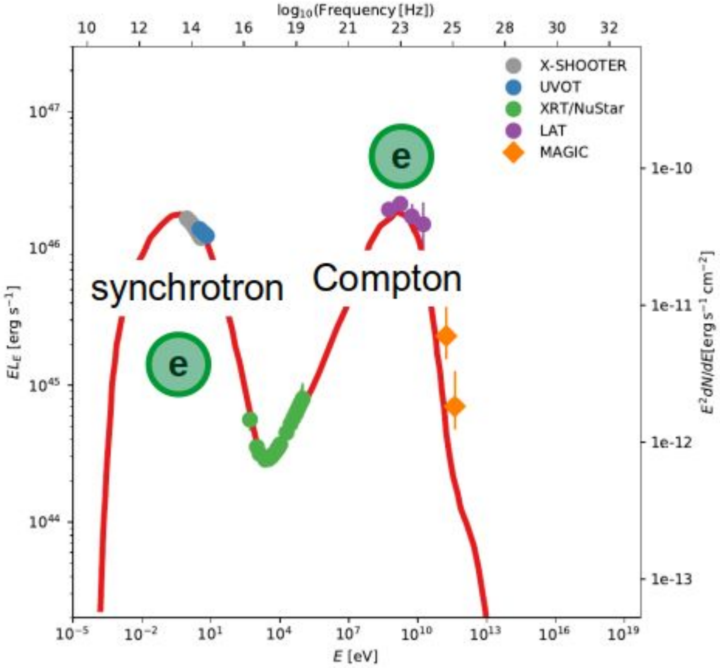
Oikonomou ICRC 21 (arXiv:2201.05623)

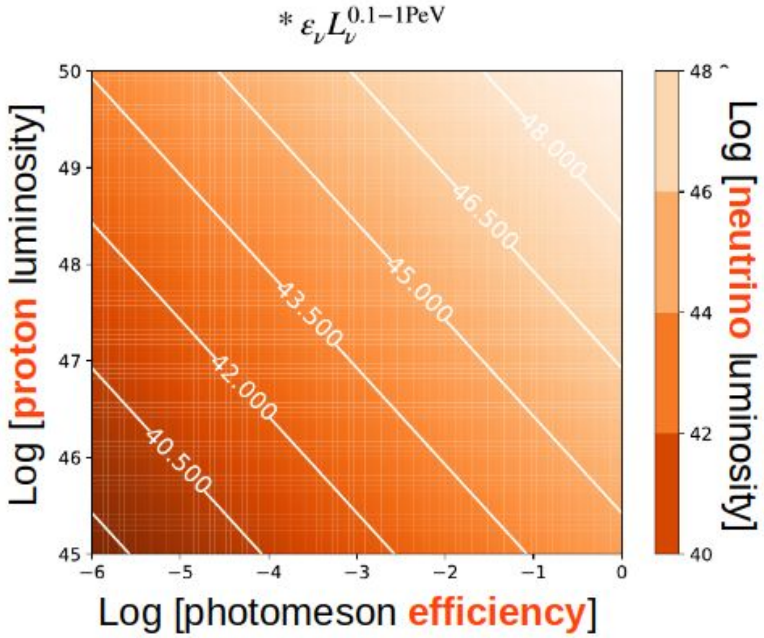


- Blazars (BL Lacs) explain 100% of EGB > 100 GeV and 10% of diffuse ν flux with Y ~ 0.8
- Absence of event clustering → blazar contribution <10-20% to diffuse ν flux
- Stacking limits (Fermi 3LAC) → blazar contribution <5-15% to diffuse ν flux
- IceCube 9yr extreme high-energy (EHE, > 5 PeV) limits → <10-8 GeV cm-2 s-1 sr-1 → **Y < 0.1**

What sets the max ν luminosity ?

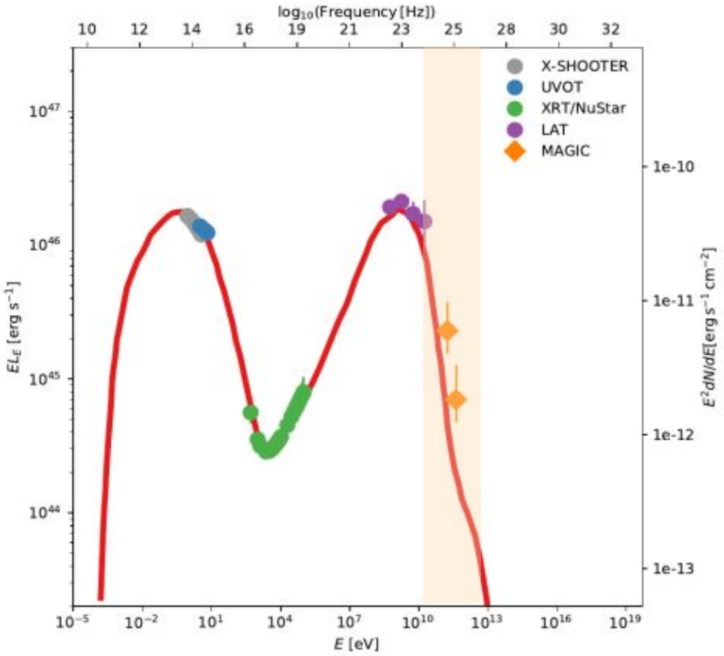
$$\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$$

