IV PHD SUMMER SCHOOL ON

NEUTRINOS

HERE, THERE & EVERYWHERE

Neutrino Astrophysics & Astronomy

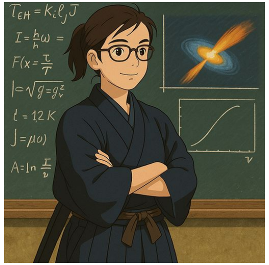
with a focus on High-Energy Sources

July 7 - 11 2025

Maria Petropoulou

HELLENIC REPUBLIC
National and Kapodistrian
University of Athens

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
  - Neutrinos from stellar cores (MeV scale)
  - Neutrinos from high-energy compact sources (TeV - PeV scale)
  - Neutrinos from cosmic-ray propagation (EeV scale)
- **Lecture 2:** High-Energy Neutrinos from Compact Sources
  - Theoretical background
  - Active galactic nuclei (AGN)
  - Numerical codes for source modeling
- **Lecture 3:** Extragalactic Neutrinos in a Multi-messenger Context
  - AGN multi-messenger models
  - Multi-messenger case studies: TXS 0506+056, NGC 1068
  - Open questions & prospects

Goals

- Build intuition about the origin of astrophysical neutrinos from MeV to EeV energy scales

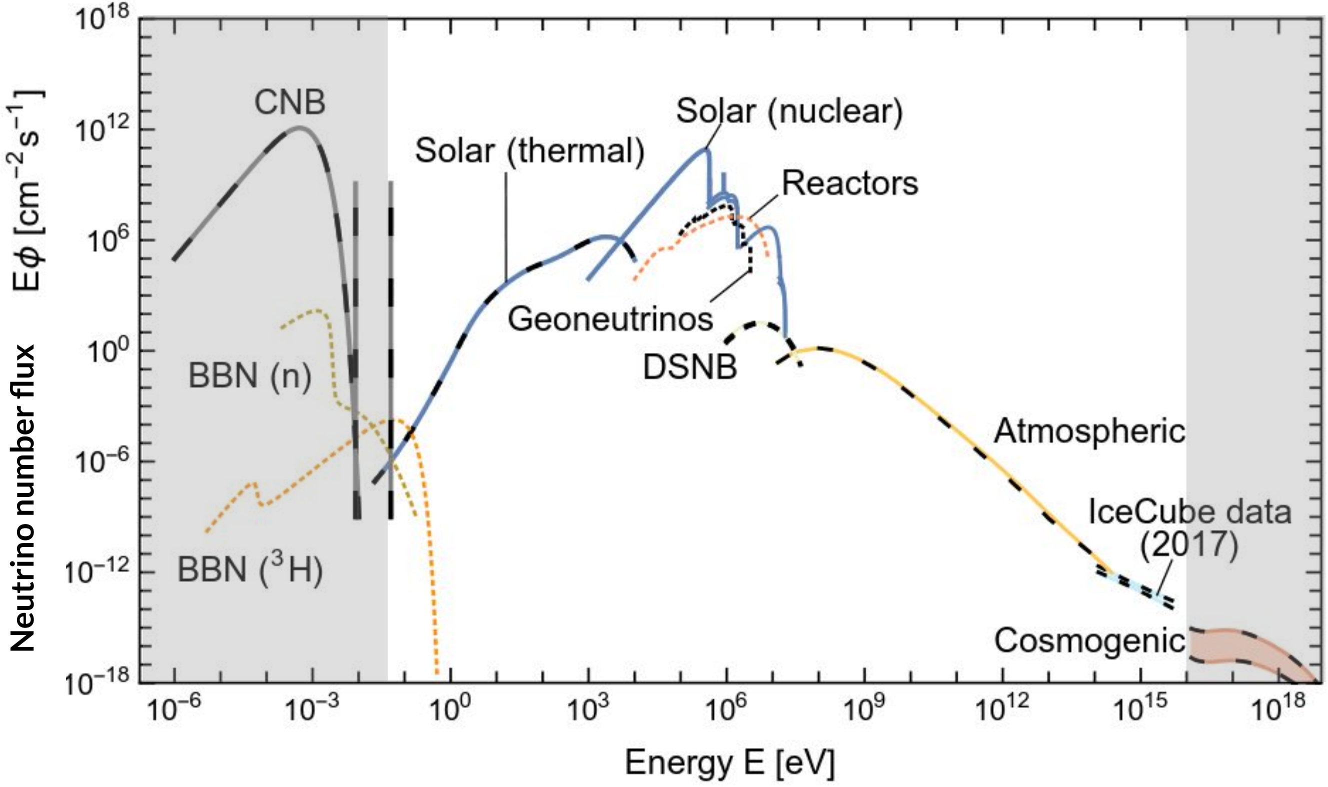
- Focus on physical conditions leading to neutrino production in compact sources, such as AGN and GRBs, and familiarize with source modeling

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

Lecture 1

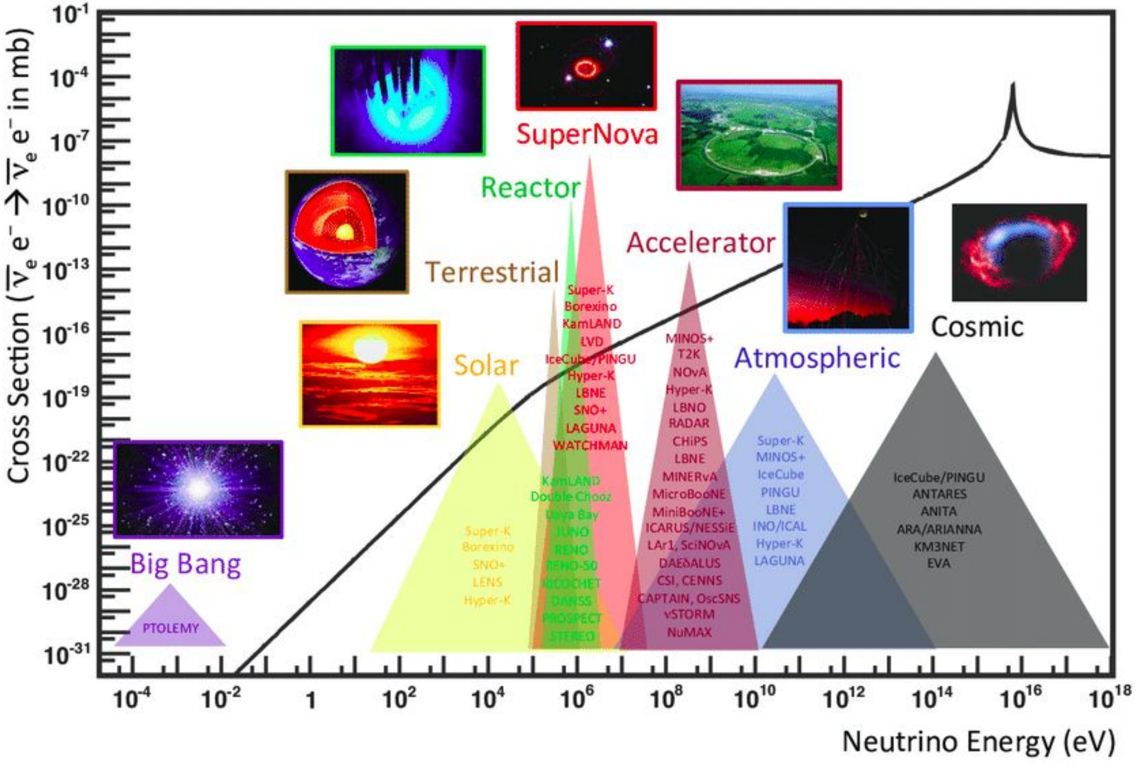
Astrophysical Origins of Neutrinos

Here, There & Everywhere



Vitagliano, Tamborra, Raffelt (2020)

Neutrino cross section



- The cross section of neutrino-electron scattering for solar neutrinos (~0.1 MeV) is about **10^{22}** times smaller than electron Thomson cross section (photon-electron scattering) !!!

- Extremely small cross sections → detection challenging

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

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:

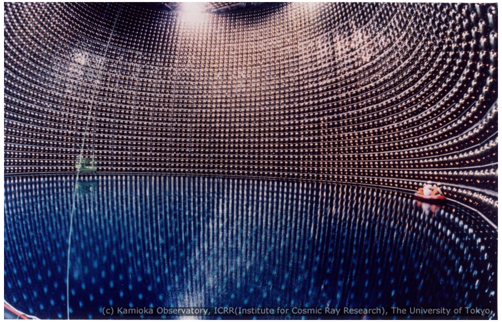
$$R = N_t \cdot \sigma_{\nu e} \cdot E\varphi_E\Big|_{E=0.1MeV}$$

Number of target e-:

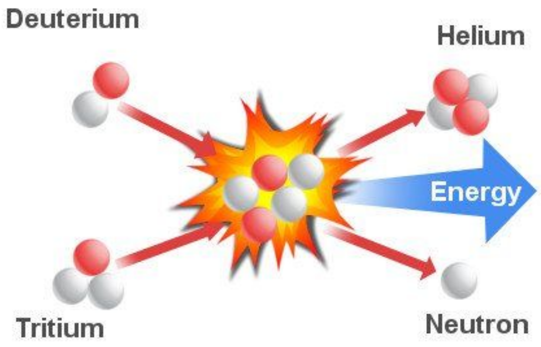
$$N_t \approx 10^{31}\left(\frac{R}{10\ d^{-1}}\right)$$

For water detector (1 ton → 3e29 e-):

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

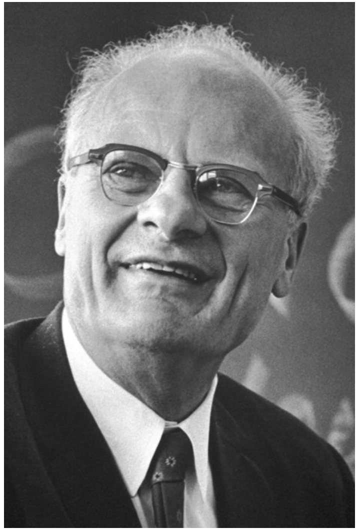


What is the energy source of stars ?



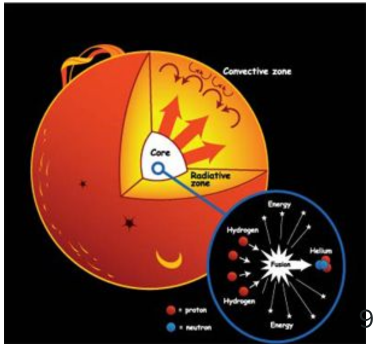
Fusion

In 1938 Hans Bethe showed that nuclear fusion of H to He can produce large amounts of energy needed to explain the high luminosity of the Sun (~ 2e+33 erg/s) for billions of years!



Nobel Prize in Physics 1967 To Hans A. Bethe

“for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars”



Rate of nuclear interactions

What are the main ingredients we need for calculating the rate of nuclear interactions between species i and x ?

Number density of nuclear species i

Number density of nuclear species x

$$r_{ix} = \left(\frac{2}{kT}\right)^{3/2} \frac{n_i n_x}{(\mu_m \pi)^{1/2}} \int_0^\infty S(E)\, e^{-bE^{-1/2}} e^{-E/kT}\, dE.$$

Temperature

Term related to the non-zero probability of overcoming the Coulomb barrier due to quantum tunneling

High-energy tail of the thermal distribution of nuclei (Maxwell-Boltzmann)

Units: $s^{-1}\ cm^{-3}$

Rate of nuclear interactions

Energy production rate per unit mass: $\boldsymbol{\varepsilon_{ix}}$ **(erg s^{-1} g^{-1})**

Interaction rate per volume

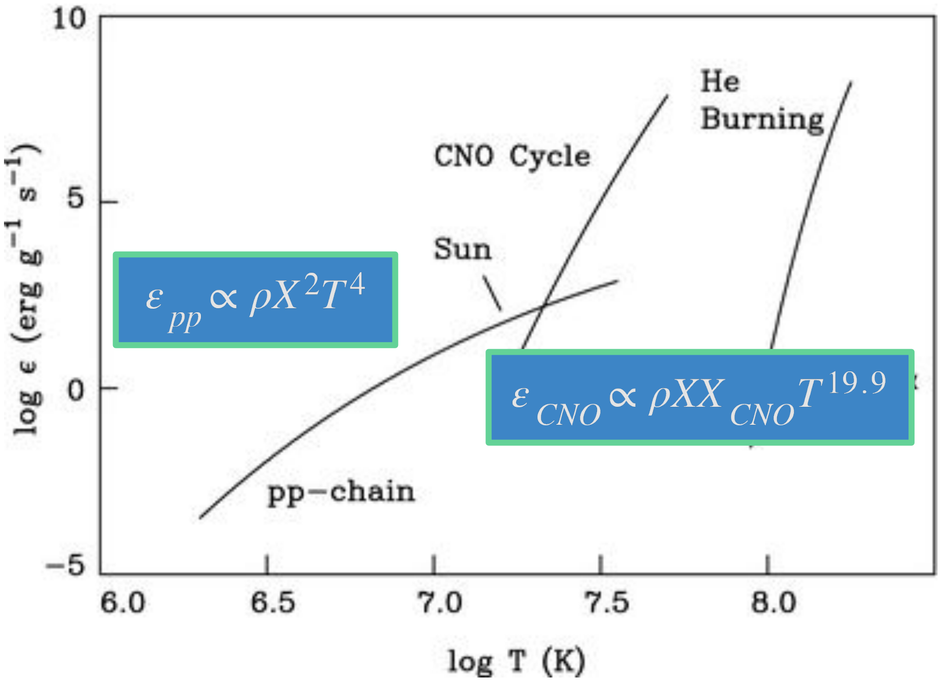
Energy released per interaction

$$\epsilon_{ix} = \left(\frac{\mathcal{E}_0}{\rho}\right) r_{ix}$$

Mass density

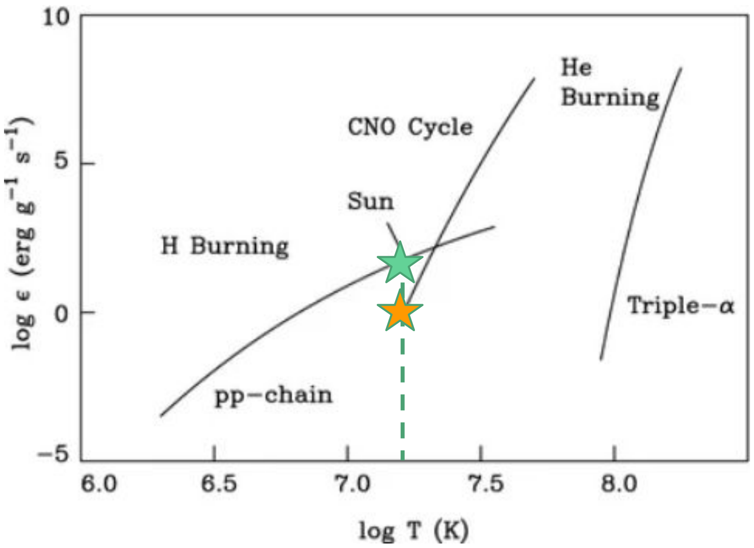
Usually, the energy production rate is expressed as:

$$\epsilon_{ix} = \epsilon_0' X_i X_x \rho^\alpha T^\beta$$

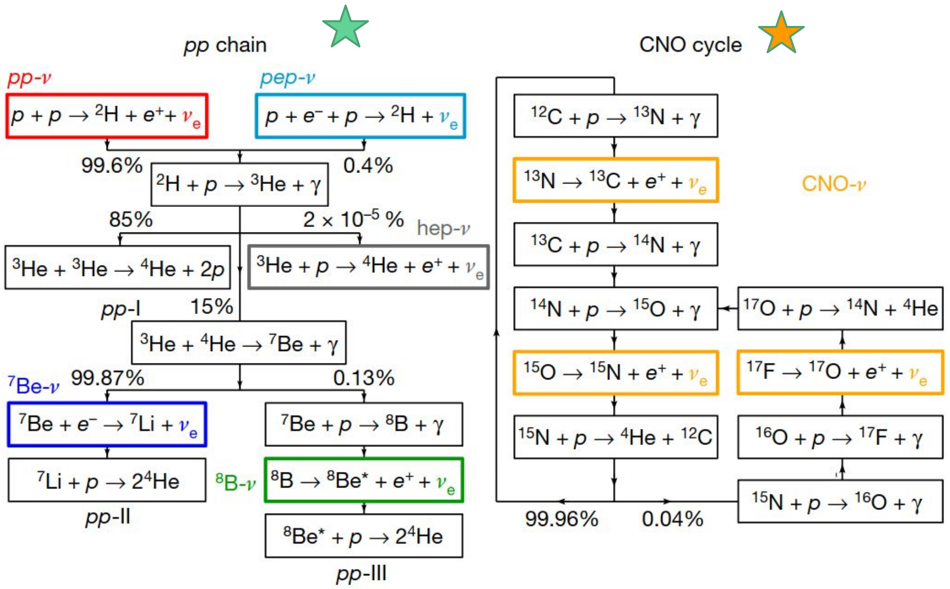


Walter J. Maciel, *Introduction to Stellar Structure*, Springer

Solar neutrinos: how are they produced ?



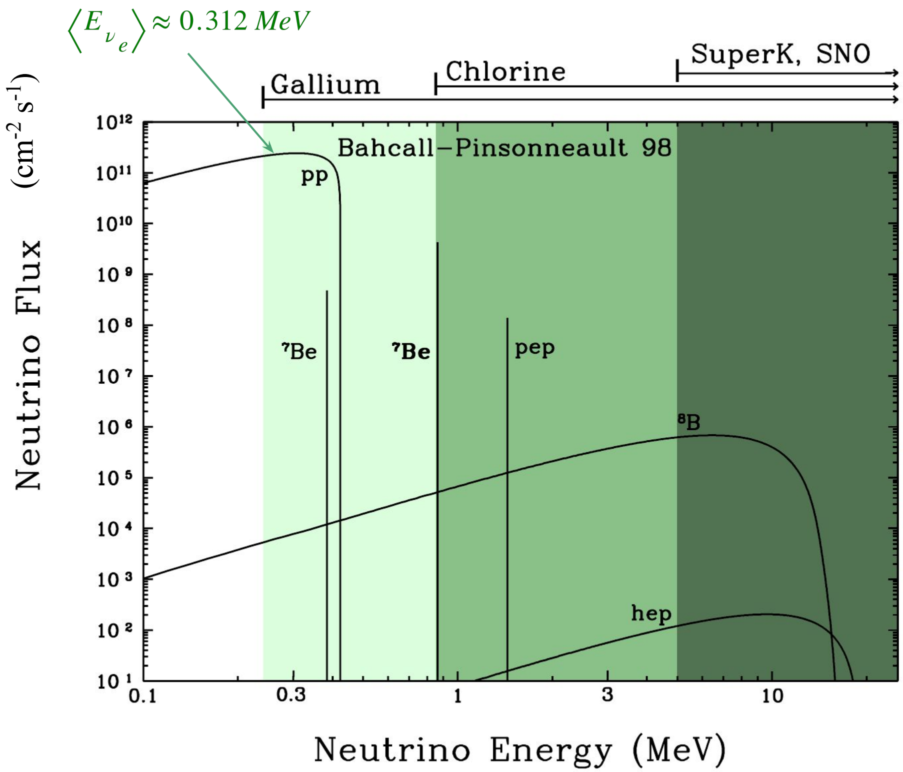
Maciel, W.J. (2016)

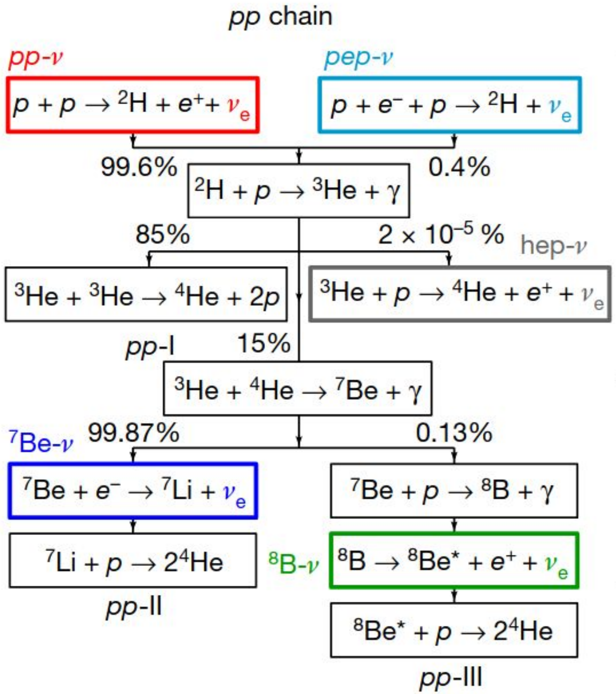


The Borexino Collaboration (2018)

The solar neutrino spectrum

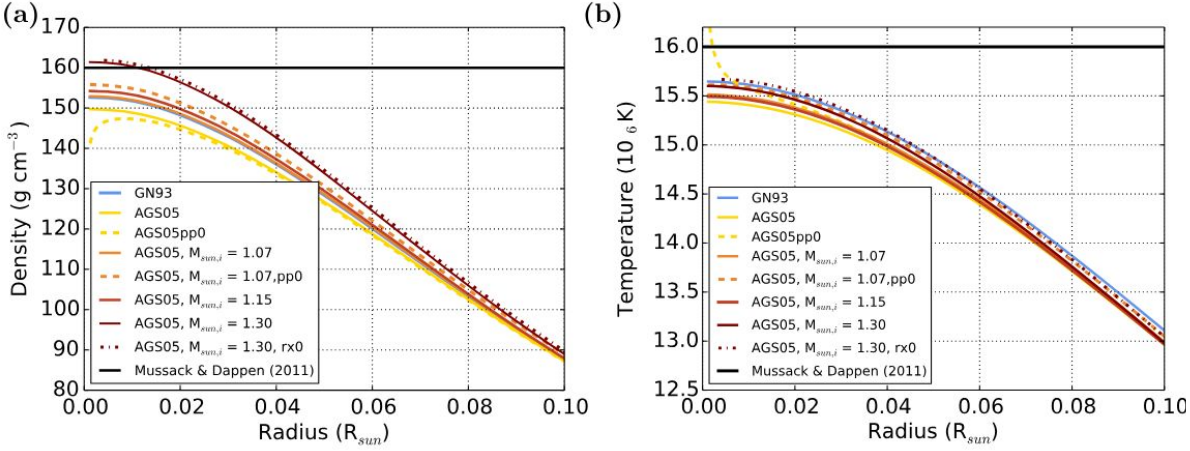
Detectors with different targets probe different ν production channels