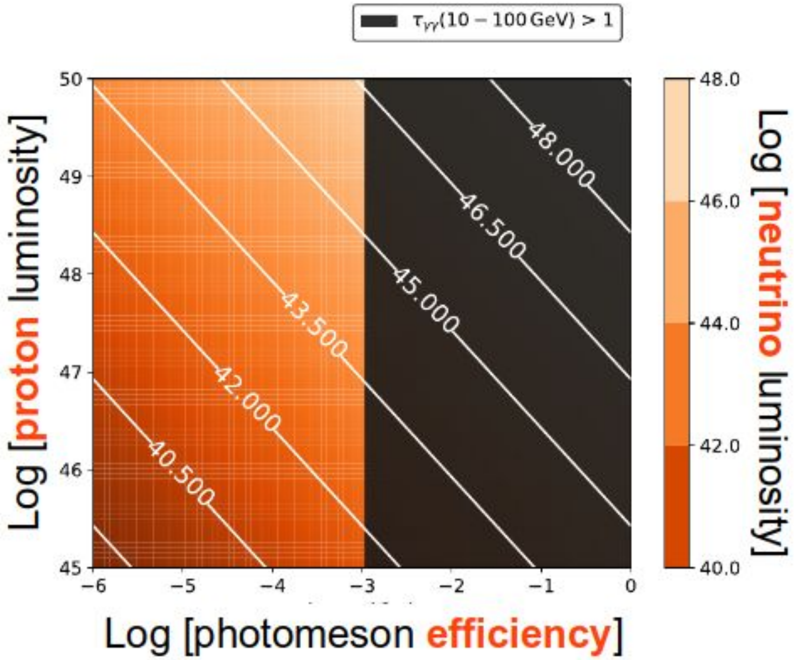




Murase, Oikonomou, Petropoulou (2018), ApJ

What sets the max ν luminosity ?

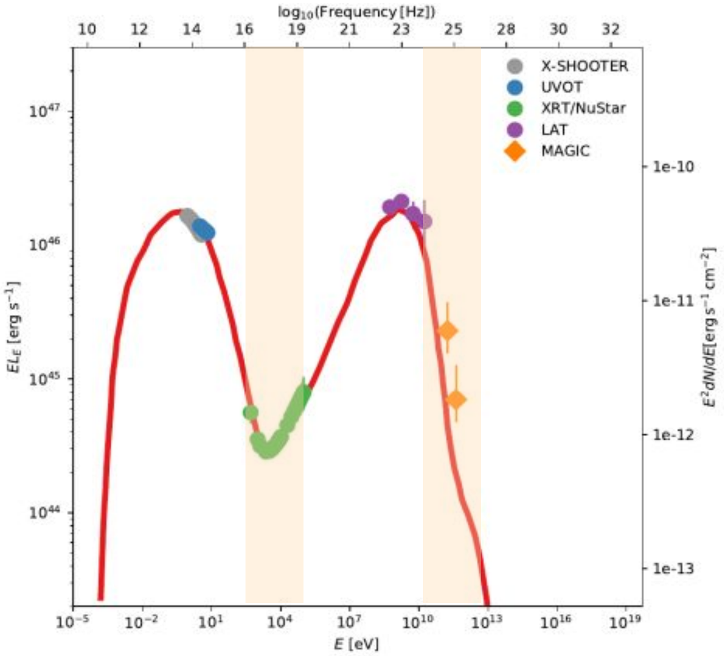


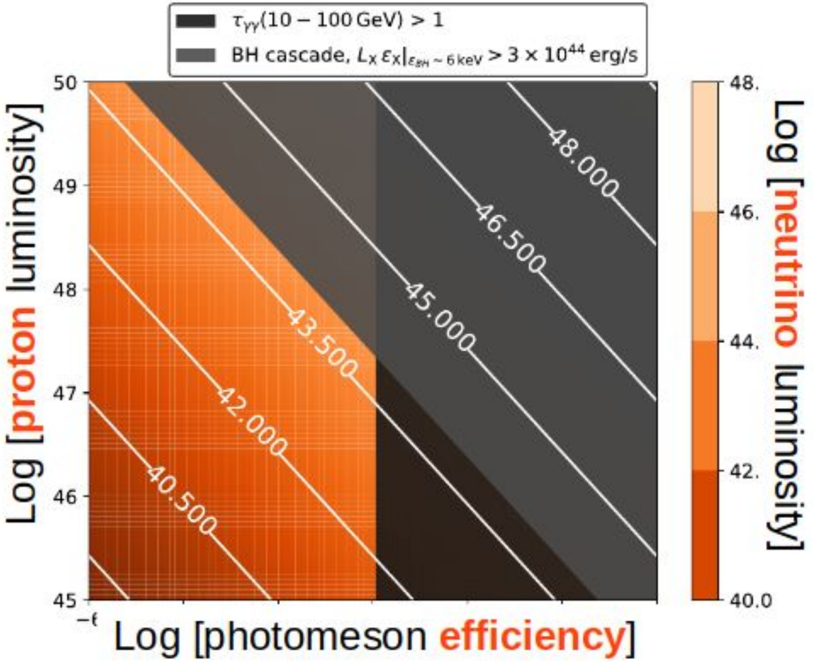


- Optical depth for attenuation of 10 - 100 GeV γ - rays must be low ($\tau_{\gamma\gamma}$ < 1)
- PeV γ-rays are attenuated in source by the synchrotron jet photons

What sets the max ν luminosity ?

$$E_\nu L_{E_\nu} \lesssim 10^{45}\ \mathrm{erg\ s^{-1}}\ \frac{L_{\mathrm{X,lim}}}{3\times10^{44}\ \mathrm{erg\ s^{-1}}}\frac{0.1}{f_x}$$



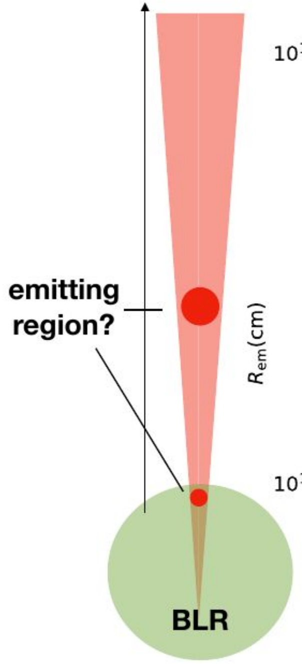


- Synchrotron emission by Bethe-Heitler pairs must not overshoot X-rays

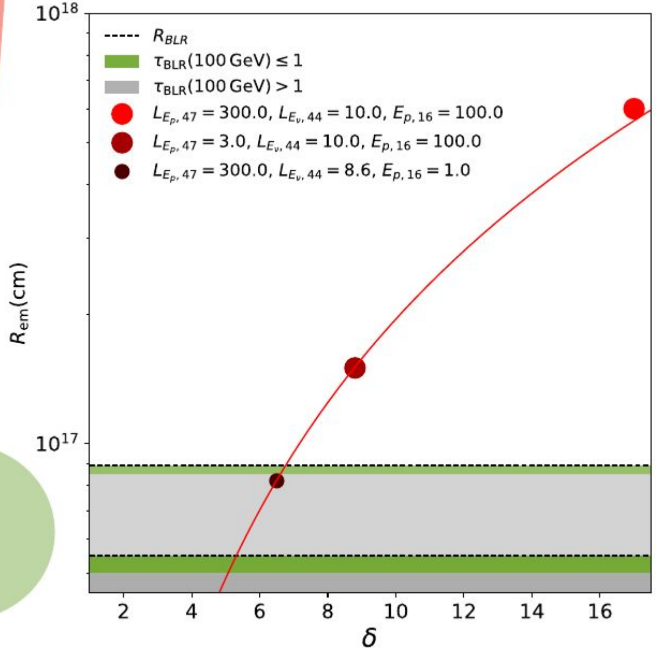
$$\varepsilon_\nu L_{\varepsilon_\nu}^{0.1-1\ \mathrm{PeV}} \sim \varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon_{\mathrm{syn}}^{\mathrm{BH}}} \sim \frac{1}{4} g[\beta] f_{p\gamma}\, \varepsilon_p L_p \leq 3\times10^{44}\ \mathrm{erg/s}$$

$$\varepsilon_{\mathrm{syn}}^{\mathrm{BH}} \approx 6\ \mathrm{keV} B_{0.5\ \mathrm{G}} (\varepsilon_p/6\ \mathrm{PeV})^2 (20/\delta)$$

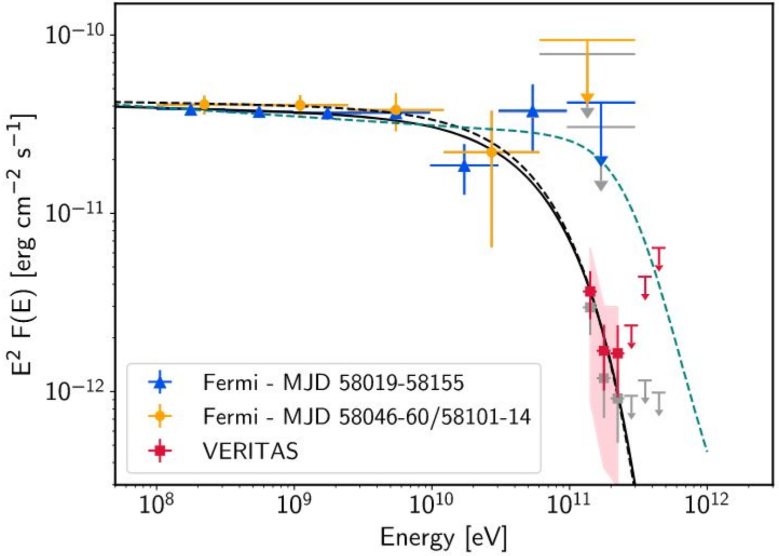
Where is the flaring region located ?



Padovani et al. (2019)



Veritas Collaboration (2018)



- γγ opacity constraints place the flaring region at the outer edge of the BLR
- Max. ν luminosity is independent of the location along the jet
- Proton luminosity increases if the flaring region is located very far from BLR

Why ?