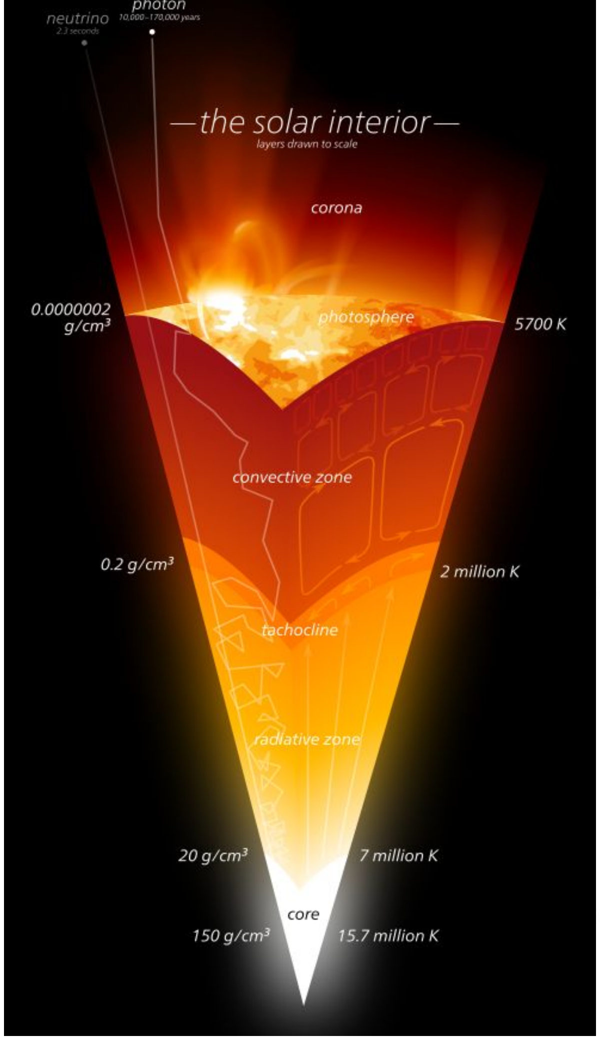




Radial dependence of ν production

Solar models: radial profiles of density and temperature

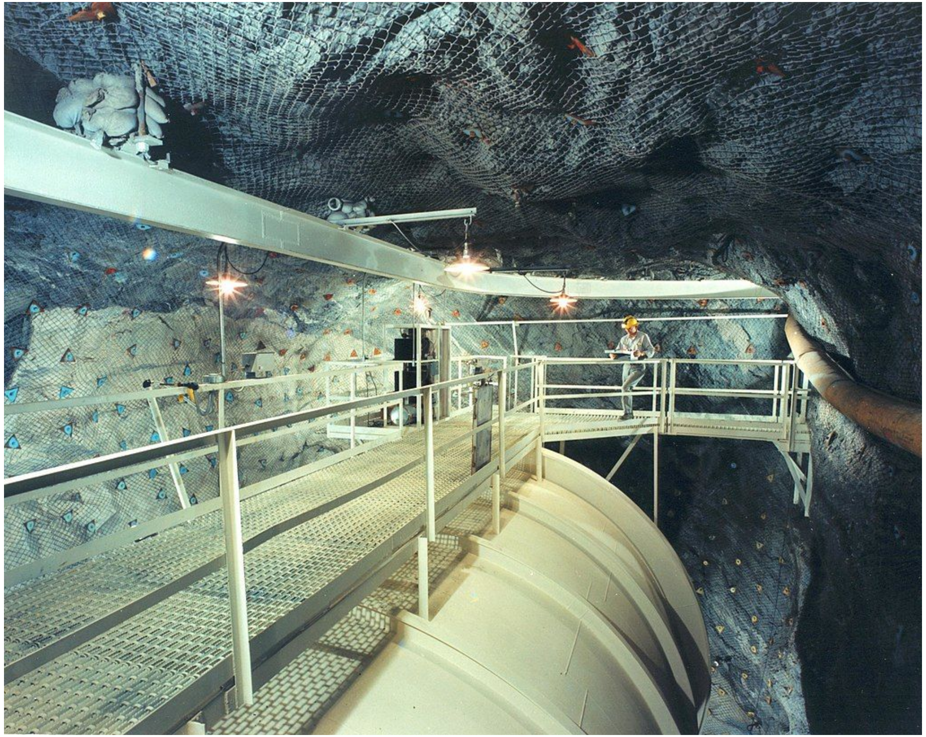


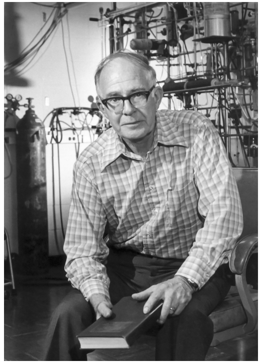


Blue-yellow: standard solar models
Orange-maroon: non-standard solar models (with mass loss)

Wood, S. R. (2018)

Davis experiment (1970-1994)



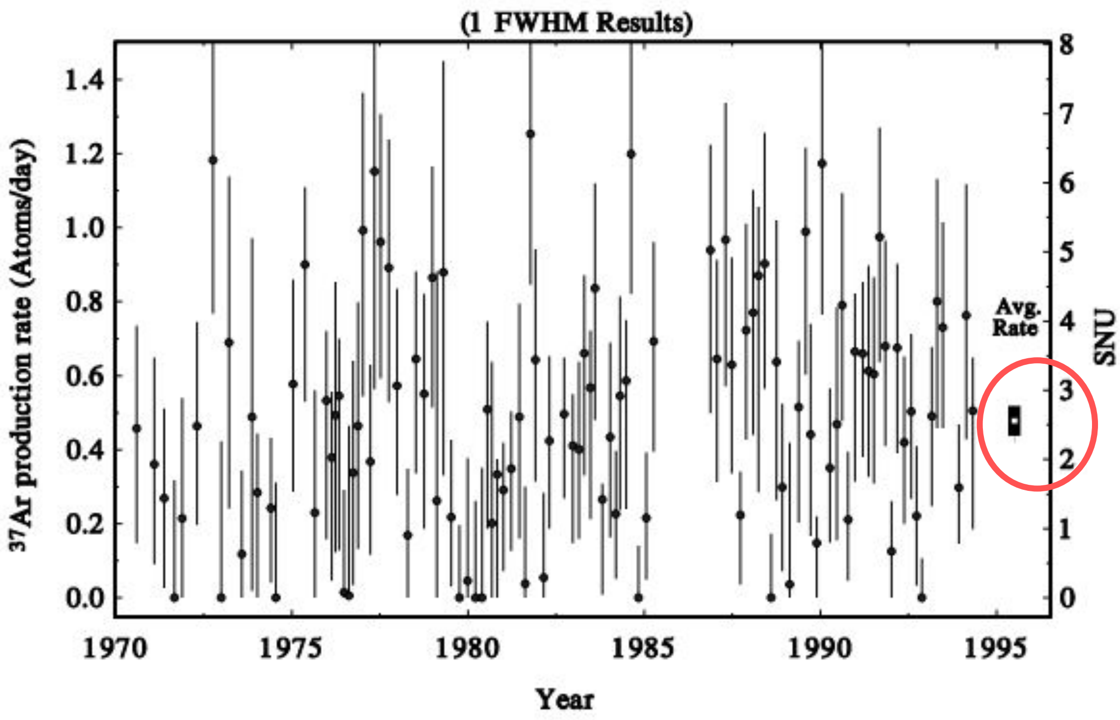


- 1st experiment for solar neutrino detection
- Designed by R. Davis (1965)
- Mining site (~1.5 km depth), South Dakota, USA
- Detection method: $\nu_e + {}^{37}_{17}Cl \rightarrow e^- + {}^{37}_{18}Ar$
- Radiochemical experiment

- Tank with 610 tons liquid C_2Cl_4 → **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

Video link

Results from Davis experiment (1970-1994)



solar neutrino unit or SNU
(1 SNU ≡ 10^{-36} interactions/atom/sec)

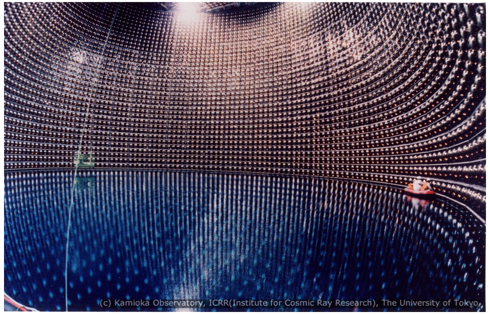
John Bahcall calculated theoretically the ν detection rate from Davis experiment based on the standard solar model and found ~7.9 SNU

The average SNU from Davis experiment was ~ 3 times lower than predicted!!

Cleveland et al. (1998)

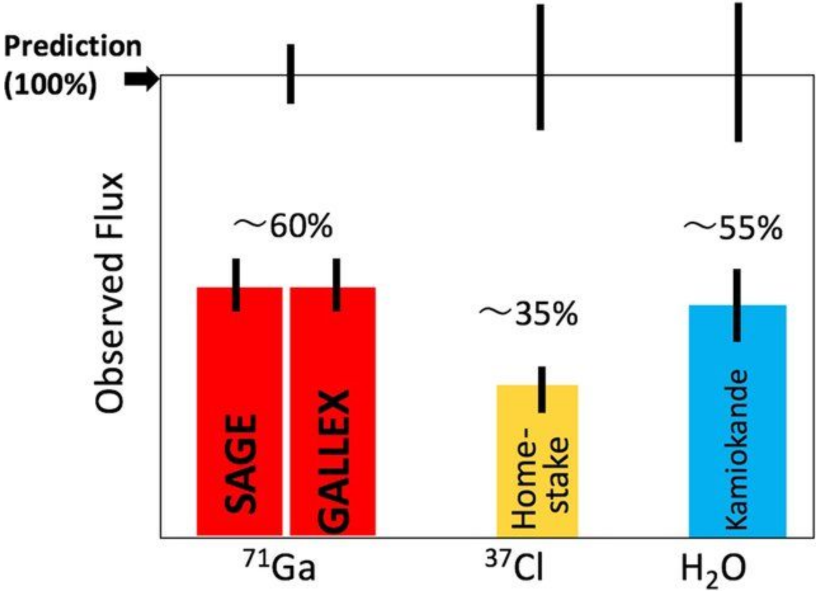
The missing ν problem

Super-Kamiokande (water) - Japan

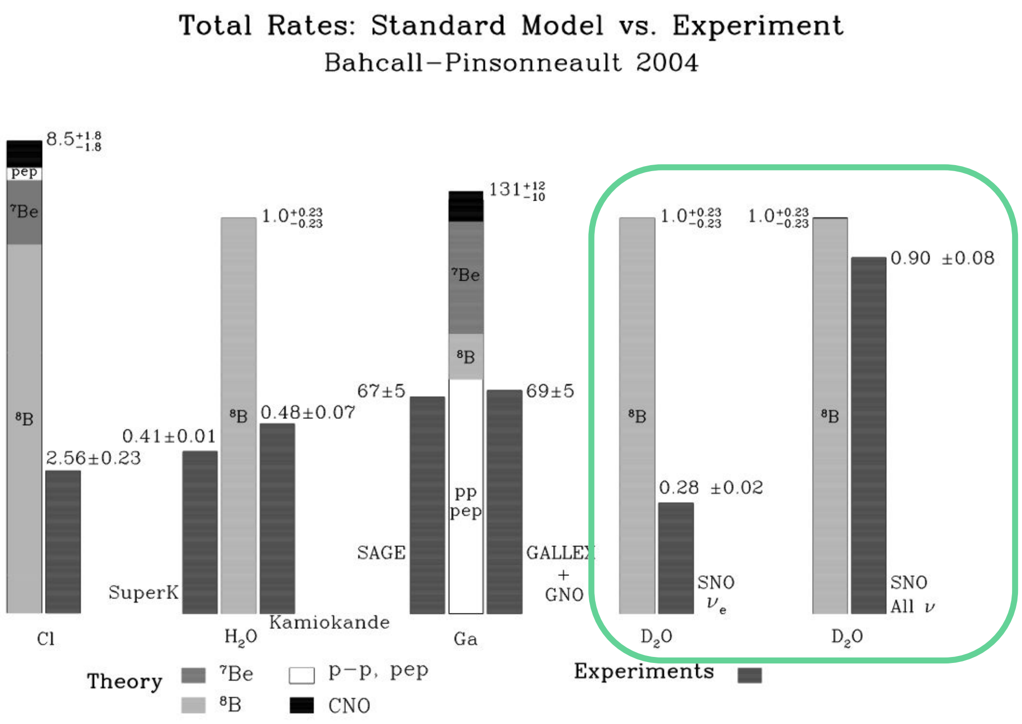


GALLEX (Gallium) - Gran Sasso Italy

4 experiments with different target material confirm the missing neutrino flux problem

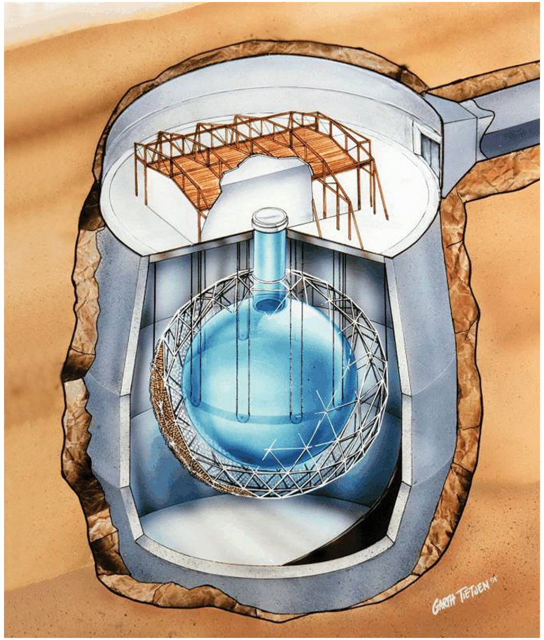


The missing ν problem (not anymore)



Sudbury Neutrino Observatory (SNO)

- Location: Canada
- Target: heavy water experiment
- Sensitive to all ν flavors
- First results in 2001



Neutrino oscillations

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

- 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

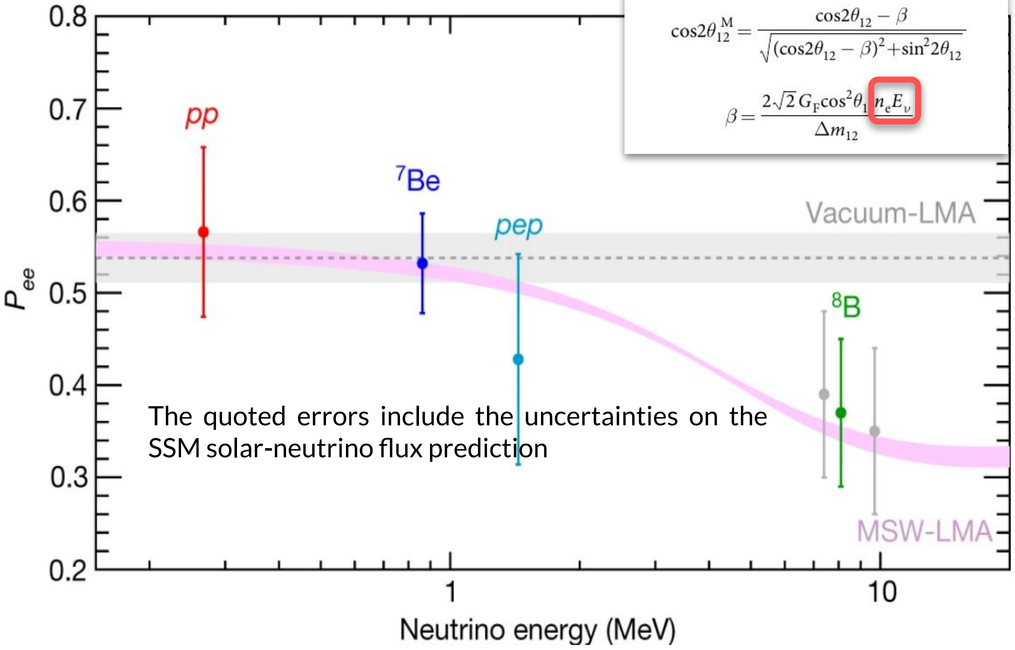
$$P_{\alpha\to\beta} = \left|\langle \nu_\beta \,|\, \nu_\alpha(L)\rangle\right|^2 = \left|\sum_j U^*_{\alpha j}\, U_{\beta j}\, e^{-im_j^2 L/(2E)}\right|^2 .$$

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

$$P_{ee}^{\text{MSW-LMA}} = \frac{1}{2}\cos^4\theta_{13}(1+\cos 2\theta_{12}^{M}\cos 2\theta_{12})$$

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

$$\beta = \frac{2\sqrt{2}\,G_F\cos^2\theta_{13}\,n_e E_\nu}{\Delta m_{12}}$$



The Borexino Collaboration (2018)

Nobel Prizes

The Nobel Prize in Physics 2002

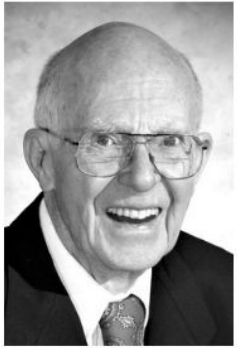


Photo from the Nobel Foundation archive.

Raymond Davis Jr.

Prize share: 1/4

Photo from the Nobel Foundation archive.

Masatoshi Koshiba

Prize share: 1/4

Photo from the Nobel Foundation archive.

Riccardo Giacconi

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."*

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

The Nobel Prize in Physics 2015

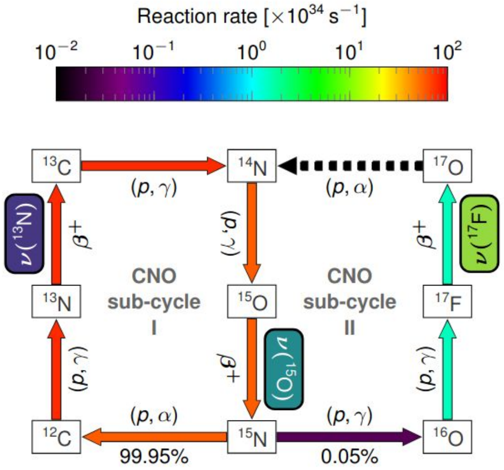
Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

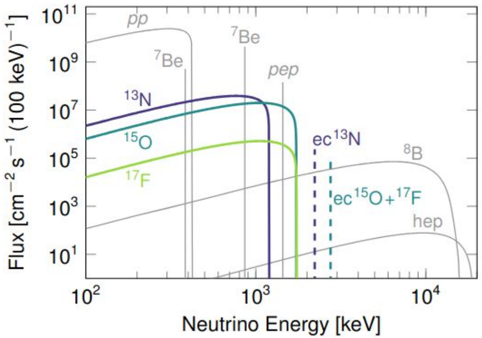
and

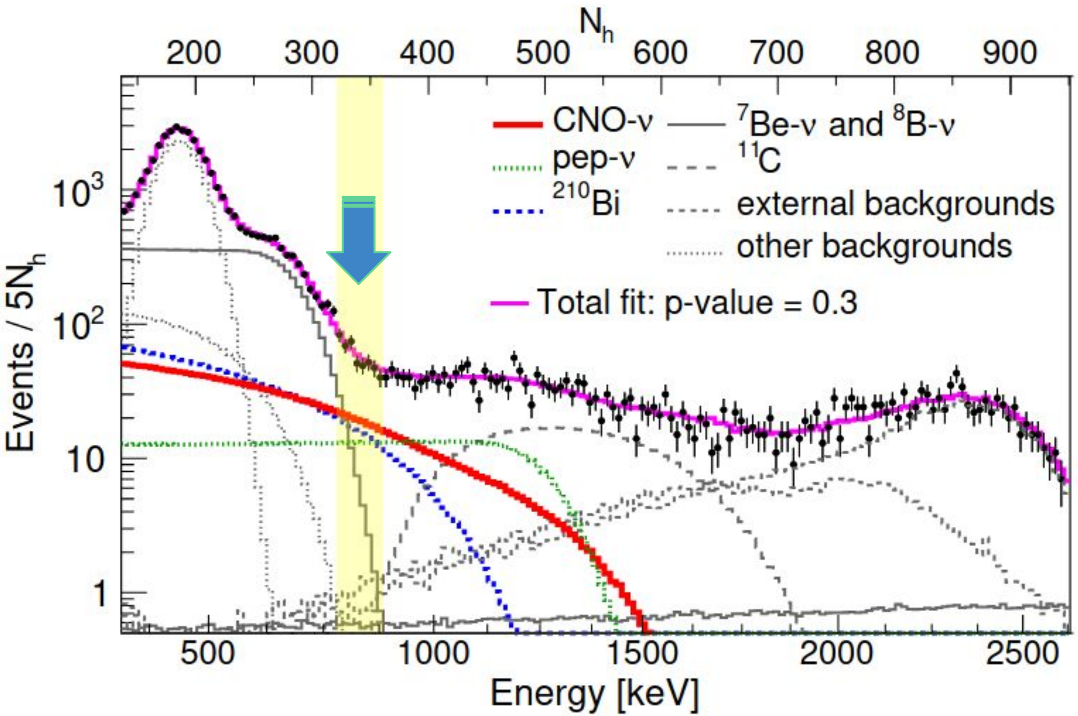
Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

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

Experimental evidence of ν_e from CNO cycle

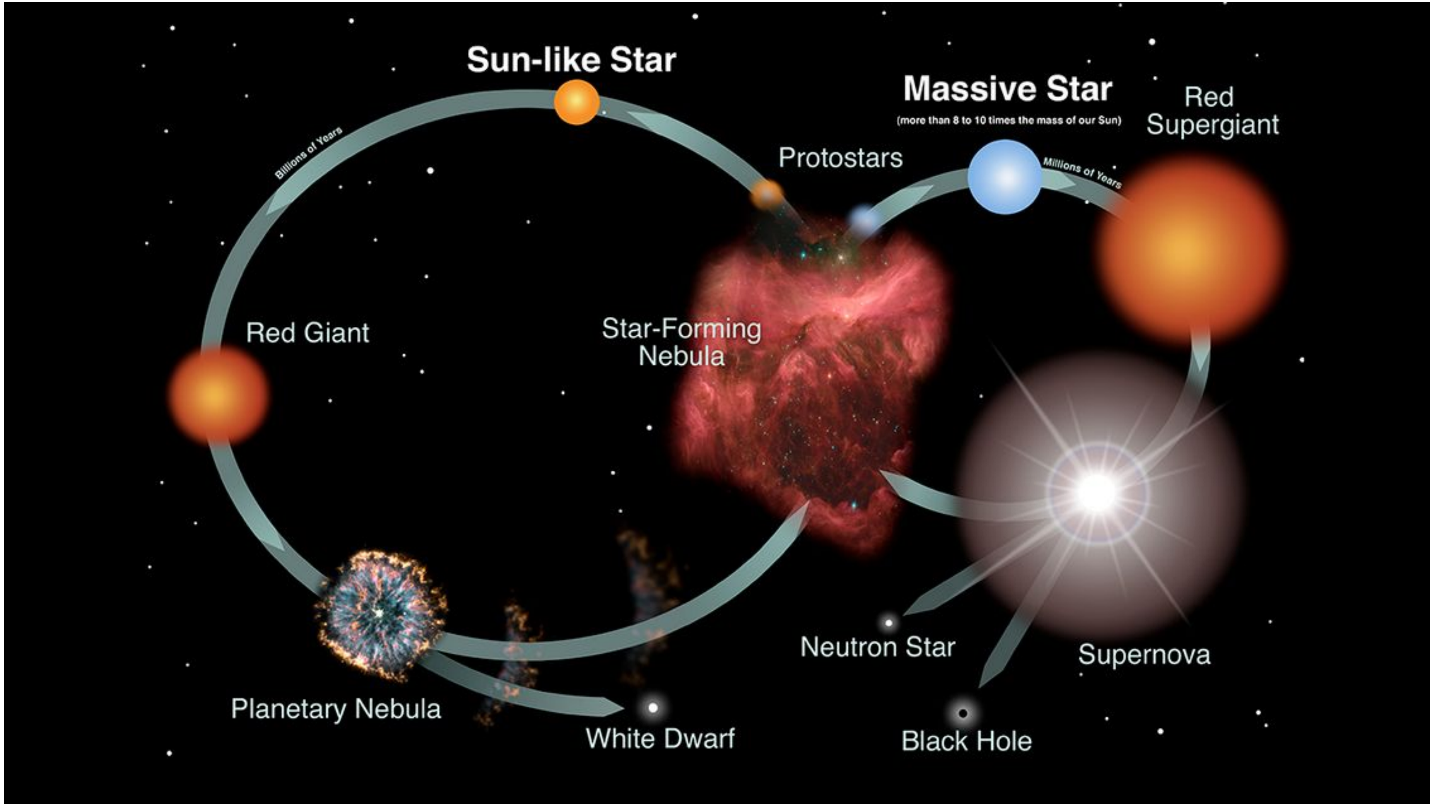






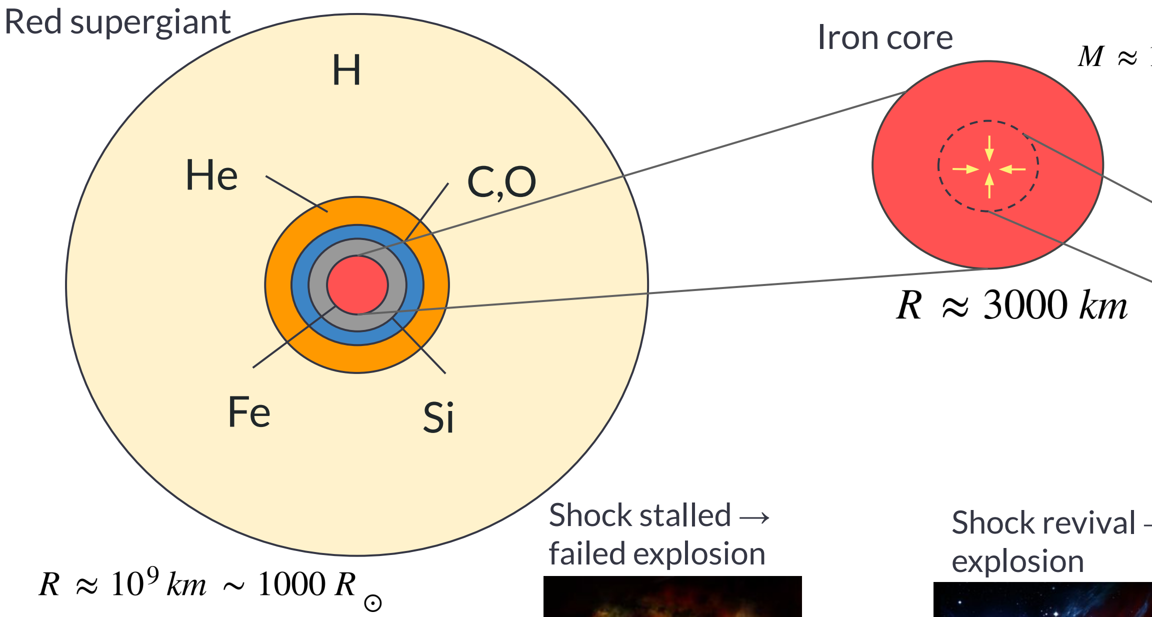
The Borexino Collaboration (2020)