NGC 1068 models: pick your flavor

Different hypotheses

- CR acceleration:
  - Generic mechanism → power law
  - Stochastic acceleration in turbulence (Murase+2020, Murase 2022, Eichmann+2022, Fiorillo+2024b, Lemoine & Rieger 2025, Le Bihan+2026)
  - Diffuse shock acceleration (Inoue et al. 2019, 2024, Eichmann+2022)
  - Magnetic reconnection (Kheirandish+2021, Fiorillo+2024a, Karavola+2025)

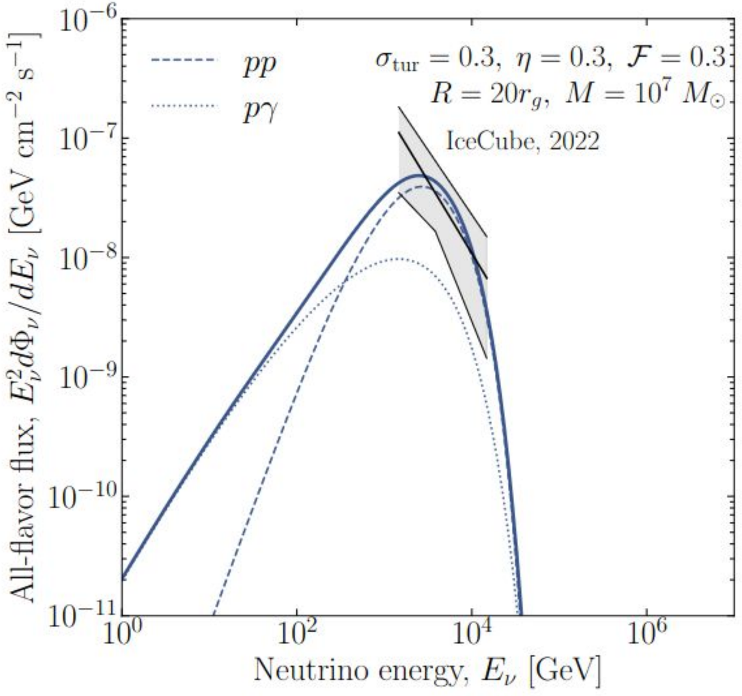
Common findings

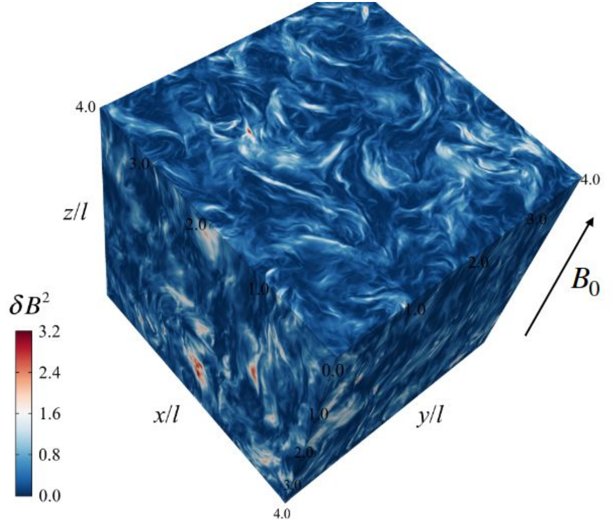
- Neutrino production site:
  - inner disk and/or corona
  - opaque to TeV γ-rays → constraints on coronal size
- GeV γ-rays: starburst
- MeV γ-rays: hadronic cascade

Different findings

- Properties of corona:
  - Pair dominated plasma
  - Electron-proton plasma
  - Plasma magnetization
  - Size

Proposal No. 2: strong turbulence





Main results

- Compact corona: $L \sim 20\ R_g$
- Strong turbulence: $\delta B/B_o \sim 1$
- Electron-proton corona: $n_e/ n_p \sim 1$
- Weakly magnetized corona: $\sigma_e \sim \sigma_p < 1$
- Non-thermal-to-thermal fraction: $\sim 10^{-6}$

For particle acceleration, see: Comisso & Sironi 2019

Fiorillo et al., 2024b, in prep.

Neutrino Emission from AGN corona

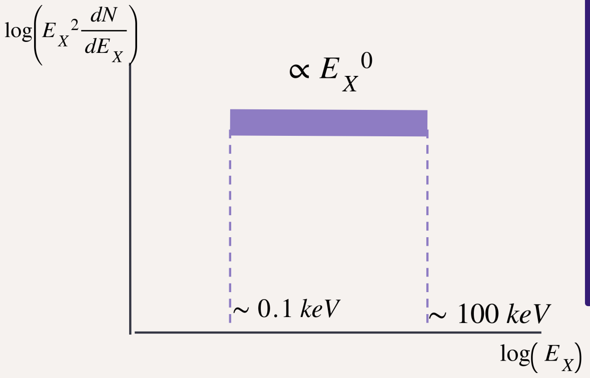
Poynting Flux

Comptonized X-ray Luminosity	Relativistic Proton Luminosity
$L_X = 0.1\,\eta_{X,-1}\,L_{Poyn}$	$L_P = 0.1\,\eta_{P\text{-}1}\,L_{Poyn}$
Corona photon spectrum	Accelerated proton spectrum

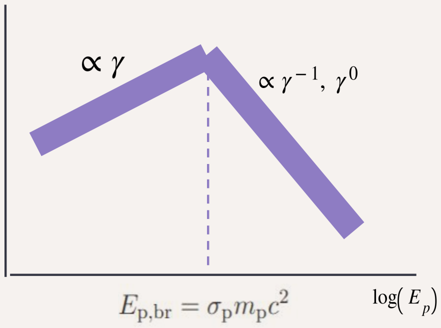
p-*γ* collisions

Neutrino spectrum

Corona Photon Spectrum



Acc. Proton Spectrum



Key Parameters:

$$\lambda = \frac{L_X}{L_{Edd}} \propto \frac{L_X}{M_{BH}}$$

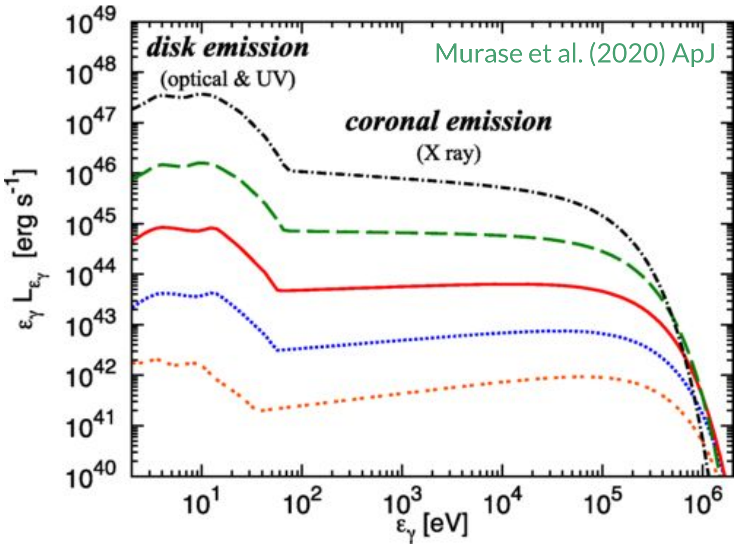
$$\sigma_p = \frac{B^2}{4\pi n_p m_p c^2}$$

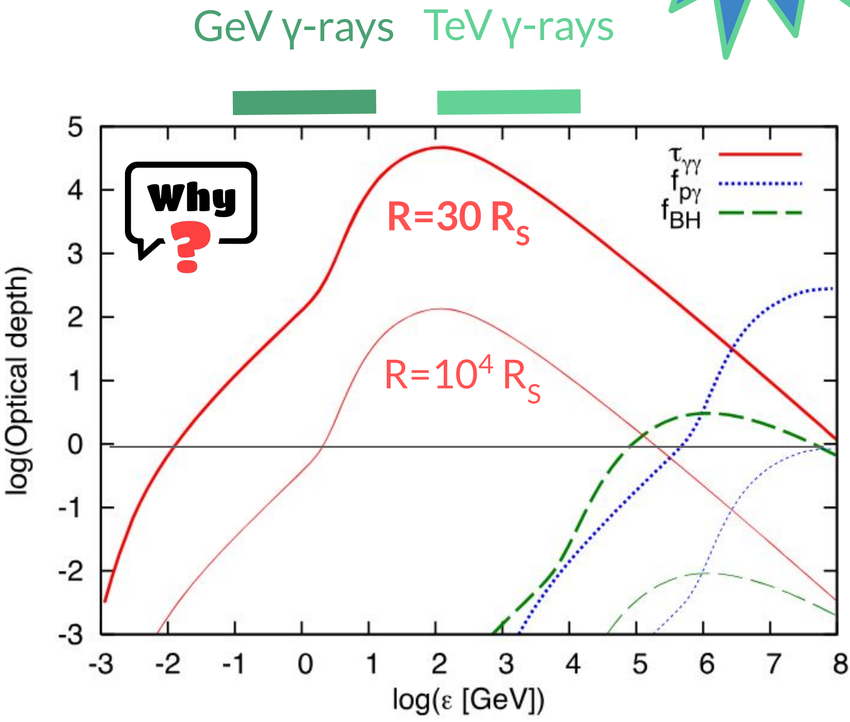
What can we learn from the non-detection of TeV γ-rays?

Lab Exercise

Energy threshold for γγ → e+e-: $\frac{E_\gamma}{GeV} \cdot \frac{E_s}{keV} \geq 0.25$

Number density of photons: $\varepsilon_\gamma \cdot n_{\varepsilon_\gamma} \approx \frac{3\,L_{\varepsilon_\gamma}}{4\pi R^2 c}$