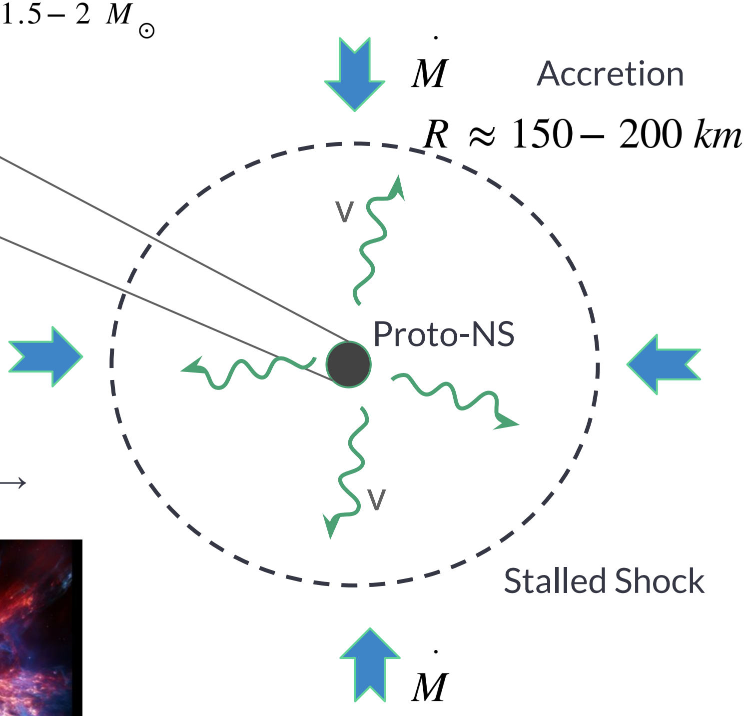
The life cycle of stars



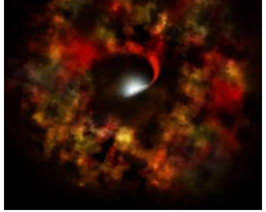
Credit: NASA, Night Sky Network

Core-collapse SNe: the explosive death of massive stars





Shock stalled → failed explosion

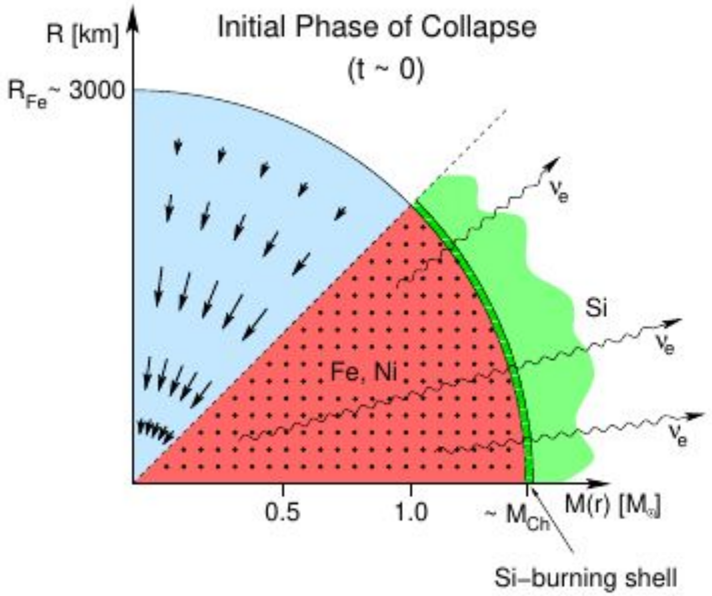


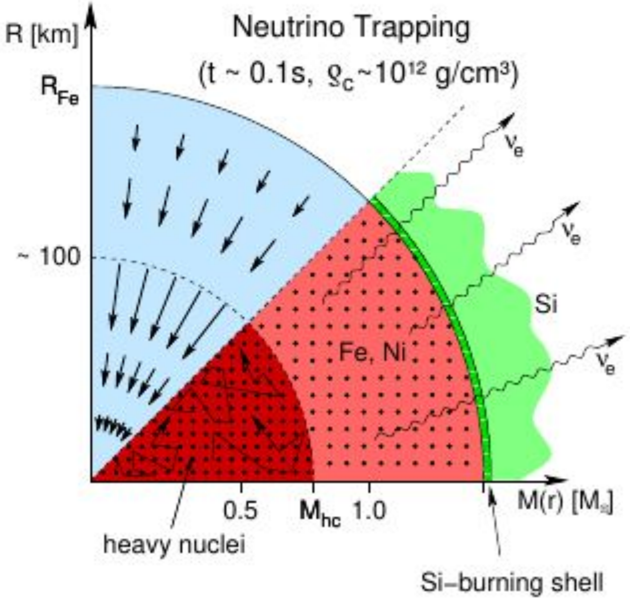
Shock revival → explosion

Seminars by Shashank Shalgar & Mariam Gogilashvili

Core collapse SNe: a closer look

Janka et al. (2007)



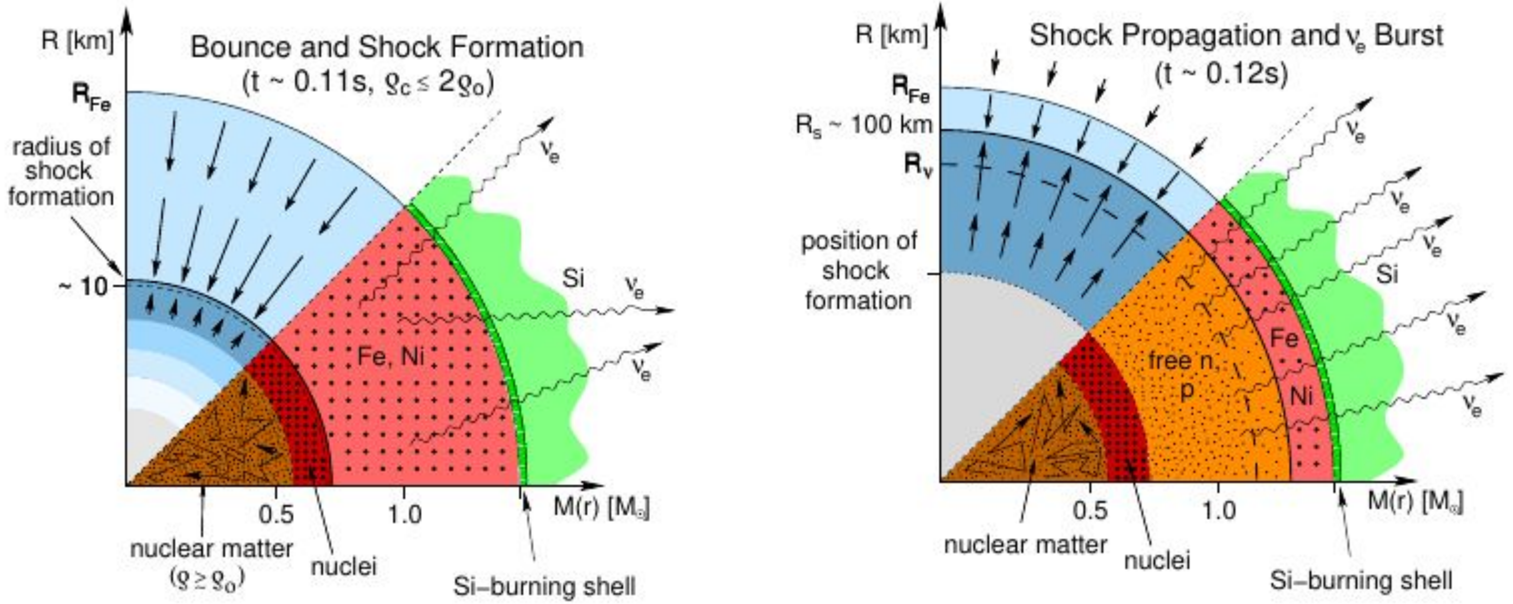


- Fusion of Fe to heavier does not release energy
- Ashes from the Si-burning shell increase the mass of the core → not enough pressure to oppose to gravity → collapse
- ve are produced through e-capture from Fe-peak nuclei, β decay of nuclei, (+photodisintegration)

- Density + Pressure of e- decreases → homologous collapse
- Increase of density to ~1e12 g/cm3 → neutrinos are trapped in the inner core

Core collapse SNe: a closer look

Janka et al. (2007)

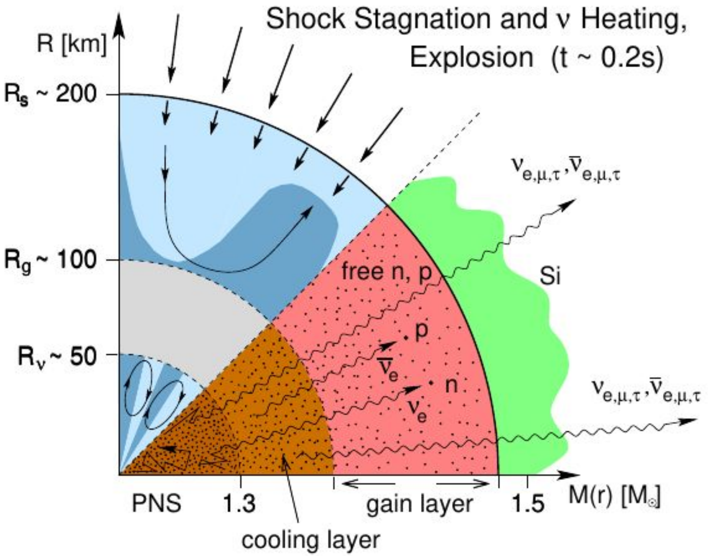


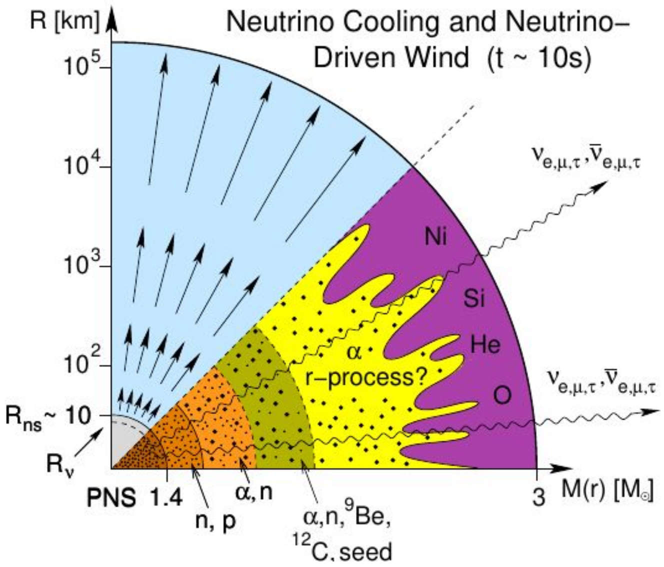
- Homologous collapse → nuclear densities reached in the core
- Nuclear matter is less compressible → the material bounces and a shock wave propagating outward is formed

- Shock wave uses energy to dissociate nuclei into n, p
- e-capture rate by free n,p is higher → leading to neutrino burst → carries away energy
- Shock loses so much energy that stalls → accretion shock

Core collapse SNe: a closer look

Janka et al. (2007)





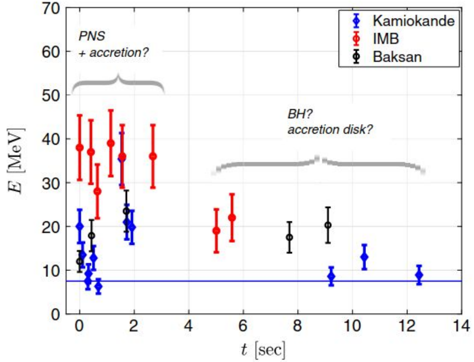
- Formation of proto-NS
- Formation of cooling layer (due to neutrino pair production + diffusive losses) and heating layer (neutrinos deposit their energy via charged - current interactions with n,p)
- Heating → Expansion behind the shock → shock revival is possible

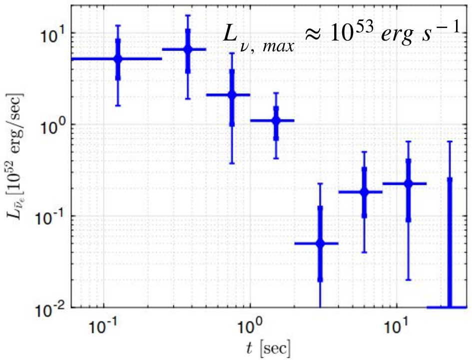
- Shock is revived and star explodes

SN 1987A: the first extragalactic ν source

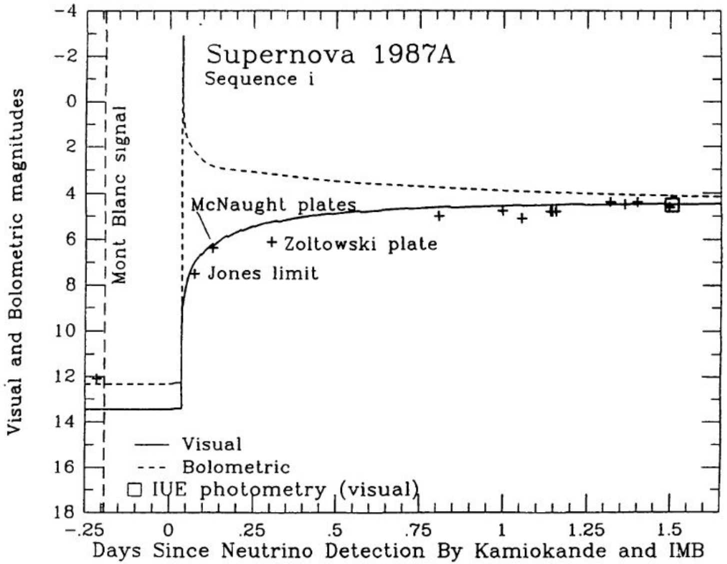
@ Large Magellanic Cloud (~51 kpc)

Credit: Anglo-Australian Observatory/David Malin





Bar, Blum, D'Amico (2020)



Arnett et al. (1989)

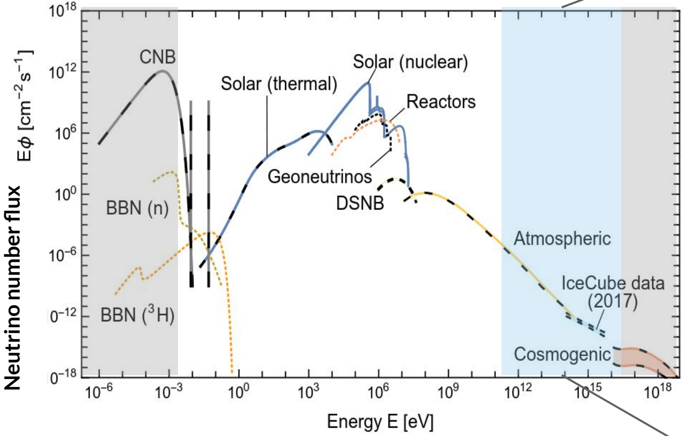
The Nobel Prize in Physics 2002

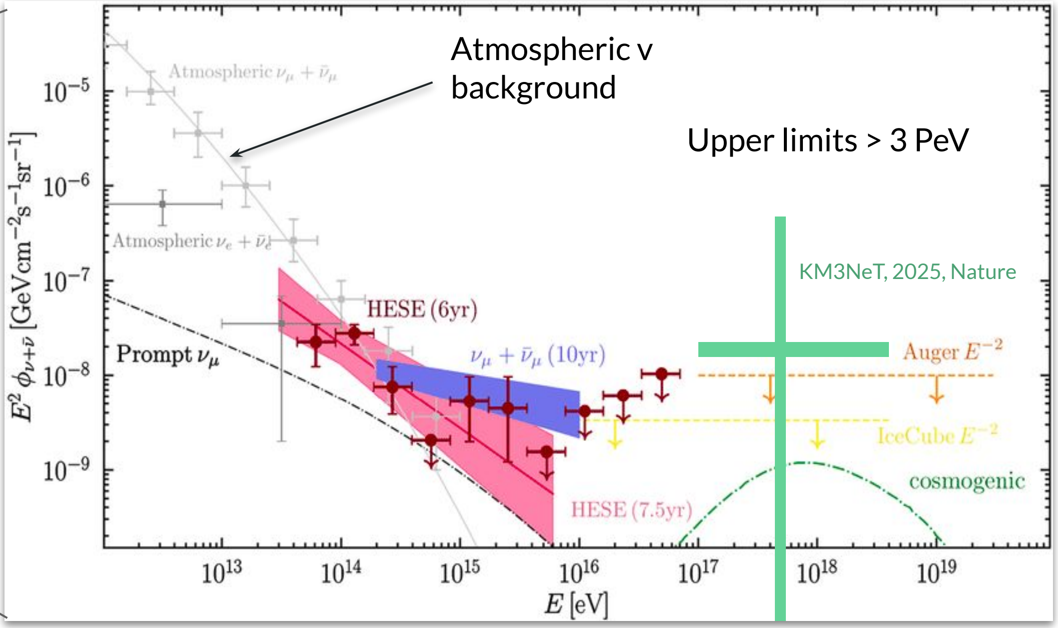
Photo from the Nobel Foundation archive.

Masatoshi Koshiba

Prize share: 1/4

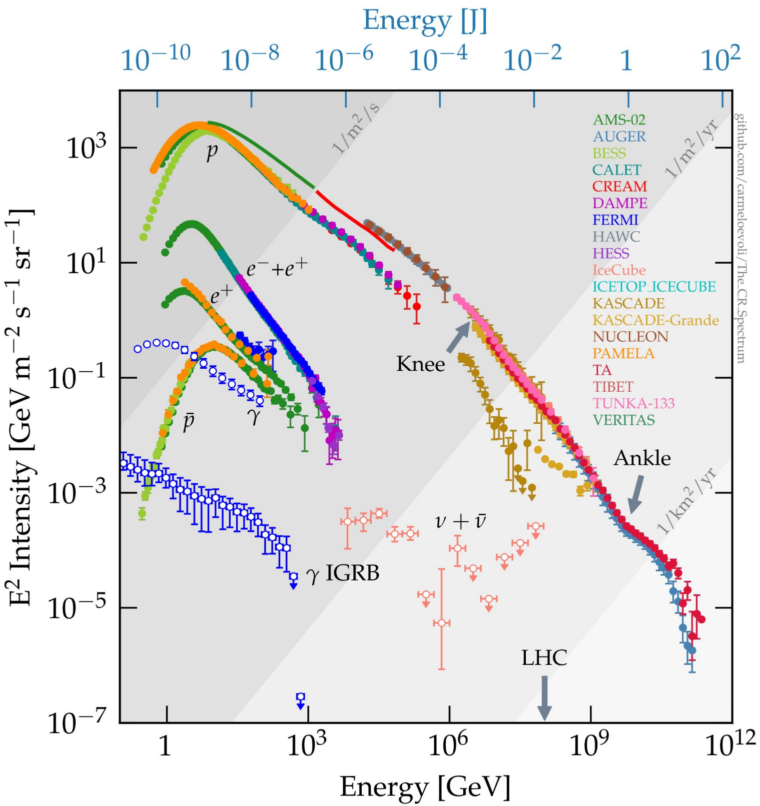
Moving to higher energies ...



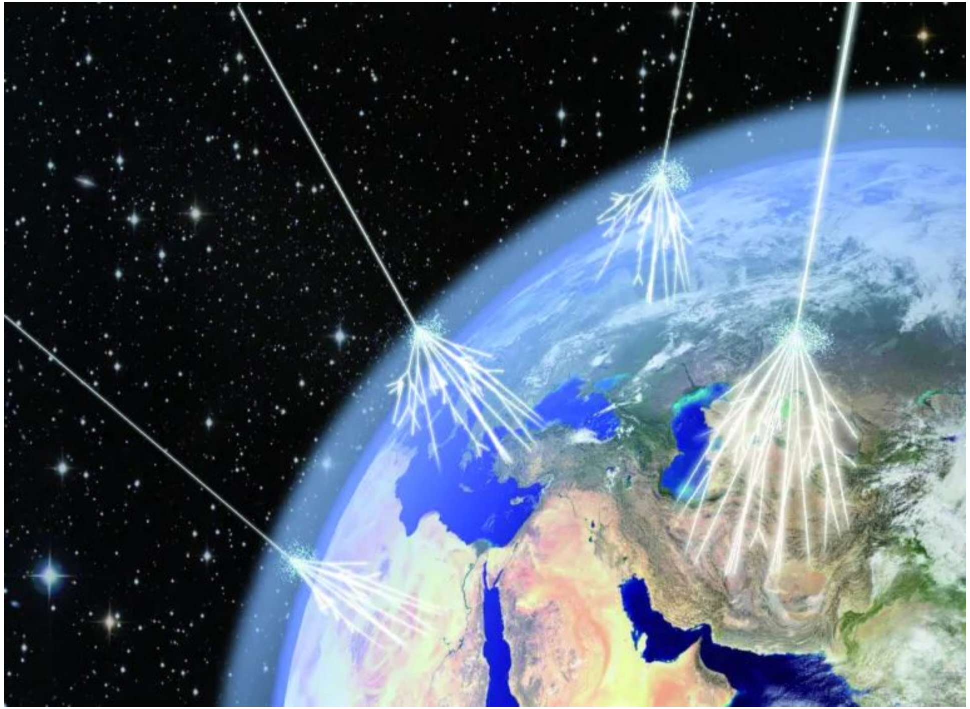


Kheirandish, A. (2020) A&SS

The cosmic-ray spectrum



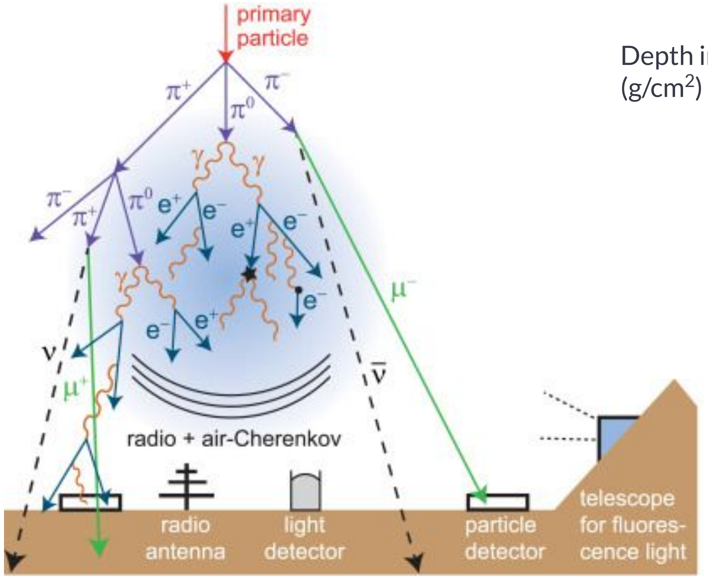
Credit: C. Evoli



Credit: Asimmetrie/INFN

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

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

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

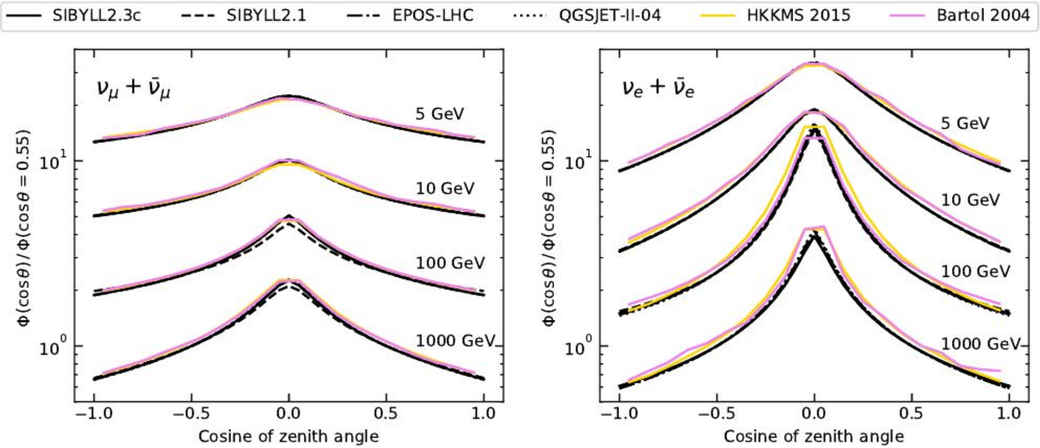
Depth in atmosphere (g/cm^2)

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

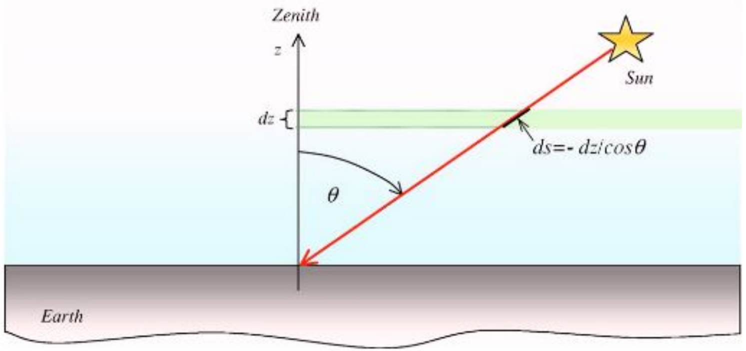
$$F_{ji}(E_i,E_j) \equiv E_i \frac{1}{\sigma_j^{\text{air}}} \frac{\mathrm{d}\sigma_{j\,\text{air}\to i}}{\mathrm{d}E_i}$$

Gaisser T. (2019)

Atmospheric neutrino spectra



Fedynitch et al. (2018)



Analytical approximate spectrum (without μ decays)

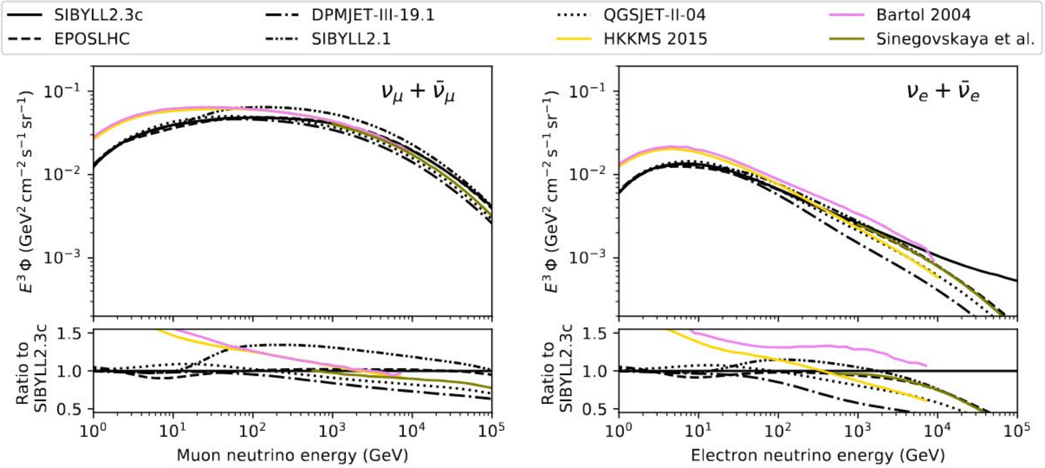
$$\frac{dN_\nu}{dE_\nu} \simeq \frac{N_0(E_\nu)}{1-Z_{NN}}\left\{\frac{\mathcal{A}_{\pi\nu}}{1+\mathcal{B}_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + 0.635\frac{\mathcal{A}_{K\nu}}{1+\mathcal{B}_{K\nu}\cos\theta\, E_\nu/\epsilon_K} + \sum_i B_{D_i}\frac{\mathcal{A}_{D\nu}}{1+\mathcal{B}_{D\nu}\cos\theta\,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

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

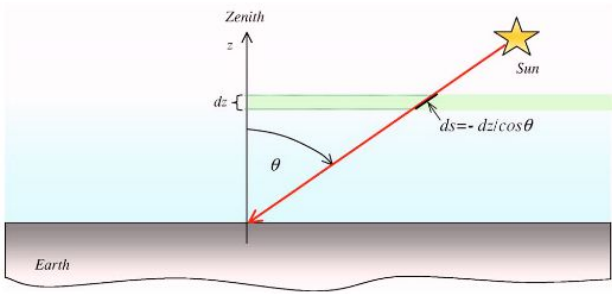
(GeV)

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

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)

- 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 neutrino production mechanisms

p-p collisions

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

p-γ collisions

Photo-pion production

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

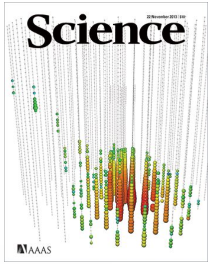
Photo-pair production

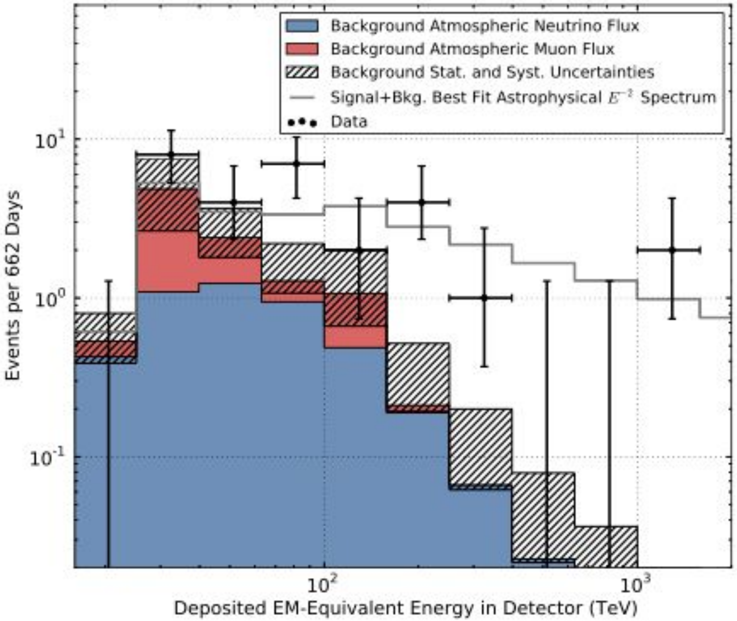
$$p + \gamma \to p + e^- + e^+$$

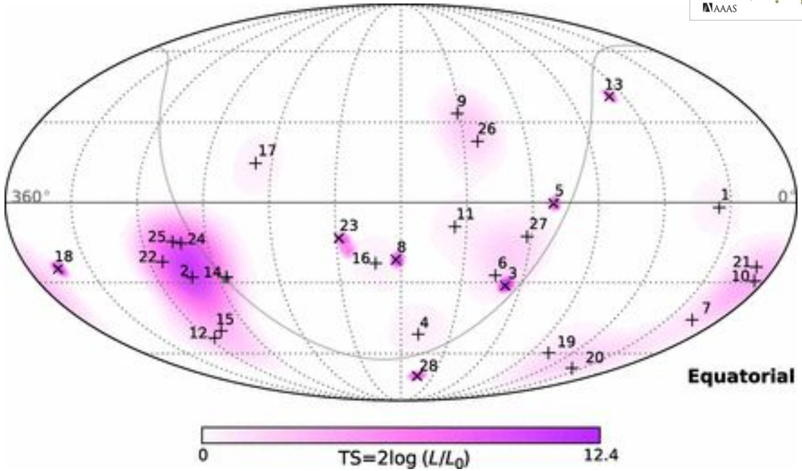
Even though is not a neutrino production mechanism is a key process for relativistic pair enrichment in astrophysical sources

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

High-energy astrophysical neutrinos -
Experimental Highlights 1



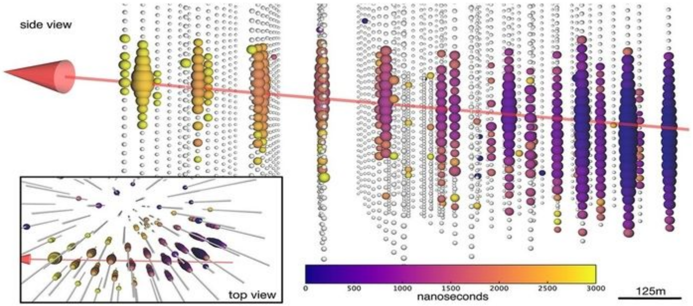


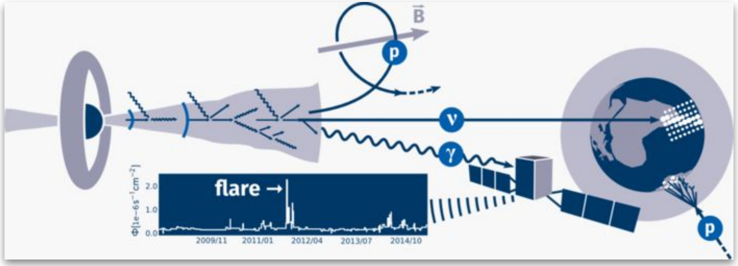


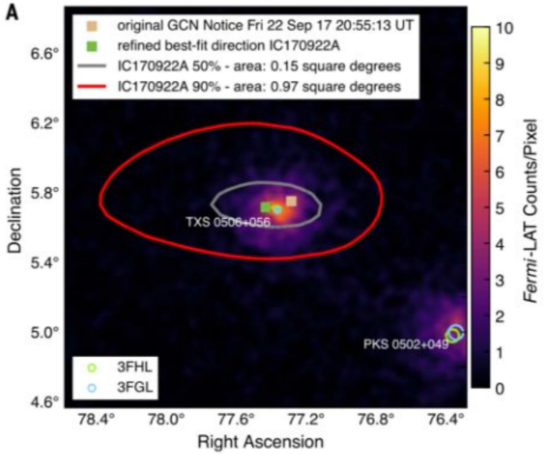
- 28 events above atmospheric background with energies > 30 TeV
- Arrival directions consistent with isotropic distribution

IceCube Collaboration, Science (2013)

High-energy astrophysical neutrinos - Experimental Highlights 2





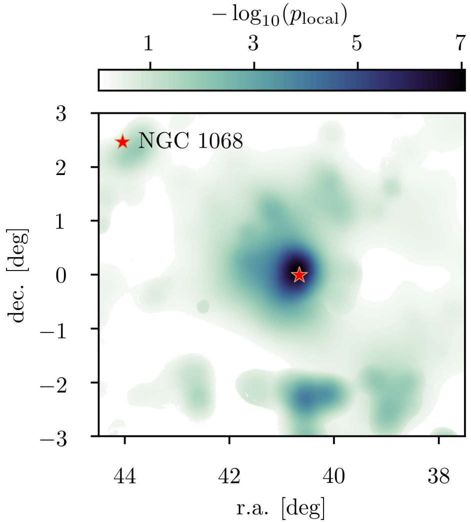


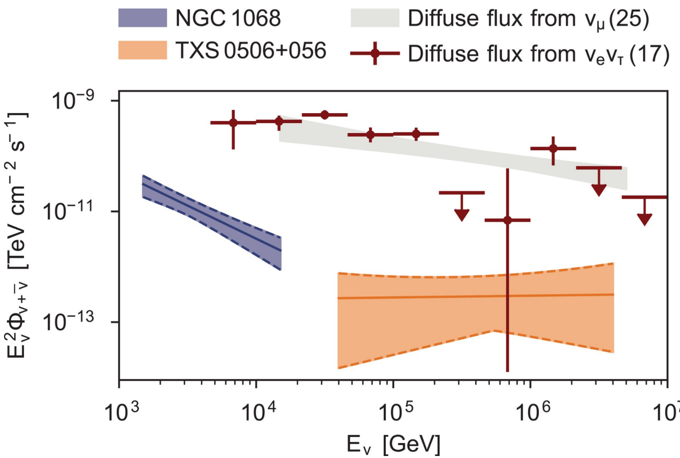
- High-energy neutrino (~290 TeV) detected during a γ-ray flare from active galaxy TXS 0506+056
- First spatial & temporal 3σ association with an astrophysical source

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

High-energy astrophysical neutrinos -
Experimental Highlights 3

IceCube Collaboration, Science 378 (2022) , Issue 6619

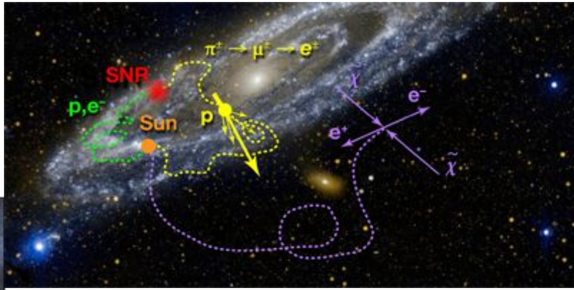


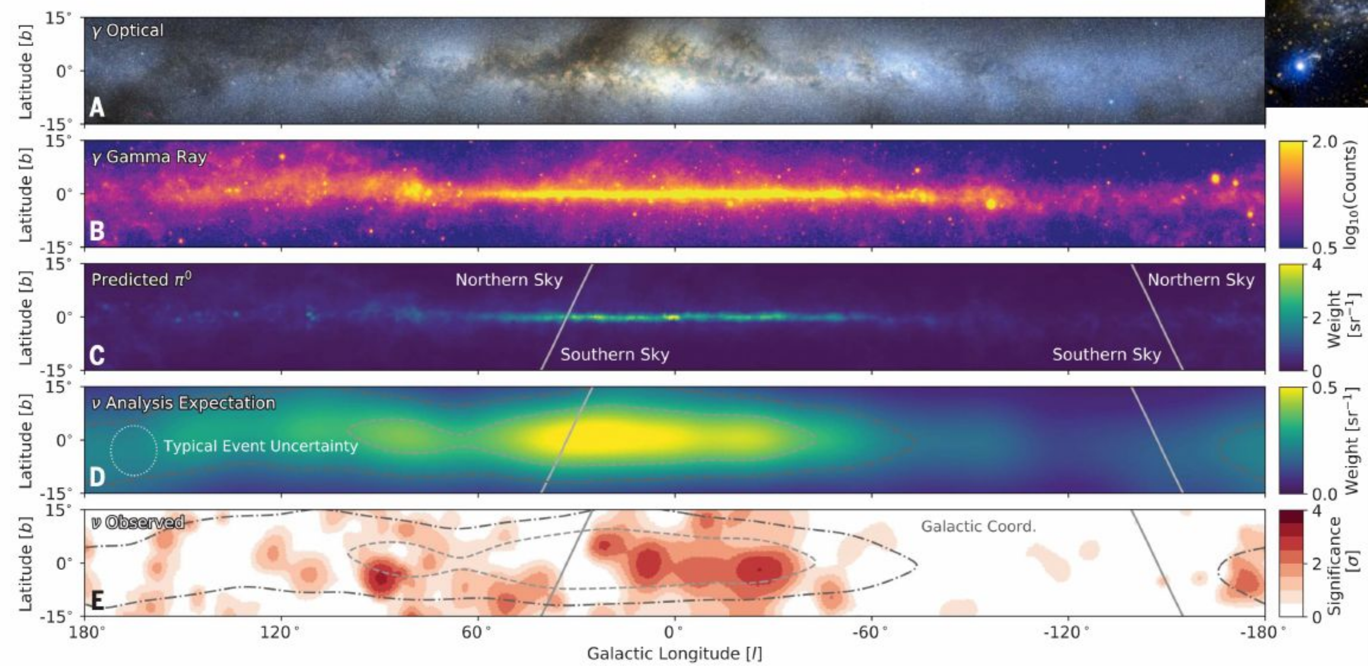


- N=79 (+22,-20) with E > 3 TeV detected from the location of active galaxy NGC 1068
- Neutrino spectrum: dN/dE ~ E^-γ, γ=3.2 +/- 0.2
- “Hottest spot” on Northern Sky in time-integrated searches

Check also talk by F. Testagrossa

High-energy astrophysical neutrinos -
Experimental Highlights 4



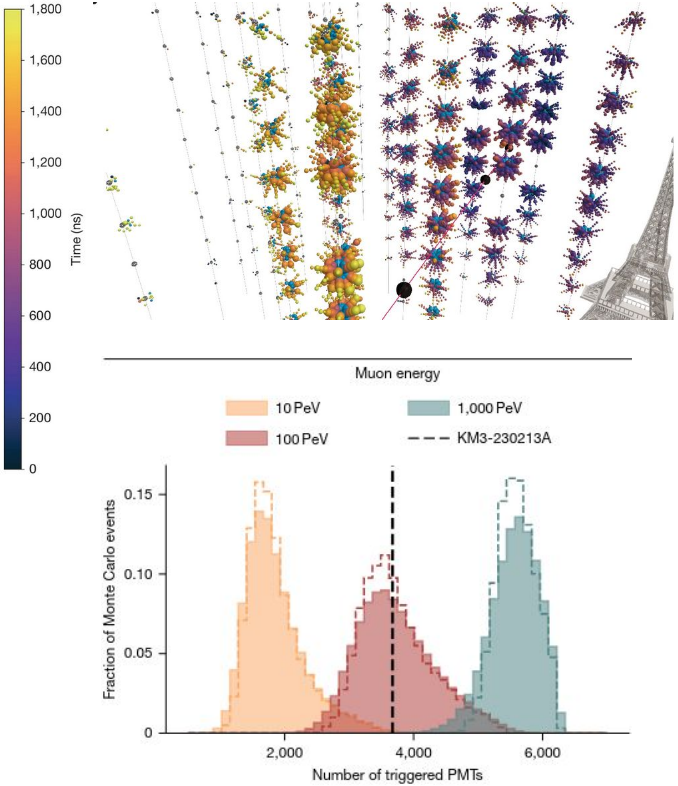


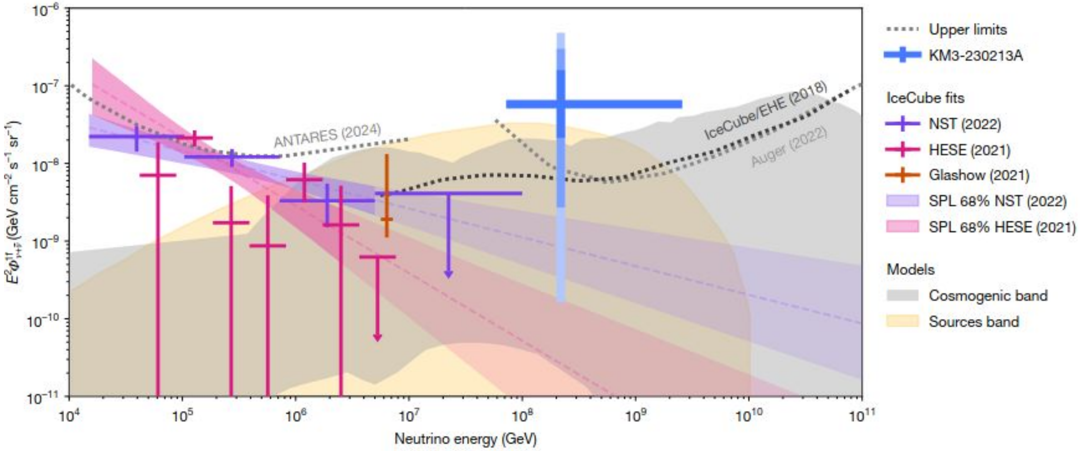
IceCube Collaboration, Science 380 (2023) , Issue 1338

- Galactic plane observed in neutrinos at 4.5σ
- Truly diffuse emission or unresolved point sources (PeVatrons?)