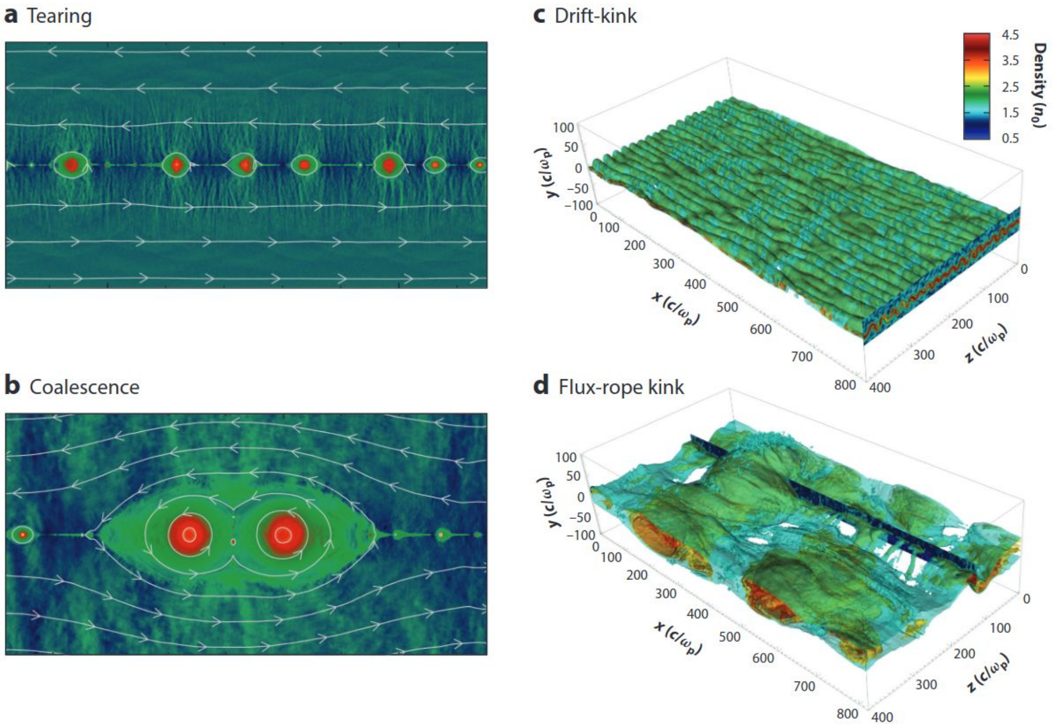


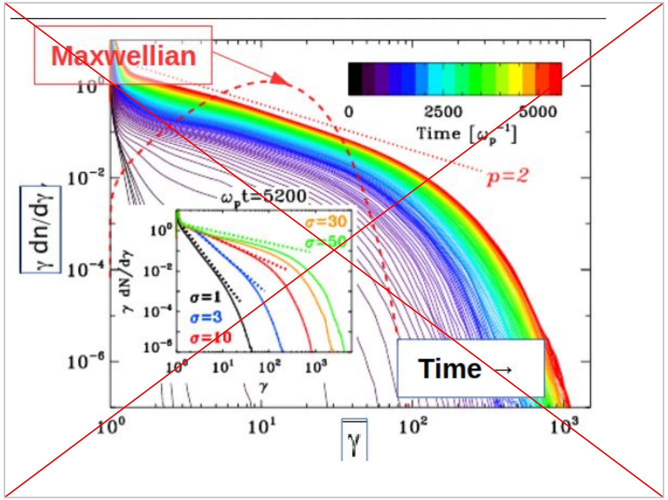
Murase (2022) ApJ

Relativistic magnetic reconnection

Key Parameter:
Plasma Magnetization

$$\sigma = \frac{B^2}{4\pi \rho c^2}$$



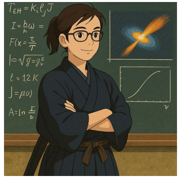


Credit: H. Hakobyan

Recent review: Sironi, Uzdensky, Giannios (2025), ARA&A, Vol. 63

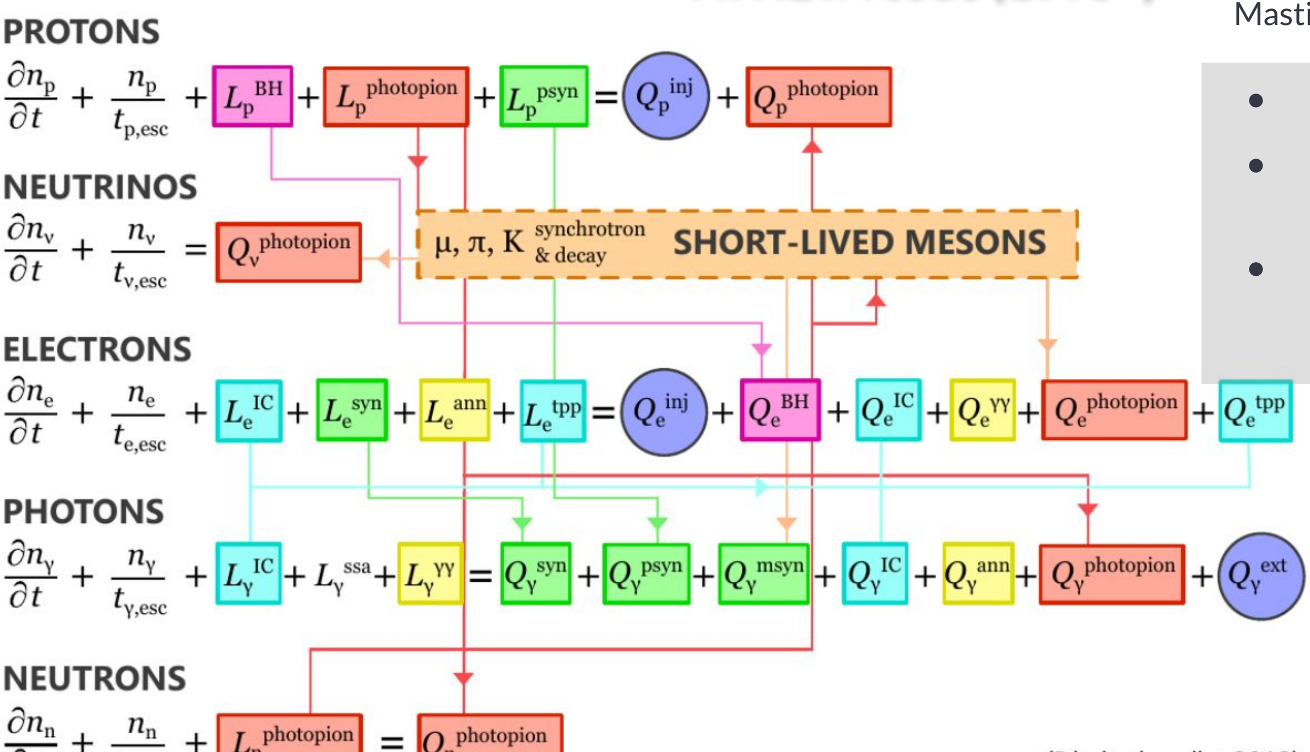
Numerical codes - 1





Mastichiadis/Dimitrakoudis/Petropoulou