High-energy astrophysical neutrinos -
Experimental Highlights 5

KM3NeT Collaboration, Nature 638 (2025)



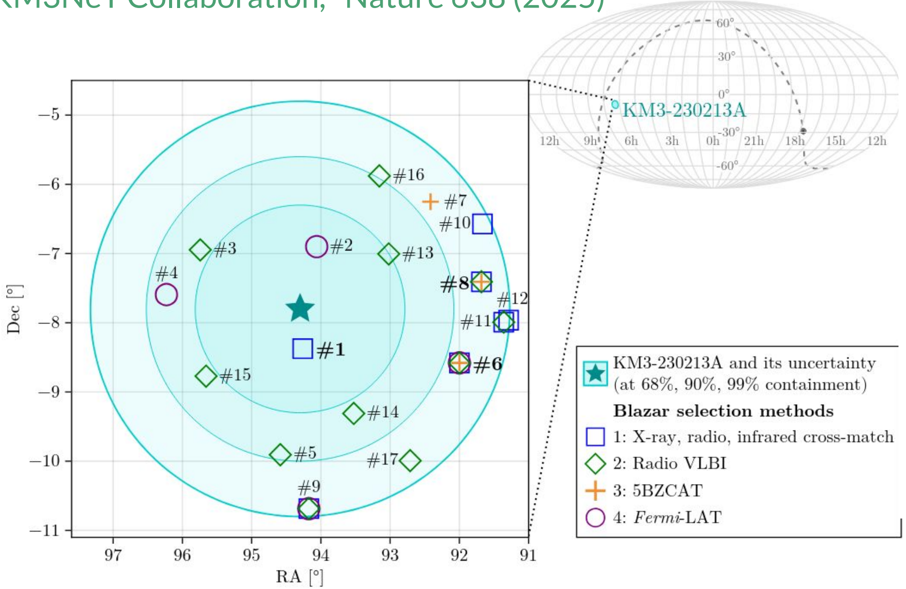


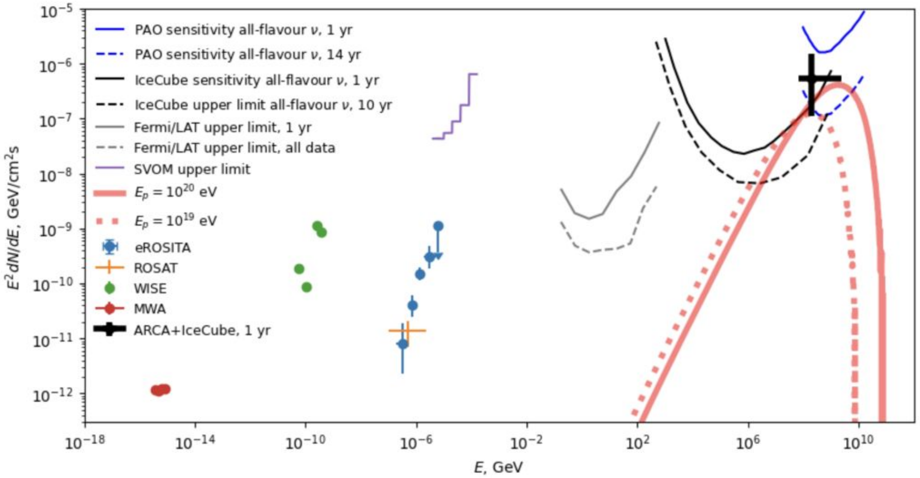
- First observation of an ultra-high-energy neutrino (>120 PeV)
- Astrophysical source not uniquely identified

High-energy astrophysical neutrinos -
Experimental Highlights 5

Neronov, Oikonomou, Semikoz (arXiv:250212986N)

KM3NeT Collaboration, Nature 638 (2025)

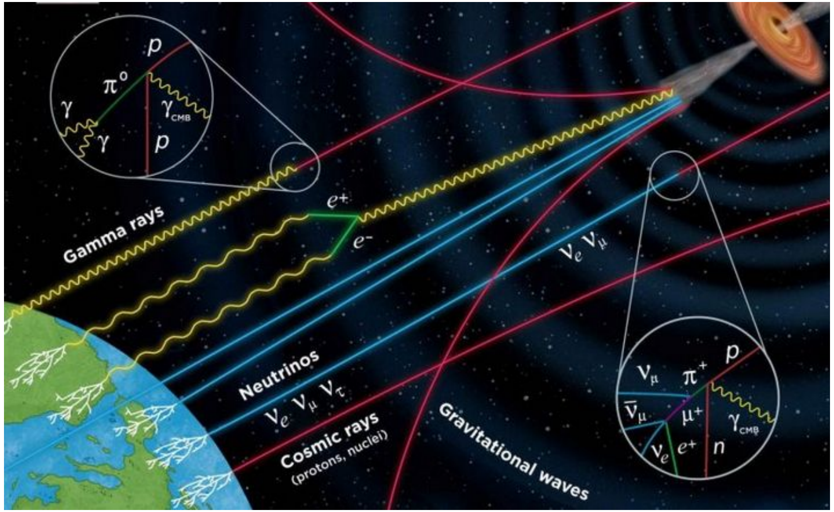




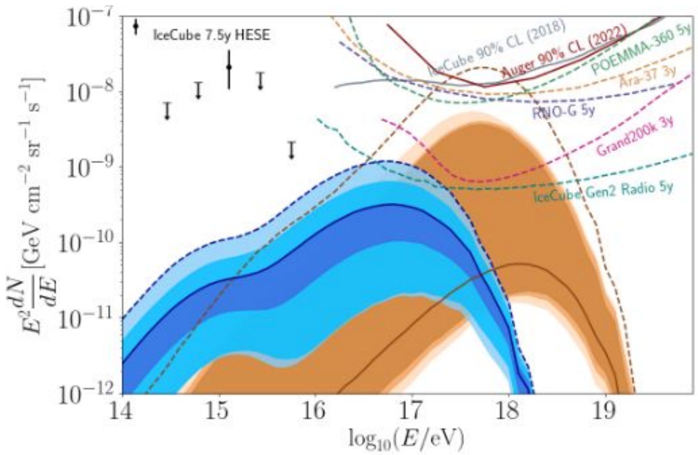
- First observation of an ultra-high-energy neutrino (>120 PeV)
- Astrophysical source not uniquely identified

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

Cosmogenic astrophysical neutrinos



Credit: Science China Press



Ehlert et al. (2023)

- Guaranteed signal: cosmic rays interacting with ambient radiation fields
- Cosmogenic neutrino flux sensitive to the
  - redshift evolution of cosmic-ray sources
  - composition of cosmic-ray spectrum at the highest energies

Key questions

What makes up the diffuse astrophysical flux ?

Are the neutrino spectra from different astrophysical sources different and why ?

What can we learn about the sources through neutrino observations?

What observables can we use to search for neutrino point sources?

Are the sources of high-energy cosmic rays the same as those of cosmic neutrinos ?

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

Summary - 1

- Astrophysical neutrinos observed from **MeV** energy scales (Sun, SN 1987A) to **TeV-PeV** energy scales (Galactic plane, Active Galaxies) to **EeV** scales (?)
- Different production mechanisms in low-energy (MeV) scales and high-energy (>TeV) scales (e.g. 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

Lecture 2

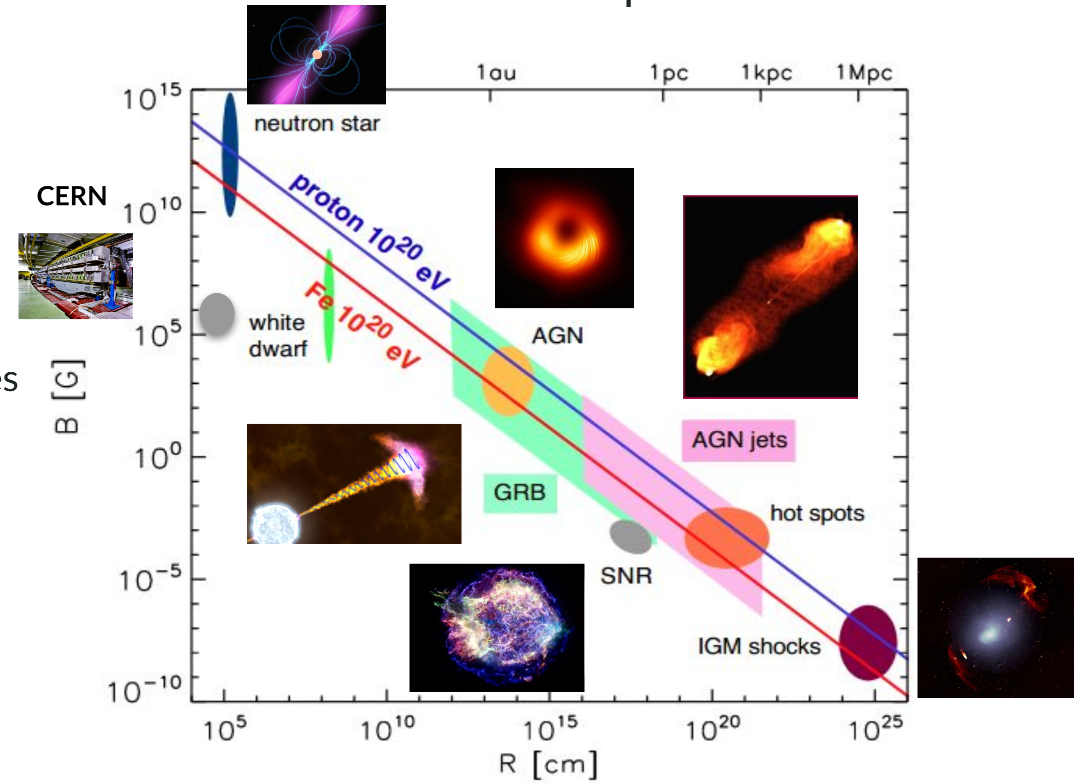
High-Energy Neutrinos from Compact* Sources

Particle confinement

$$r_g \leq R \Rightarrow B = \frac{E}{Ze} \cdot \frac{1}{R}$$

- Confinement criterion for charged particles
- Necessary but not sufficient condition for hadronic accelerators
- Source physics important for understanding the multi-messenger connection!

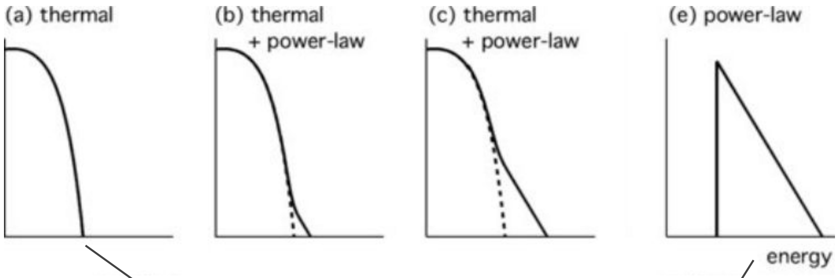
The Hillas plot



Kotera & Olinto 2011, ARA&A

Particle acceleration

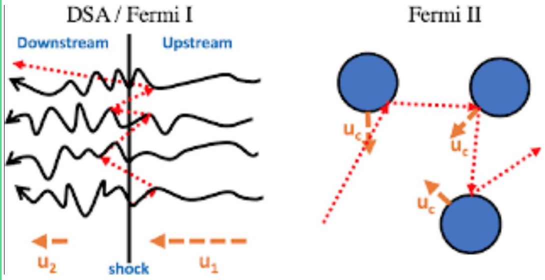
Heating → Acceleration



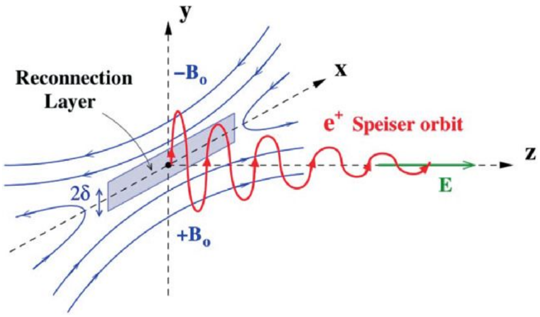
$$f(\mathbf{p}) = \frac{1}{4\pi m^3 c^3 \theta K_2(1/\theta)} \exp\left(-\frac{\gamma(p)}{\theta}\right)$$

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

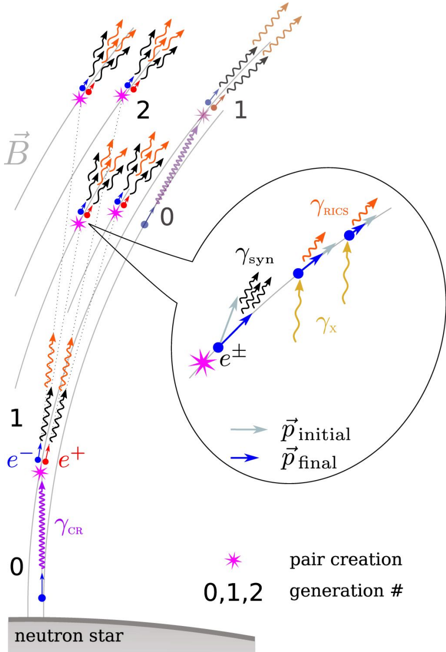
Shocks/turbulence



Magnetic reconnection

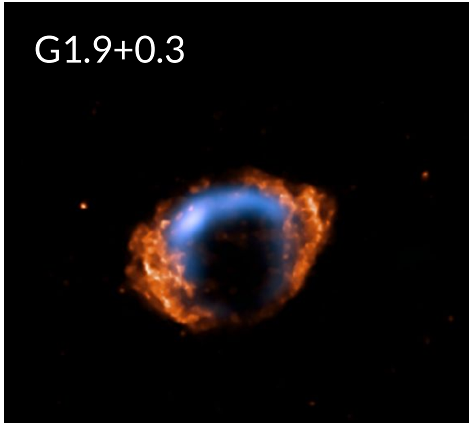


Electrostatic gaps



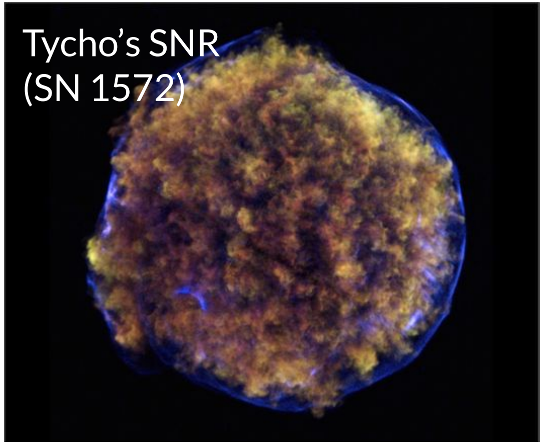
Shocks

- ***What is a shock wave ?***
    - *A discontinuity in fluid properties (ρ, T, n) moving at speed larger than speed of sound (upstream)*
- ***What does a shock wave do ?***
    - *It converts bulk kinetic energy of upstream medium to thermal (energy of random motions) in the downstream*
- ***What is a collisionless shock ?***
    - *Very low density → particle - particle collisions are rare → particle - wave interactions*



Orange: X-rays (Chandra 2007)
Blue: Radio (VLA 1985)

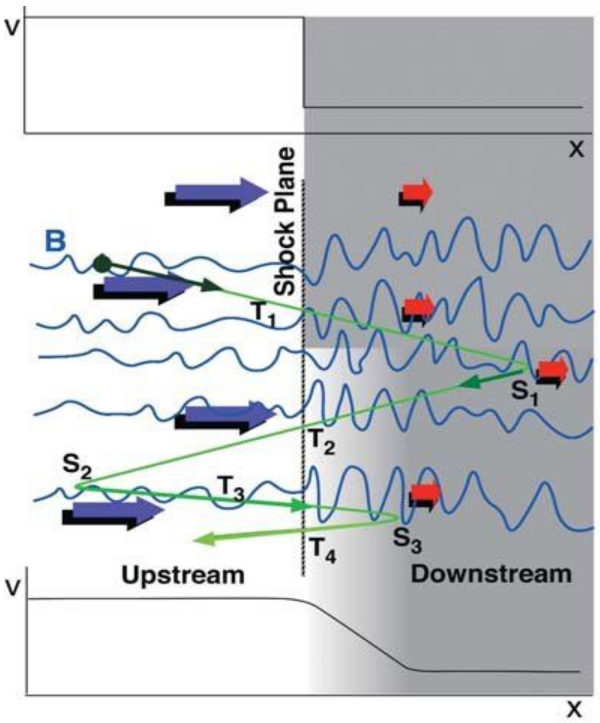
Credit: NASA/CXO



Blue: High-energy X-rays
Green: Medium energy X-rays
Red: Low energy X-rays
Credit: (NASA/CXO)

Credit: NASA/CXC/PSU/B.Posselt et al; Infrared (BACKGROUND): NASA/JPL-Caltech

Shock acceleration



Möbius & Kallenbach, 2005, ISSI Scientific Reports Series

- Shocks dissipate bulk kinetic energy → internal energy, non-thermal particle energy

- **Fermi** acceleration → particles gain energy via multiple scatterings across a velocity gradient (there is also shock-drift, ...)

- Shocks can efficiently accelerate particles with **power-law** distributions, slope depending on t_{acc}/t_{esc}

- Inefficient acceleration:
  - High-σ plasma
  - Superluminal shocks

$$\sigma = \frac{B^2}{4\pi\rho c^2} >> 1$$

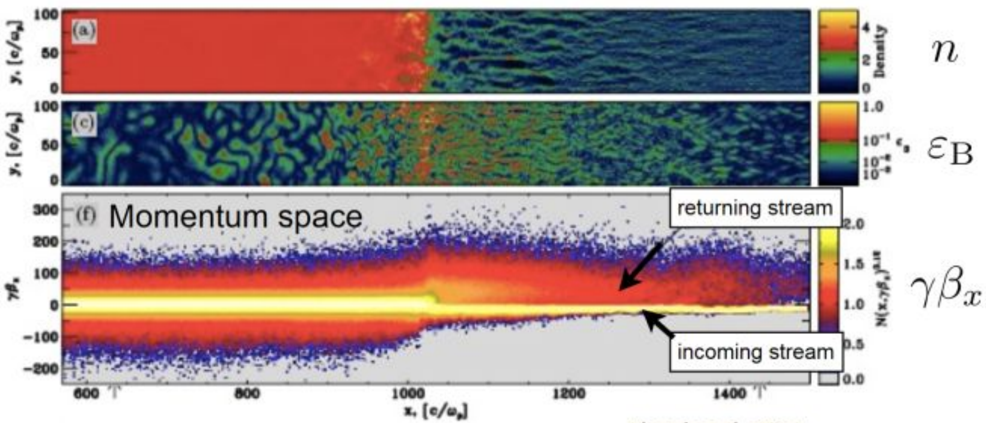
Drury 1983, ApJ; Bell 1987, MNRAS; Blandford & Eichler 1987, Phys. Rep.; Begelman & Kirk 1990; Bell 2004, MNRAS, Blasi 2013, A&ARv +++

Relativistic shock acceleration

$\sigma = 0$

$\gamma_0 = 15$

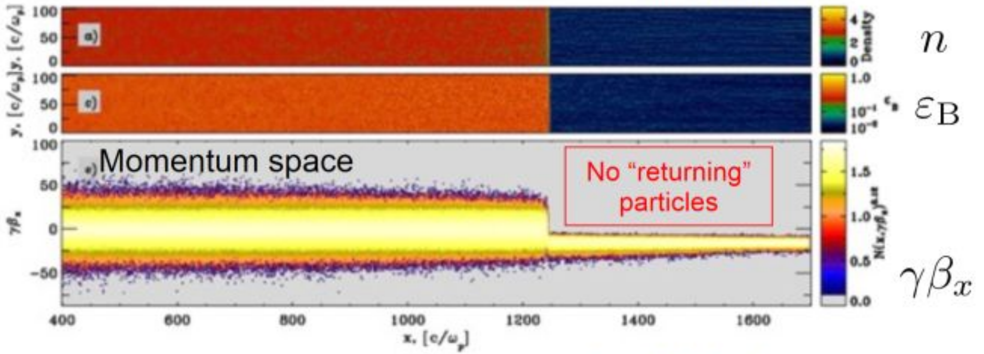
Low-σ shocks:
- returning particles
- filamentation instabilities

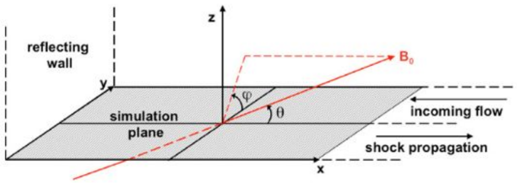


$\sigma = 0.1$

$\gamma_0 = 15$

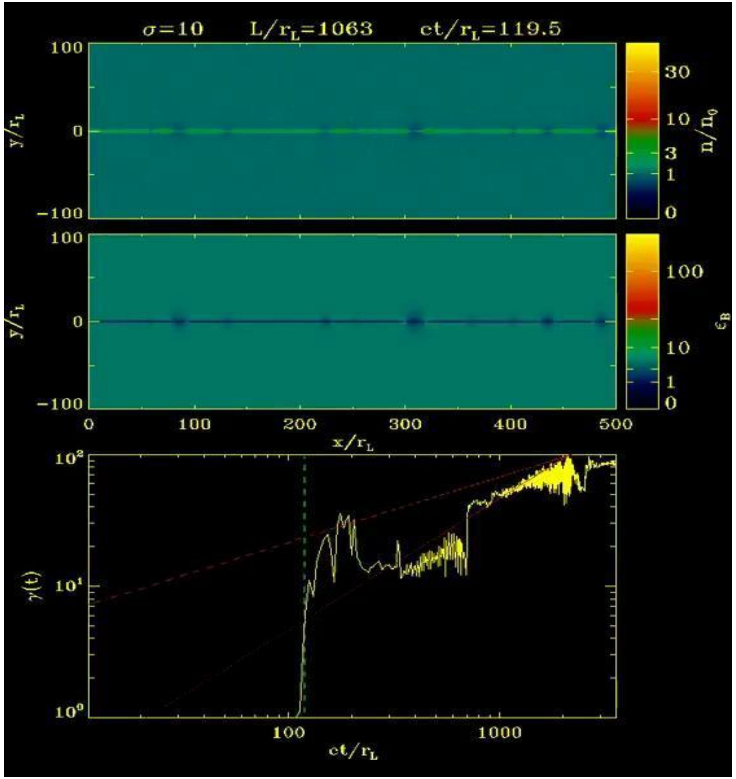
High-σ shocks:
- no returning particles
- no turbulence



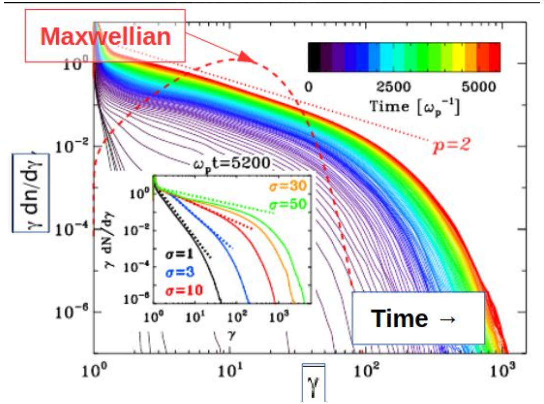


θ = 15 deg

Relativistic magnetic reconnection



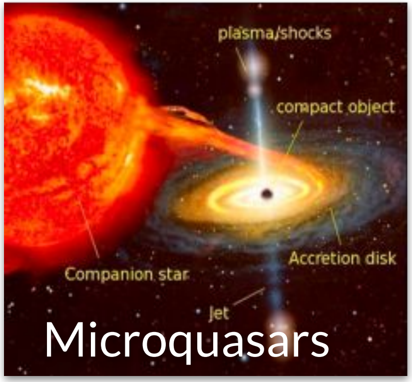
- Dissipation of magnetic energy → internal energy, non-thermal particle energy
- E-field acceleration → particles gain energy as the move along non-ideal E-fields and ideal (motional) E-fields
- Reconnection can efficiently accelerate particles with **power-law** distributions, with slope depending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

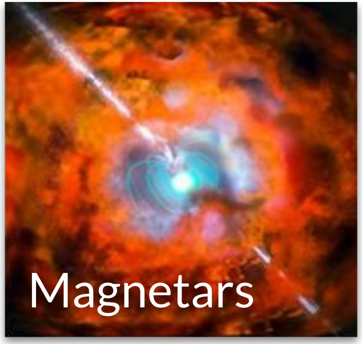


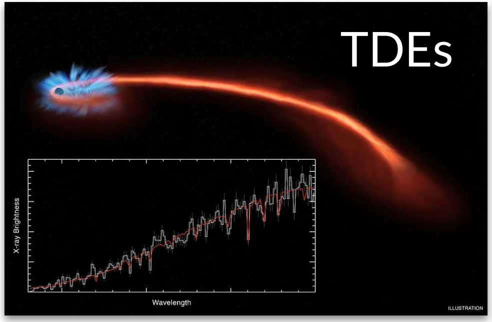
Sironi & Spitkovsky (2014)

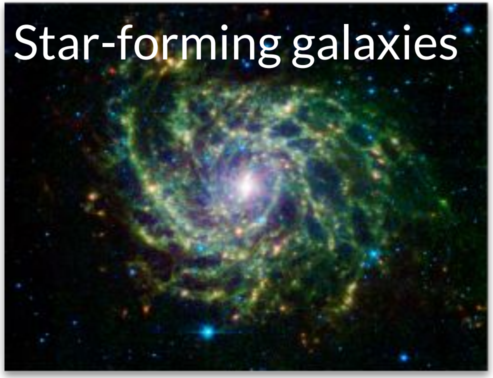
Recent review: Sironi, Uzdensky, Giannios (2025), to appear in ARA&A, Vol. 63

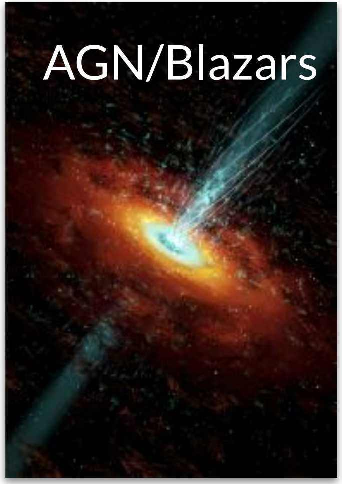
A zoo of astrophysical accelerators











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

To the blackboard ...

- Energy thresholds
- Reaction rates
- Mean free paths - opacity
- Secondary particle spectra

Energy 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: $P_{a+b} = \left(e_a + e_b, \vec{p}_a + \vec{p}_b \right)$, $\Delta m = m_c + m_d - (m_a + m_b)$

$$e'^2 = \left(e'_a + e'_b \right)^2 \geq \left(e'_c + e'_d \right)^2 \quad (1)$$

$$\|P'_{a+b}\|^2 = \|P_{a+b}\|^2 \Rightarrow \left(e'_a + e'_b \right)^2 = \left(e_a + e_b \right)^2 - \left(\vec{p}_a + \vec{p}_b \right)^2 \quad (2)$$

$$(1), (2) \Rightarrow e_a e_b - \vec{p}_a \cdot \vec{p}_b \geq m_a m_b c^2 + \Delta m\, c^2 \left(m_a + m_b + \frac{\Delta m}{2} \right) \quad (3)$$

*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!

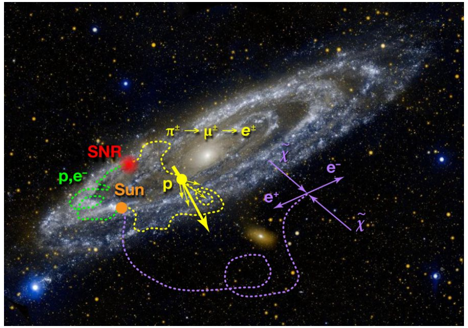


Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

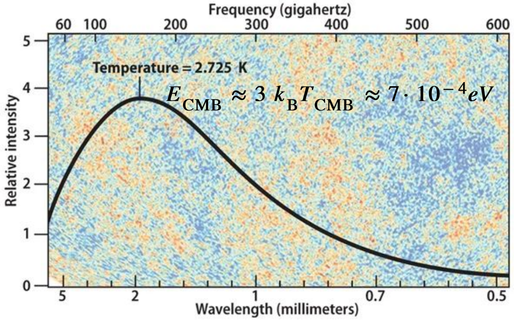
$p + \gamma \rightarrow p + \pi^0$

Collision of a cosmic-ray proton (γ > 1) with a photon from the CMB

$$\gamma E(1 - \beta\cos\theta) \geq m_\pi c^2\left(1 + \frac{m_\pi}{2m_p}\right) \approx 145\ MeV \quad \theta = \pi,\ \beta \approx 1:\ \gamma \geq \frac{145\ MeV}{2E_{CMB}} \approx 10^{11}\ !$$

Photon energy in proton's rest frame

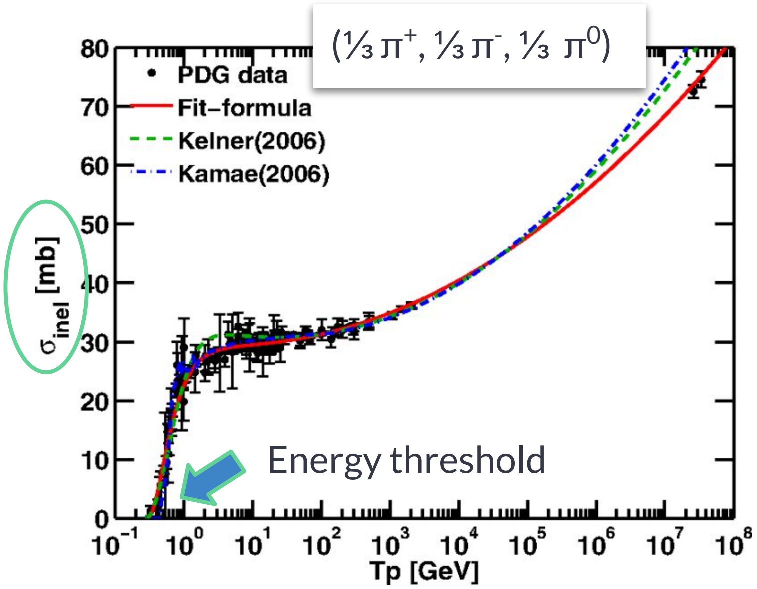
+ Exercise



Credit:Roen Kelly, after NASA/COBE/FIRAS

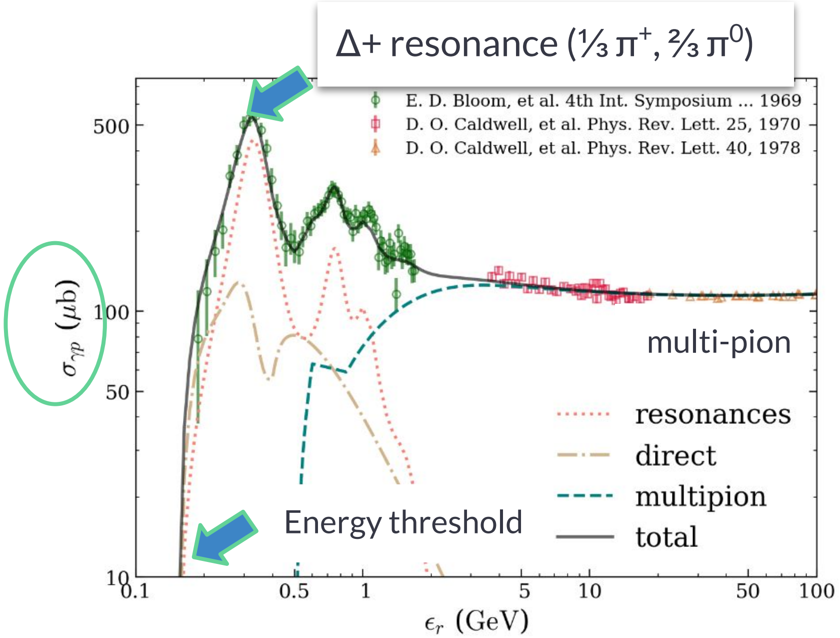
Cross sections

p-p collisions



Kafexhiu et al. (2014)

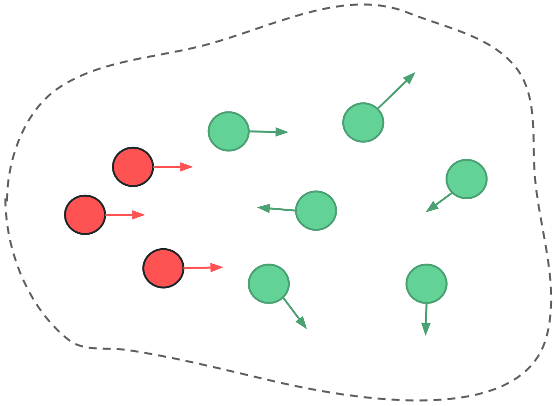
p-γ pion production



Morejon et al. (2019)

Rate of interactions

Volumetric rate = cross section * density^2 * speed



$$\dot{n}_{sc} \equiv \frac{dN_{sc}}{dt\, dV} = \sigma(\gamma_{rel}) \cdot v_{rel} \cdot n^0{}_2 \cdot n'{}_1$$

Number density of particle “1” in rest frame of particle “2”

Relative velocity of two particles

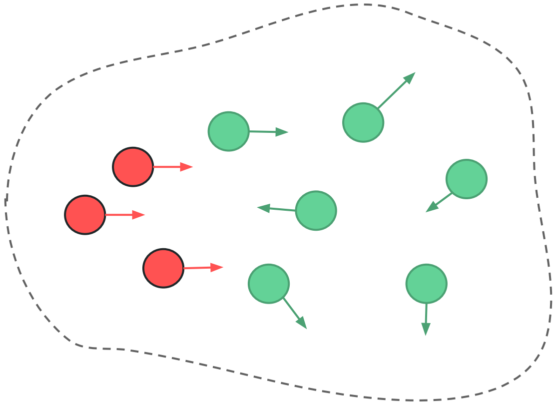
Number density of particle “2” in its rest frame (proper density)

$$\dot{n}_{sc} = \sigma(\gamma_{rel})\, c\, \beta_{rel} \frac{n_2}{\gamma_2} \frac{n_1}{\gamma_1} \gamma_{rel} \Rightarrow \dot{n}_{sc} = \sigma(\gamma_{rel})\, c\, \beta_{rel} \left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right) n_1 n_2$$

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

Rate of interactions

Volumetric rate = cross section * density^2 * speed



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

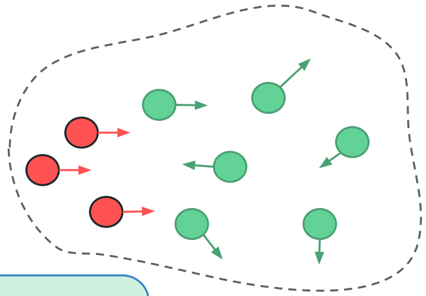
Differential number density (dN / dV dp dΩ)

"Effective" cross section

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

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

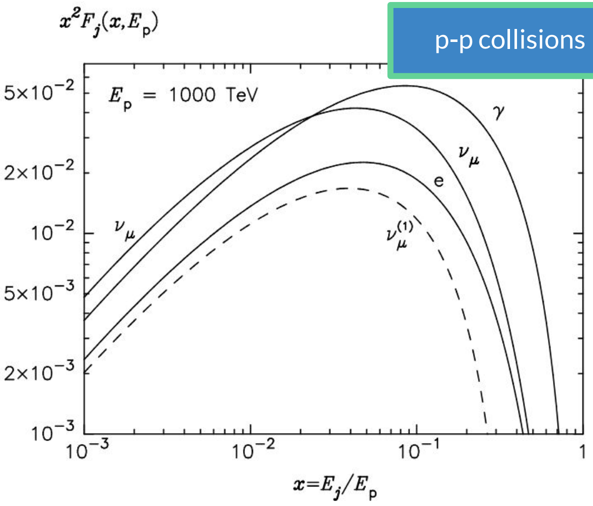
Secondary particle spectrum - 1



Production rate spectrum of secondary particles per unit volume:

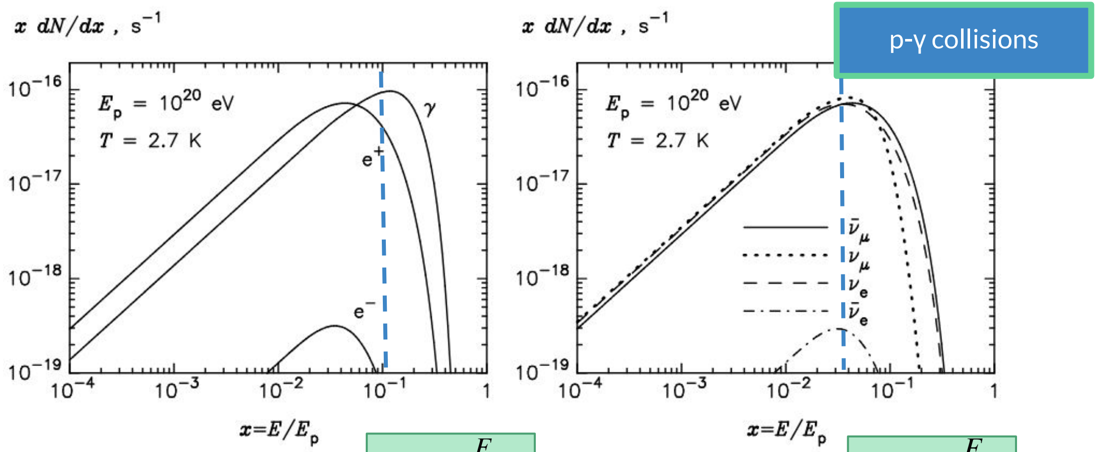
$$\dot{n}_{sc}(p_s) = c\int d\Omega_1 \int dp_1\, n_1(p_1, \Omega_1) \int d\Omega_2 \int dp_2\, n_2(p_2, \Omega_2)\, \beta_{rel}\left(1 - \vec{\beta}_1 \cdot \vec{\beta}_2\right) \int d\Omega_s \frac{d\sigma(\gamma_{rel})}{dp_s\, d\Omega_s}$$

p-p collisions



Kelner et al. (2006)

p-γ collisions



Kelner et al. (2008)

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

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

+ Exercise

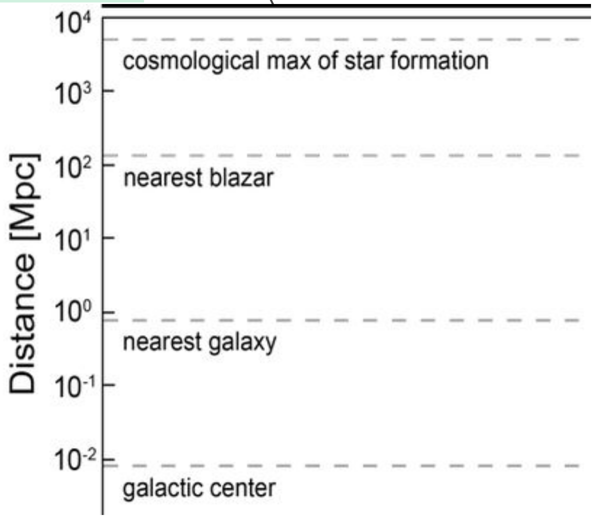
Energy loss timescale / Mean free path

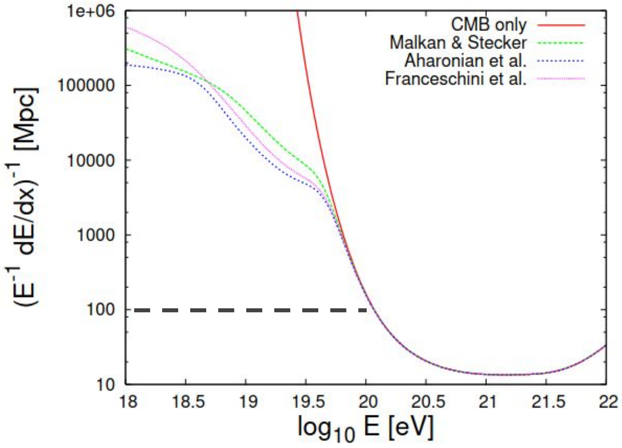
Stecker 1968; Begelman et al. 1990

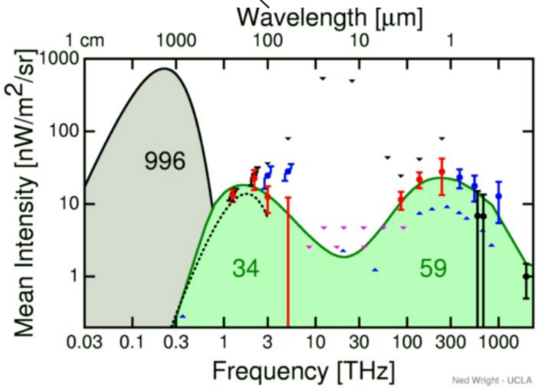
p-γ interactions with isotropic radiation field:

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

Example



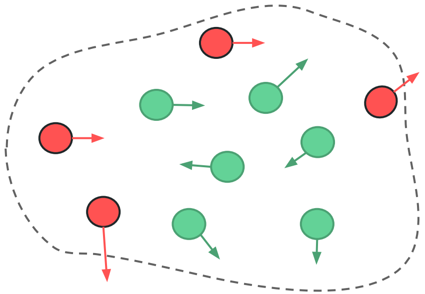




Hooper et al. (2007)

Credit: Ned Wright (UCLA)

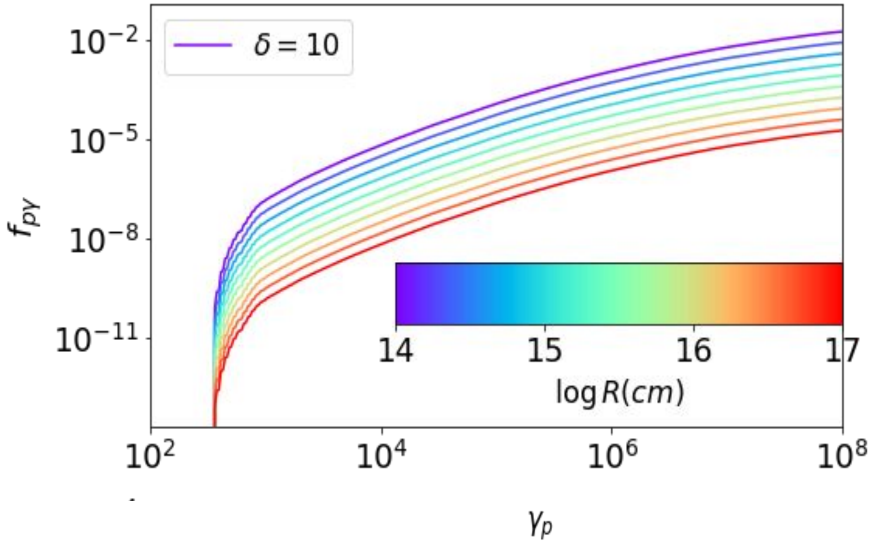
Production efficiency



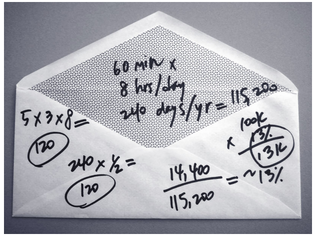
$$f_i(\gamma_p) = \frac{1}{1 + \frac{t_i(\gamma_p)}{t_{p,esc}(\gamma_p)}}, \quad i = pp,\ p\gamma$$

- Compares the timescales for particle escape - interactions
- Calorimetric limit: $f \to 1$

Example for pγ interactions in a jet



Secondary particle spectrum - 2

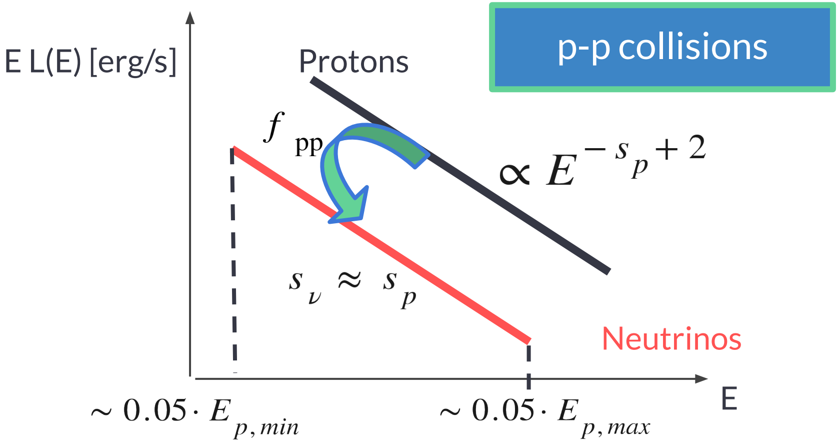


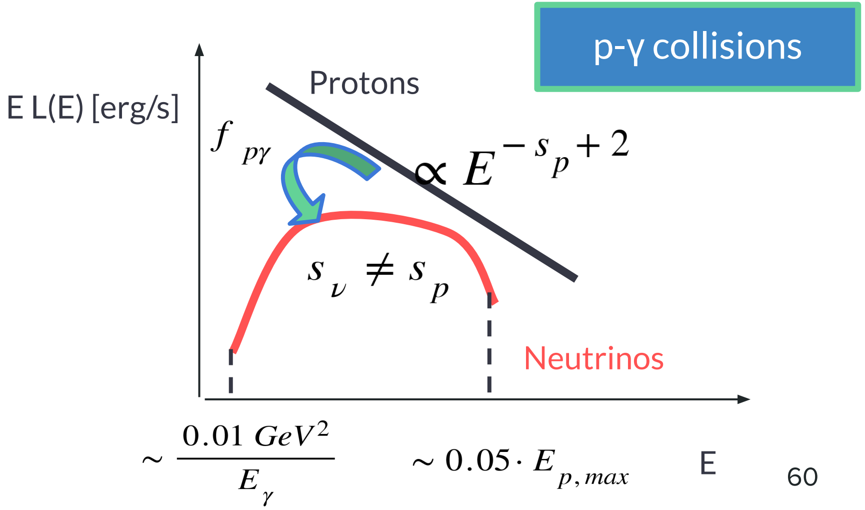
$$E_\nu L_{\nu+\bar{\nu}}(E_\nu) \approx \eta\, f_i(E_p) \cdot E_p L_p(E_p)\Big|_{E_p \approx 20\, E_\nu}$$

Interaction physics (branching ratio + typical energy)