ATHEvA code (1995 -)



(Dimitrakoudis+2012)

PROs

- Time-dependent
- Feedback of secondaries on primaries is included
- Modeling of optically thick sources and non-linear electromagnetic cascades

CONs

- Proprietary
- Fortran 77 (relying on old libraries)
- Long execution times, not designed for fitting

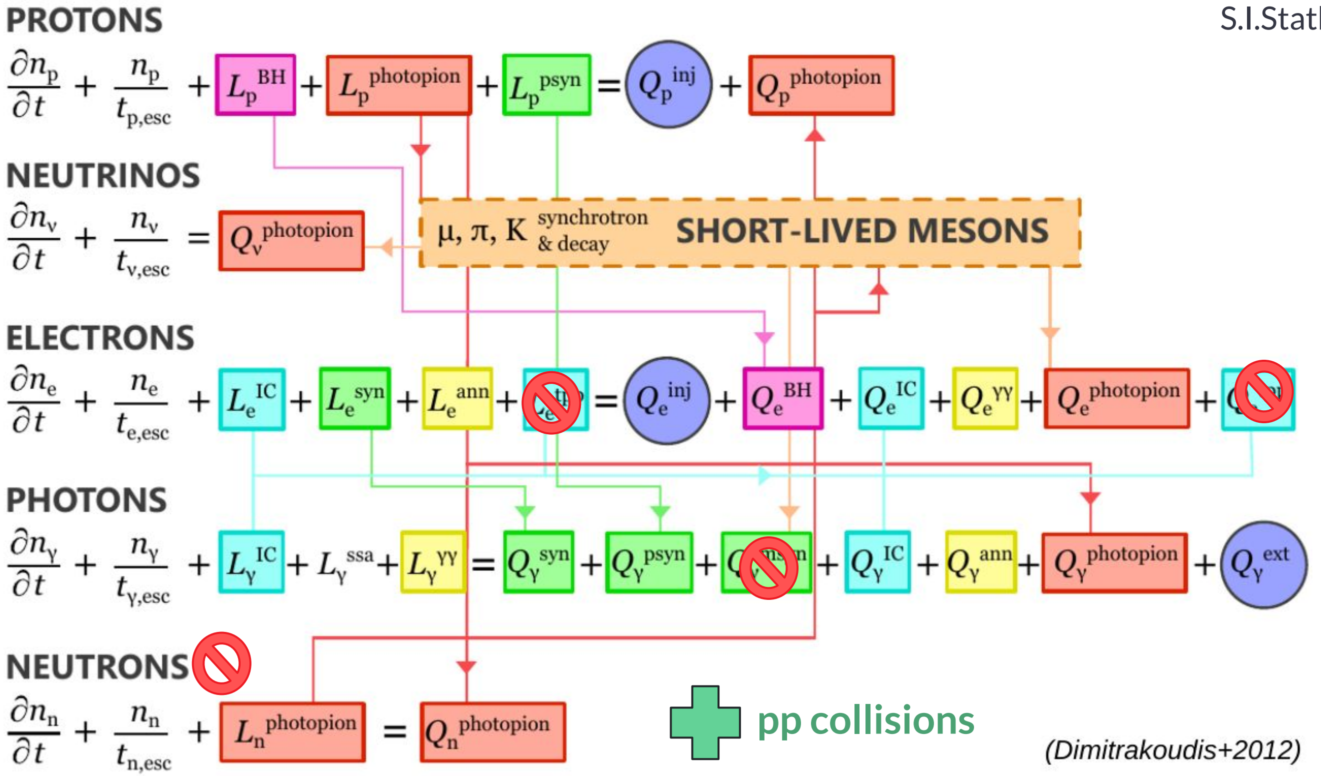
Numerical codes - 2

LeHaMoC (2024 -)

S.I.Stathopoulos

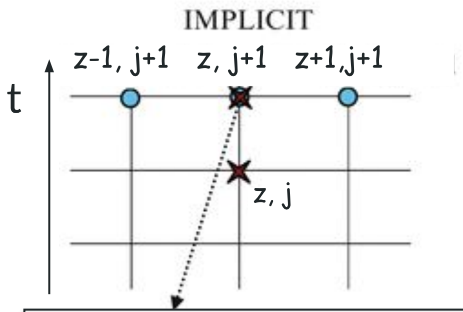
TRY...