Interaction physics + Source properties

Acceleration physics



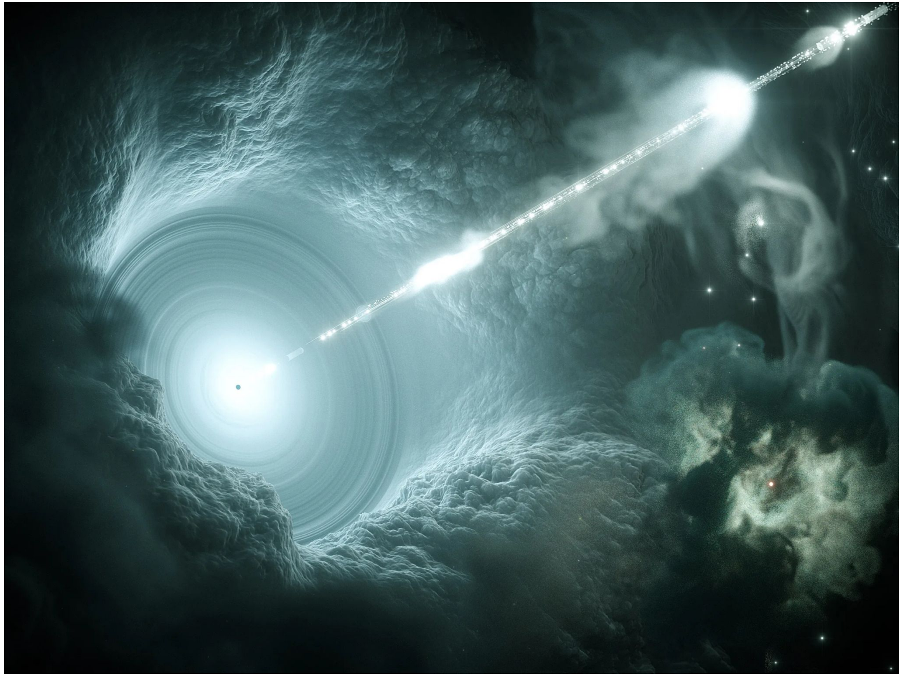


Lecture 3

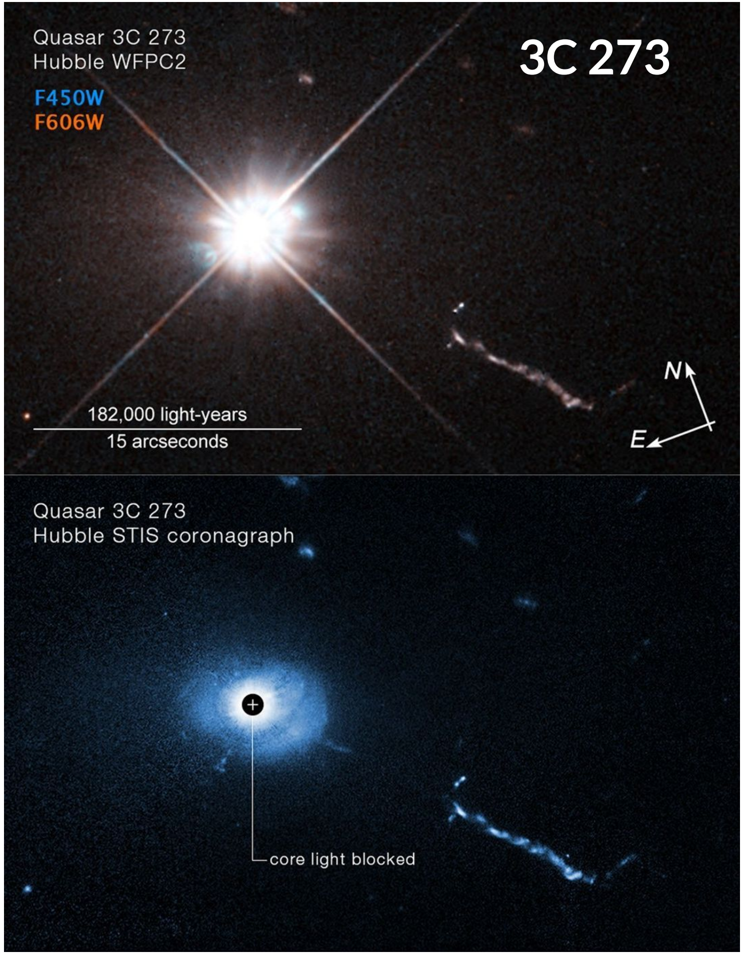
Extragalactic Neutrinos in a Multi-Messenger Context

Active galactic nuclei (AGN)

Artistic impression of an AGN



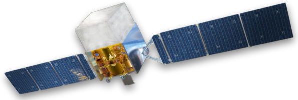
Credit: DESY

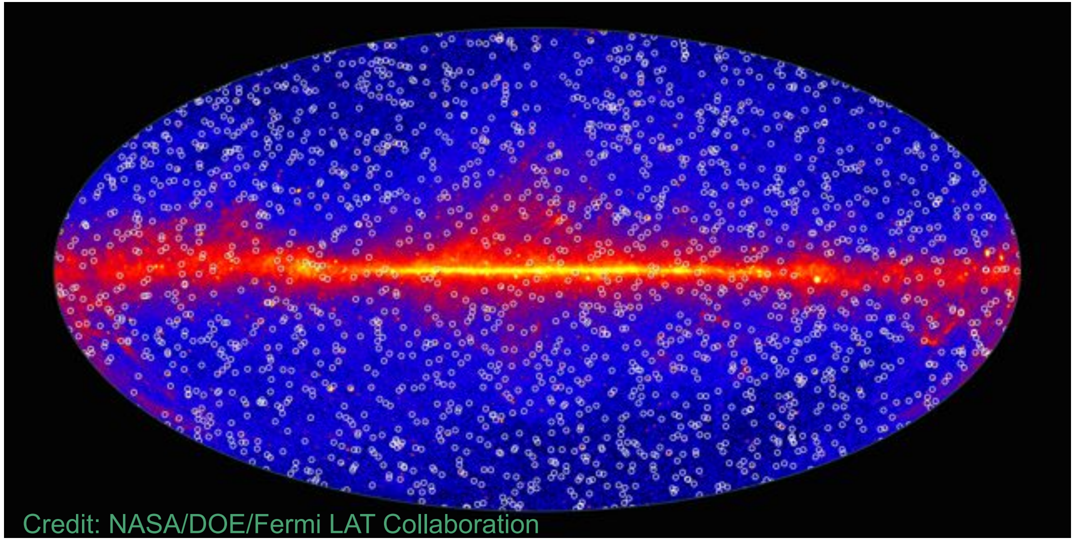


Credit: NASA, ESA, Bin Ren (Université Côte d'Azur/CNRS)

AGN dominate the GeV γ-ray sky

Sky map E_γ > 100 MeV

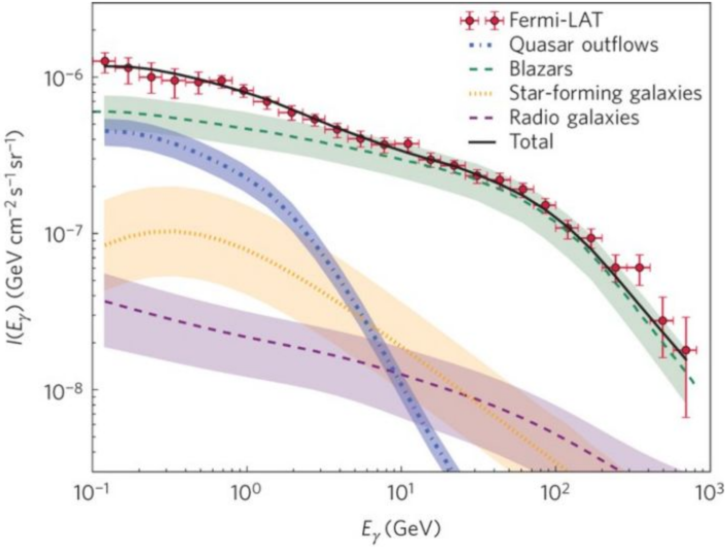




4th Fermi-LAT point-source catalog (4FGL)

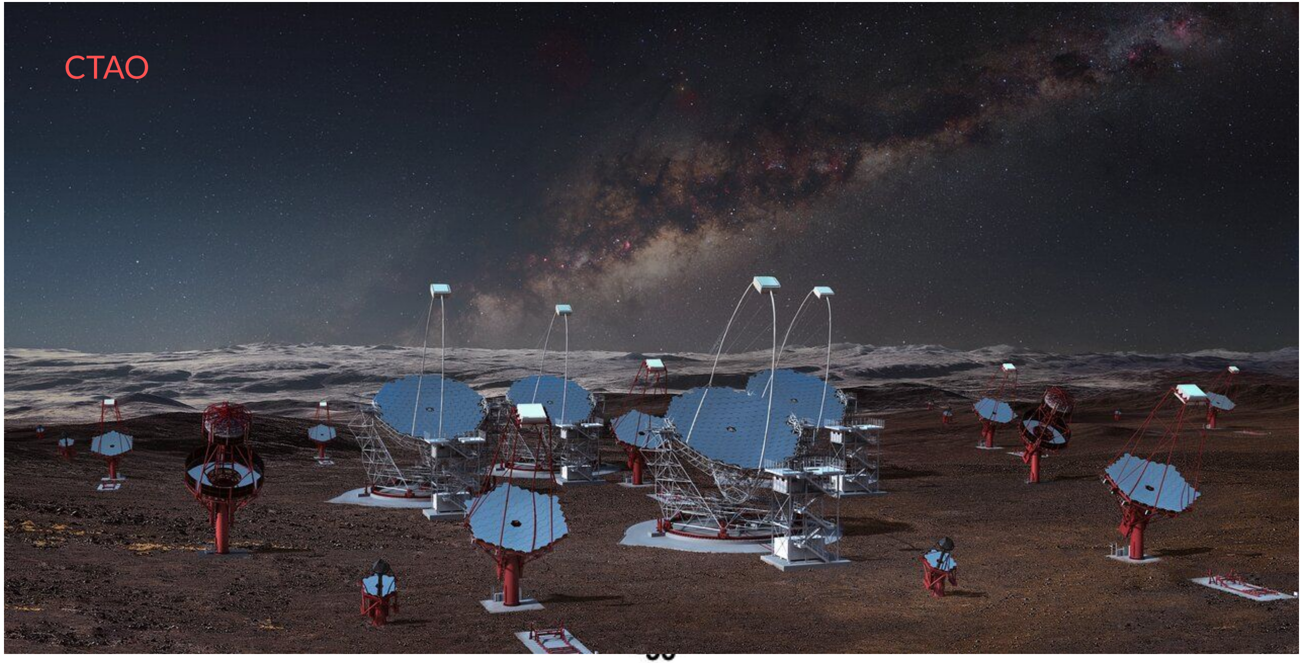
- 8 yr science data
- 5,064 sources
- ~60% AGN (~56% of AGN are blazars)

Extragalactic γ-ray background (EGB)



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

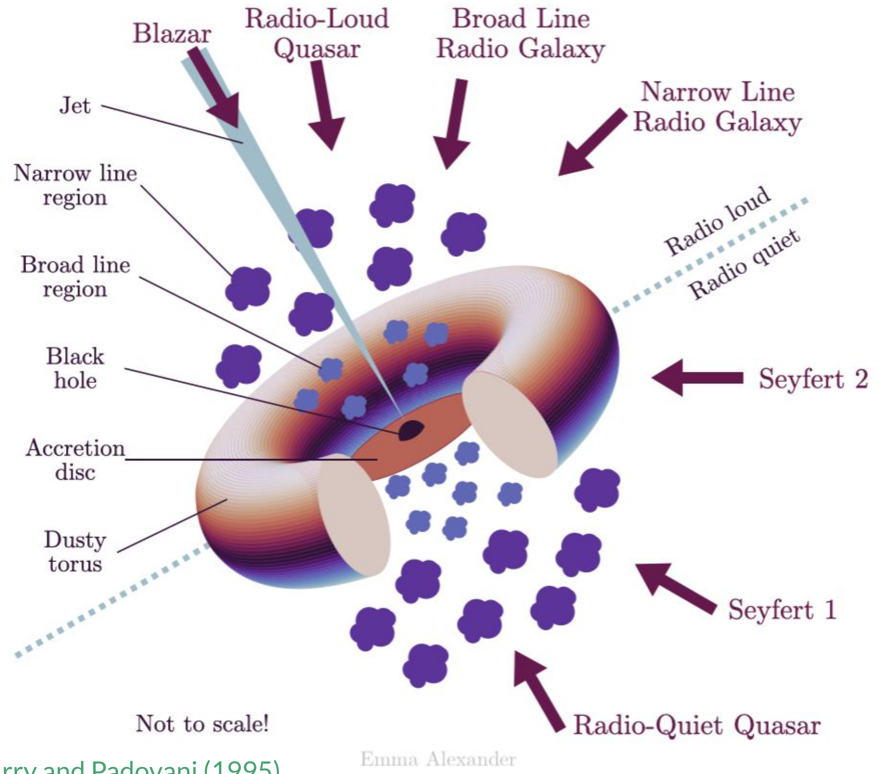
Blazars dominate the TeV γ - ray sky



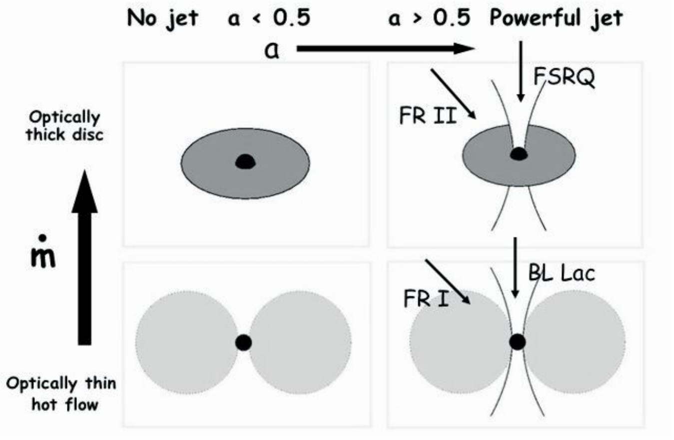
Source Types

- 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)

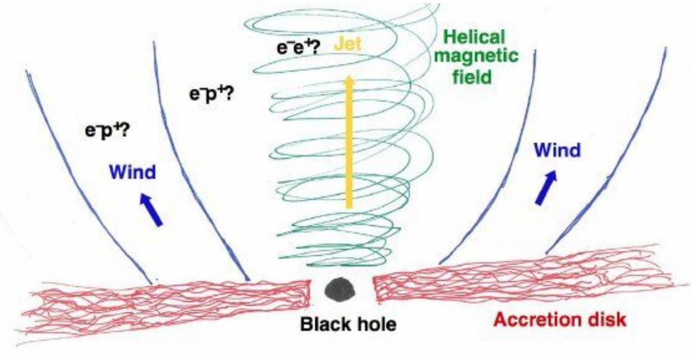
The AGN paradigm



Urry and Padovani (1995)

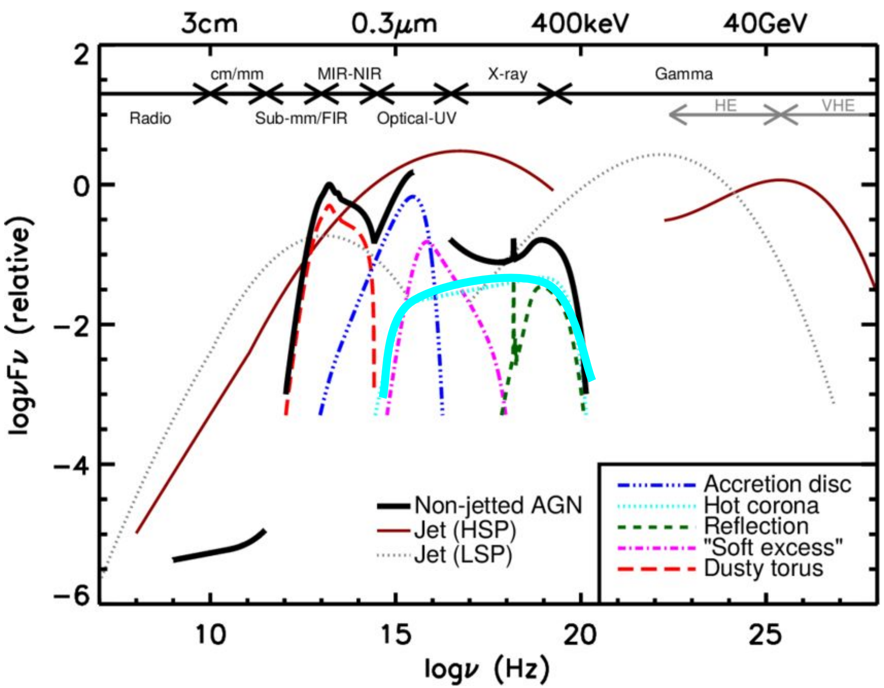


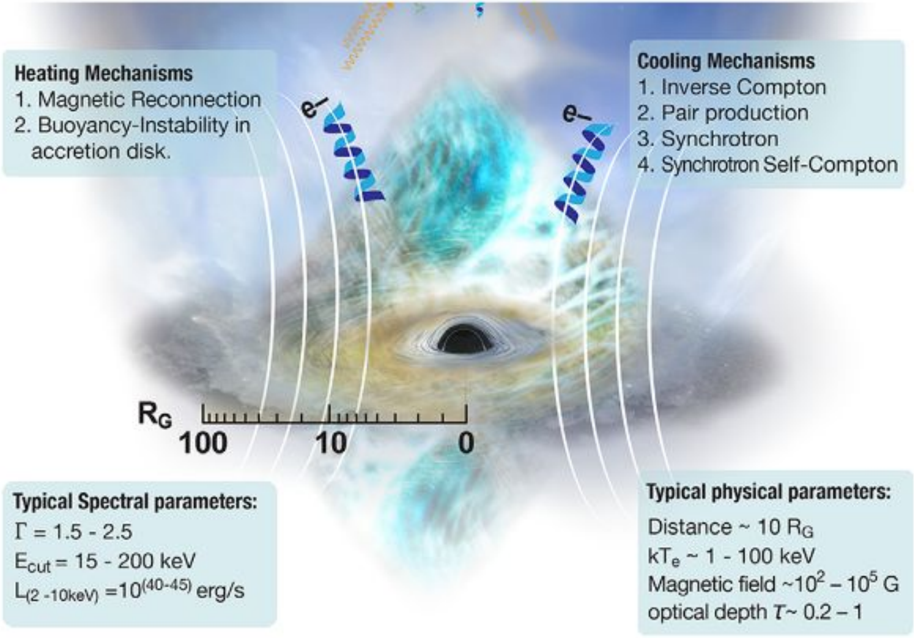
Laura Maraschi et al 2012 J. Phys.



Agudo et al. 2015

AGN corona

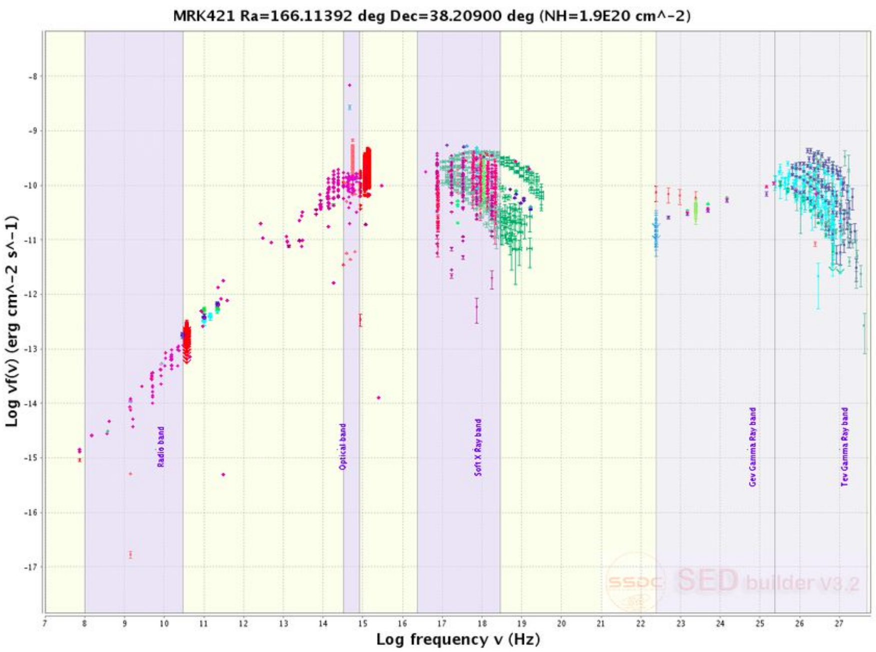




Recent review on X-ray coronae: Laha et al. (2025)

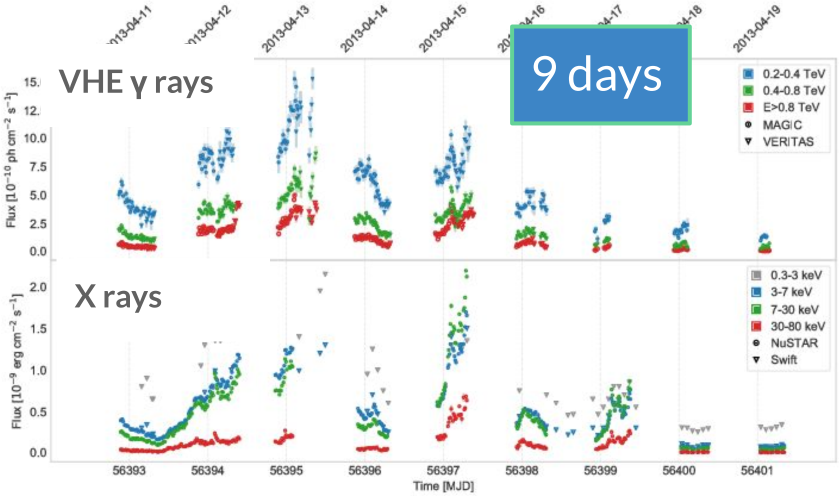
AGN blazar

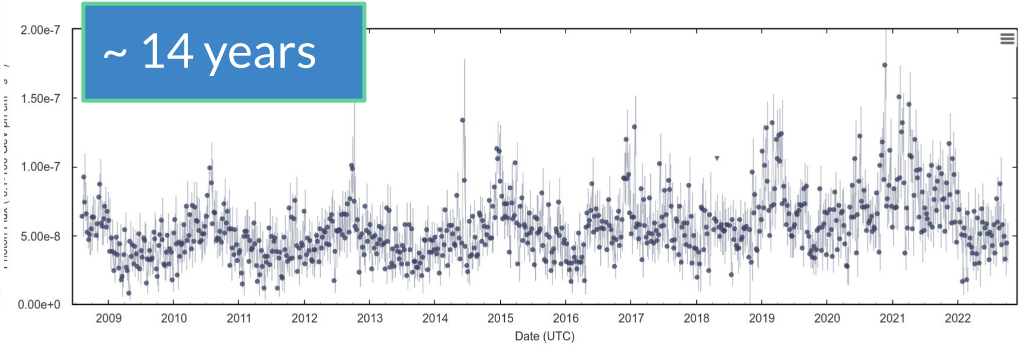
Spectral energy distribution



Credit: SED Builder

Lightcurves





Fermi Lightcurve Repository

Blazar subclasses

Narrowband spectral classification

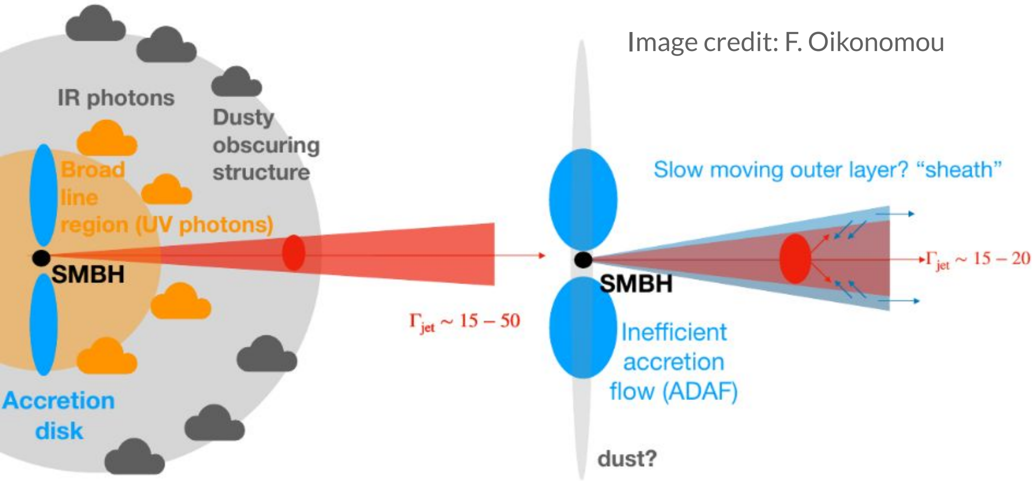
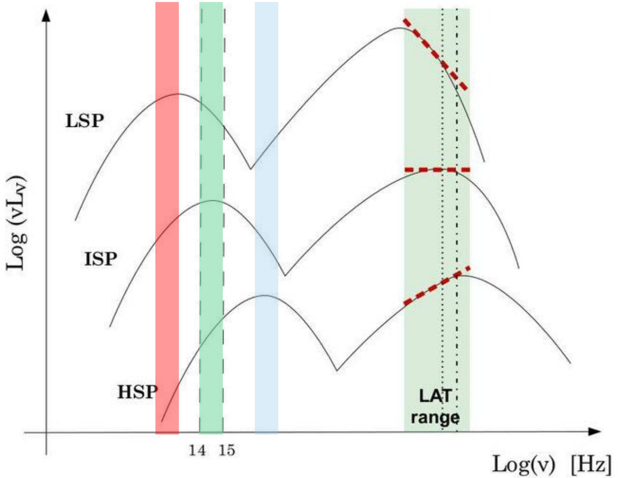