Stathopoulos et al. 2024



- Time-dependent **PROs**
- Feedback of secondaries on primaries is included
- Modeling of optically thick sources and non-linear electromagnetic cascades
- Public code in Python
- Short execution times (~1 sec for leptonic, ~20 sec for hadronic)
- MCMC fitting

Numerical scheme for solving PDEs



Common point
for time and energy difference

Points involved in time difference

Points involved in energy difference

- Faster computational time
- No constraints on time step for stationary solutions
- Unconditional stable

Chang & Cooper (1970)

PDE for particle species *i*

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial x}(\mathcal{P}_i(x,t)N_i) + \frac{N_i}{t^i_{esc}(t)} = Q_i$$

$$\frac{\partial N_i}{\partial t} = \frac{N^{j+1}_{i,z} - N^j_{i,z}}{\Delta t}$$

(Euler's Method)

$$\frac{\partial}{\partial x}(\mathcal{P}_i(x,t)N_i) = \frac{F^{j+1}_{i,z+\frac{1}{2}} - F^{j+1}_{i,z-\frac{1}{2}}}{\Delta x}, \quad F^{j+1}_{i,z\pm\frac{1}{2}} \equiv \mathcal{P}_i(x_{z\pm\frac{1}{2}}, t^j)N^{j+1}_{i,z\pm\frac{1}{2}}$$

(Fluxes at mid-points)

$$V1_{i,z}N^{j+1}_{i,z-1} + V2_{i,z}N^{j+1}_{i,z} + V3_{i,z}N^{j+1}_{i,z+1} = S^j_{i,z}$$

$$S^j_{i,z} = N^j_{i,z} + Q^j_{i,z}\Delta t$$

$$V1_{i,z} = 0$$

$$V2_{i,z} = 1 + \frac{\Delta t}{t_{i,esc}} + \frac{\Delta t}{\Delta \gamma_z}\sum_p \left(\frac{d\gamma_i}{dt}\right)^{j+1}_{p,z}$$

$$V3_{i,z} = -\frac{\Delta t}{\Delta \gamma_z}\sum_p \left(\frac{d\gamma_i}{dt}\right)_{p,z+1}$$

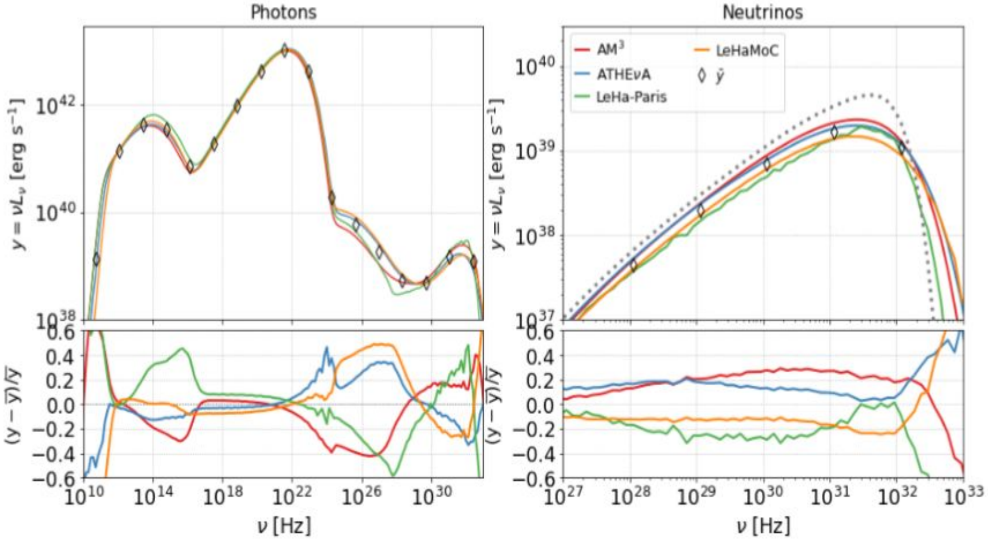
Tridiagonal matrix
(Thomas, L. H. 1949)

The Hadronic Code Comparison Project

A Comprehensive Hadronic Code Comparison for Active Galactic Nuclei

Matteo Cerruti[1], Annika Rudolph[2,3], Maria Petropoulou[4,5], Markus Böttcher[6], Stamatios I. Stathopoulos[4,5], Foteini Oikonomou[7], Stavros Dimitrakoudis[4,5], Anton Dmytriiev[8], Shan Gao[2], Susumu Inoue[9,10,11], Apostolos Mastichiadis[12], Kohta Murase[13,14], Anita Reimer[15], Joshua Robinson[6], Xavier Rodrigues[16,17], Walter Winter[2] and Andreas Zech[8]

Cerruti et al., under review ApJS (arXiv:2411.14218)



Codes				
AM^3	ATHEνA	B13	LeHa-Paris	LeHaMoC

- First comparison of codes used in source modeling
- Determine & quantify systematics
- Help to evaluate modeling results

The only time-dependent leptohadronic public codes