Image credit: F. Oikonomou

Broadband Spectral classification



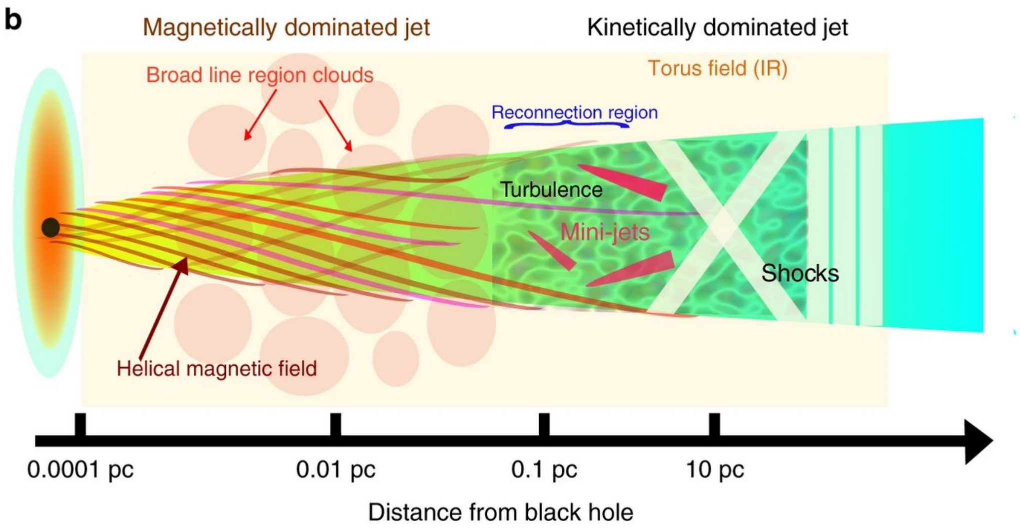
Lico et al. (2017) A&A

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

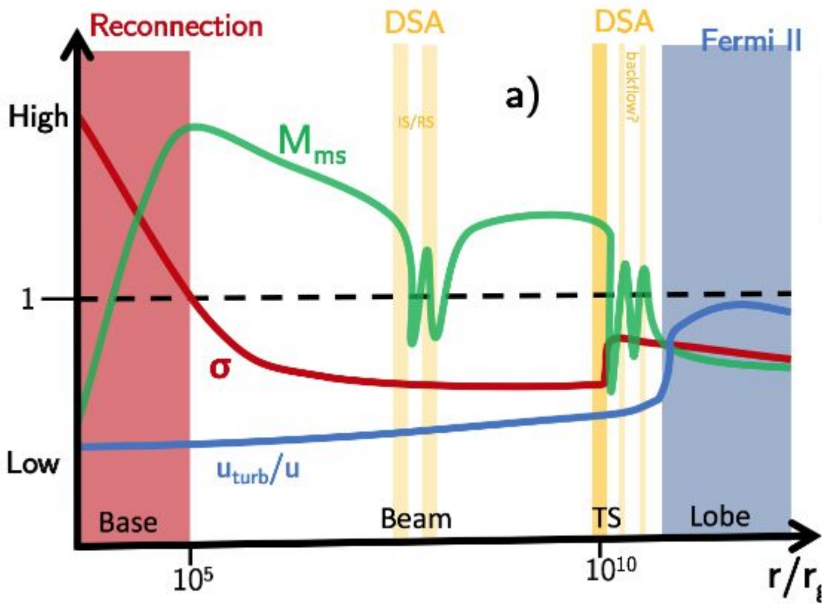
- Weak/absent broad emission lines in optical spectra
- Radiatively inefficient disks
- Accretion at sub-Eddington rates
- Low jet power & γ-ray luminosity

AGN jets: a multi-scale physical problem

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



Shukla & Mannheim, 2020, Nat. Comm.



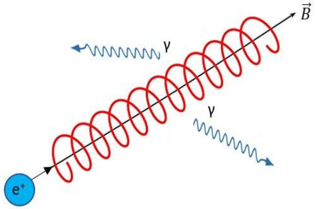
Matthews et al. 2020, NewAR

Numerical modeling

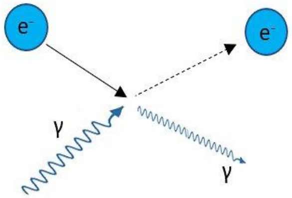
Non-thermal radiative processes

Credit: S. I. Stathopoulos

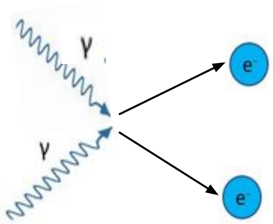
e-syn

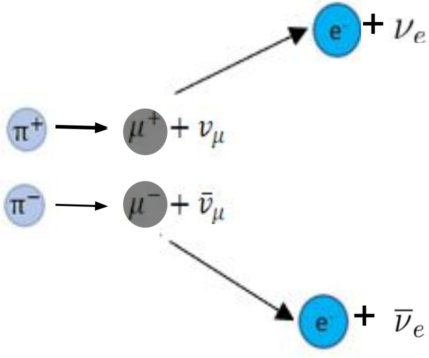


e-ICS

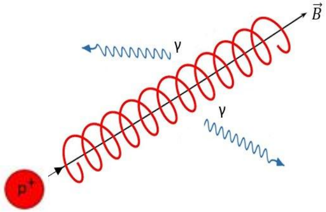


γγ pair production

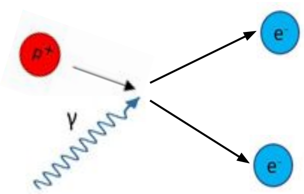




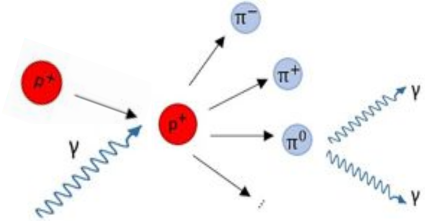
p-syn



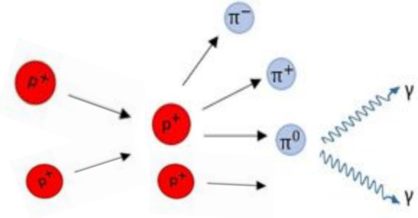
Bethe-Heitler
pair production



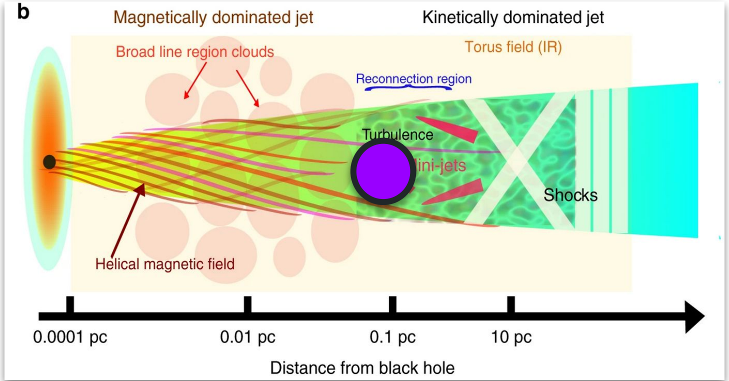
Photopion
production



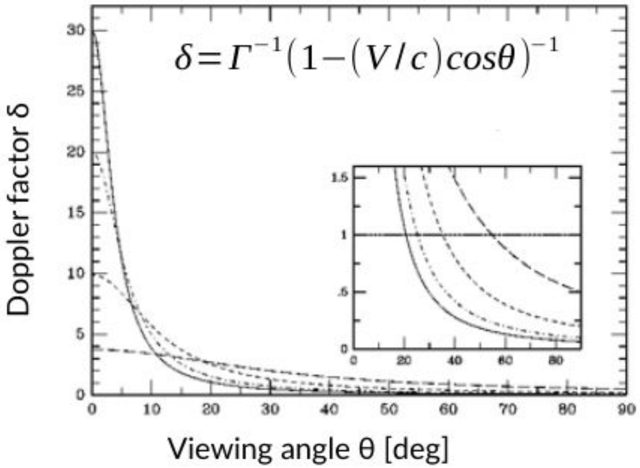
pp collisions



Recipe for radiative transfer in jets

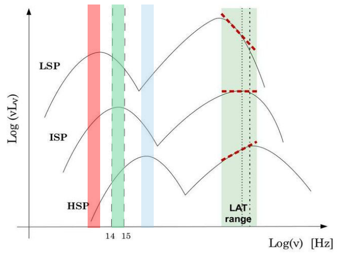


1. Specify emissivity and absorption coefficients for all relevant processes
2. Specify geometry (blob or slab)
3. Solve radiative transfer equation in jet rest frame
4. Apply Doppler boosting to calculate observed quantities



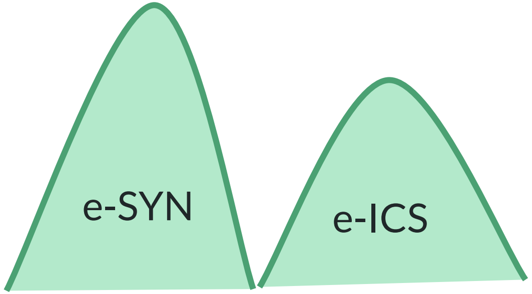
	Jet frame	Observer's frame
Emission pattern		
Luminosity	L'	$L=\delta^4 L'$
Frequency	ν'	$\nu=\delta\nu'$

One-zone emission models

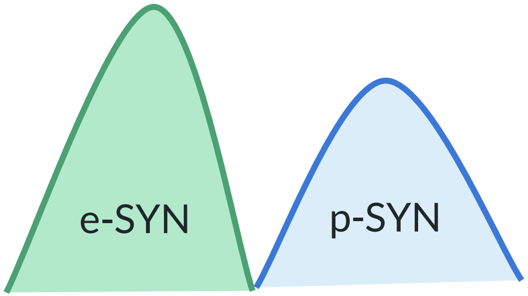


Lico et al. (2017) A&A

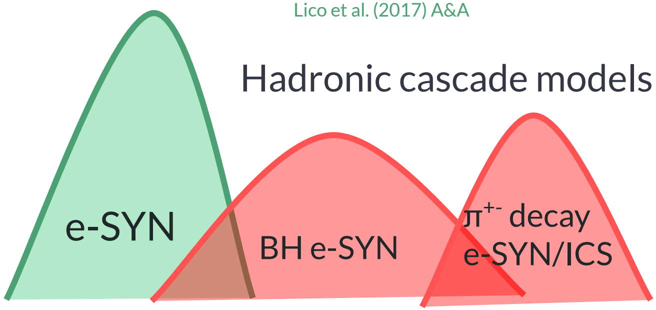
Leptonic synchro-Compton models



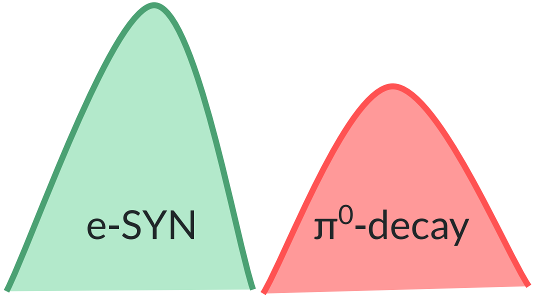
Proton synchrotron models



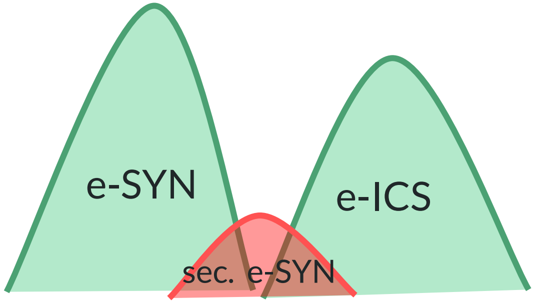
Hadronic cascade models



Neutral pion models



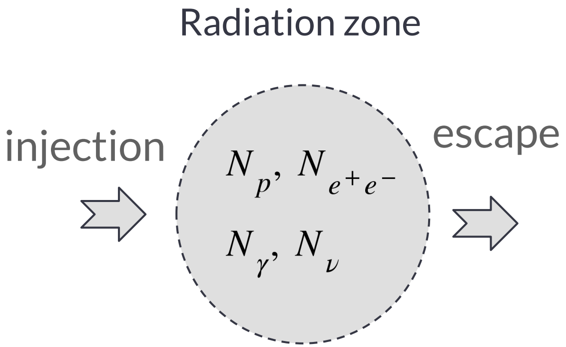
Hybrid leptonic models*



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 ...

Numerical approach



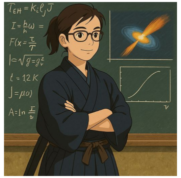
$$\frac{\partial N_i(E,t)}{\partial t} + \frac{\partial}{\partial E}\left(b(E)N_i(E,t)\right) + \frac{N_i(E,t)}{t_{esc}(E,t)} = Q_{inj}(E,t) + Q_{ext}(E,t)$$

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!

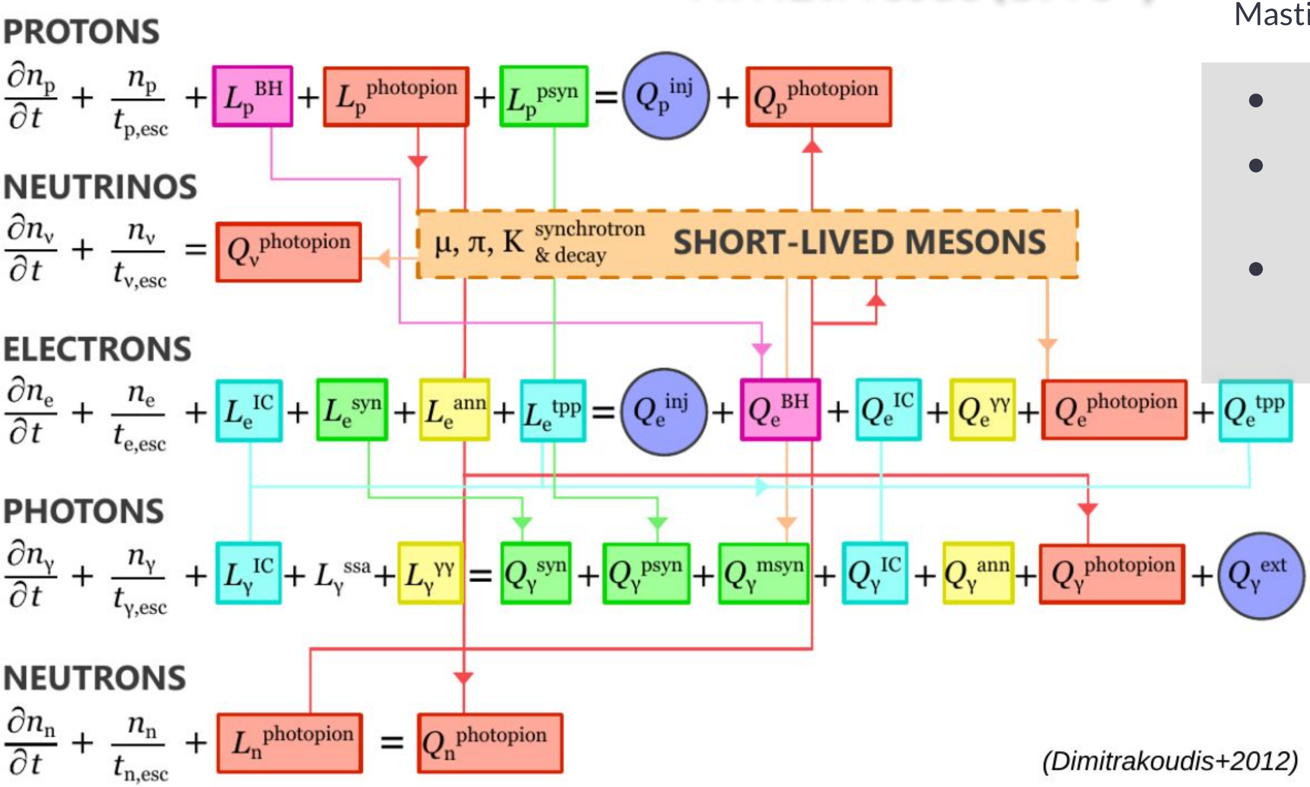
Numerical codes - 1





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

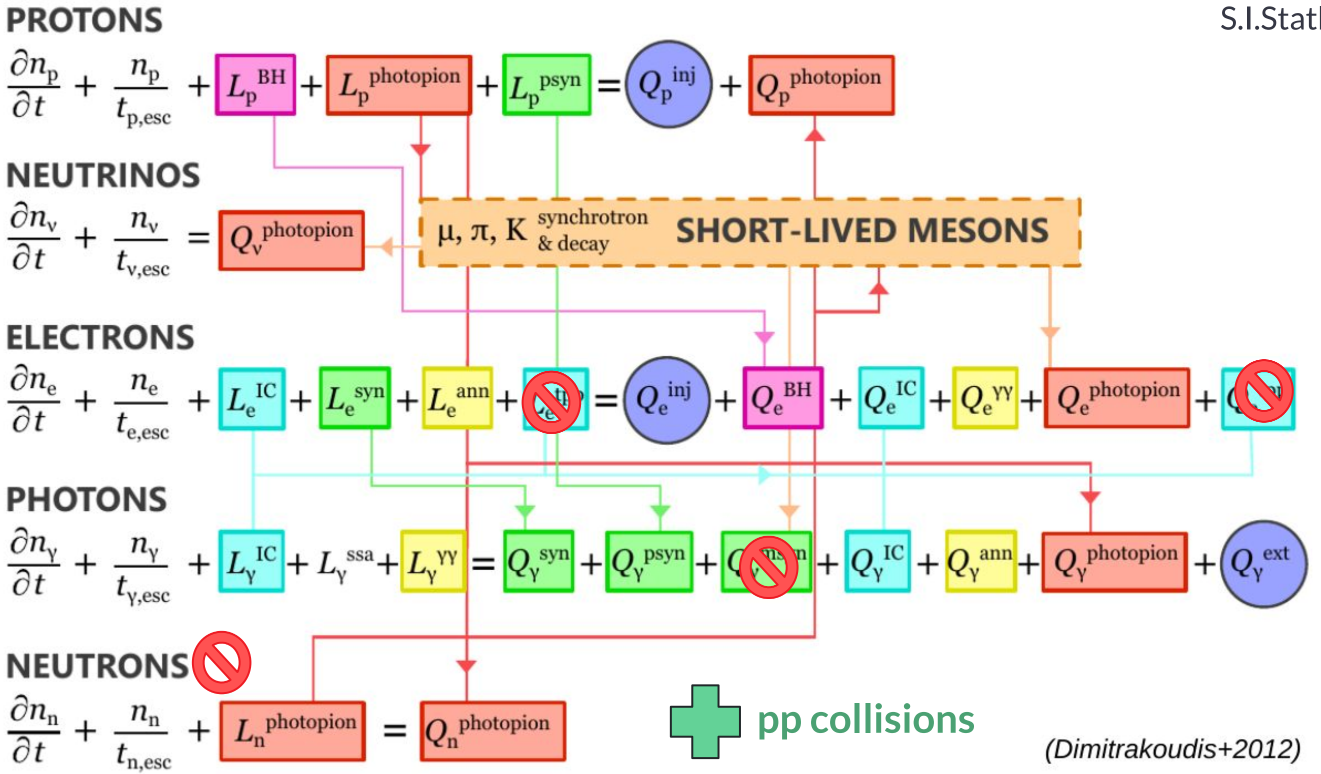
- Proprietary
- Fortran 77 (relying on old libraries)
- Long execution times, not designed for fitting

Numerical codes - 2

TRY...

LeHaMoC (2024 -)

S.I.Stathopoulos



(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

The Hadronic Code Comparison Project

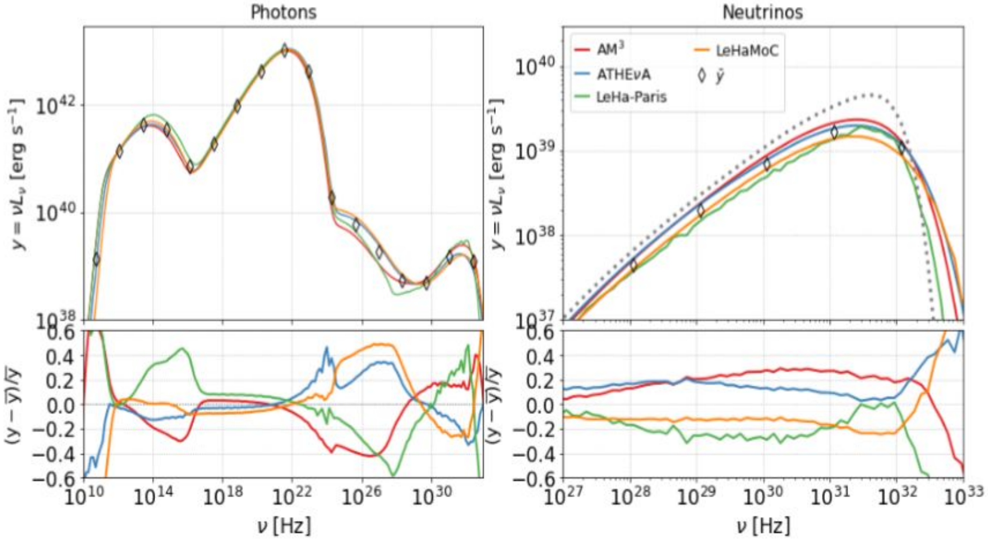
A Comprehensive Hadronic Code Comparison for Active Galactic Nuclei

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

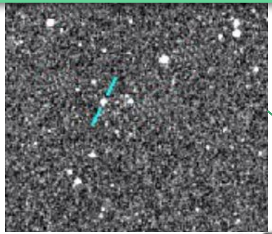
- First comparison of codes used in source modeling
- Determine & quantify systematics
- Help to evaluate modeling results



The only time-dependent leptohadronic public codes

Highlights

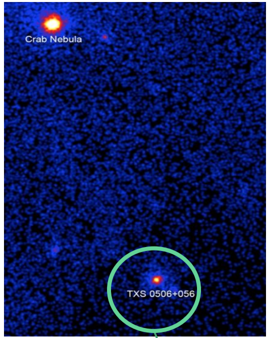
Blazar (D$_L$ > 3.5 Gpc)



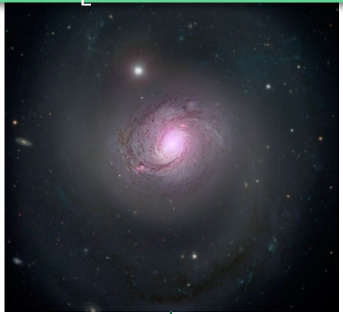
Credit:
Perugia Blazar List

Blazar (D$_L$ ~ 1.8 Gpc)

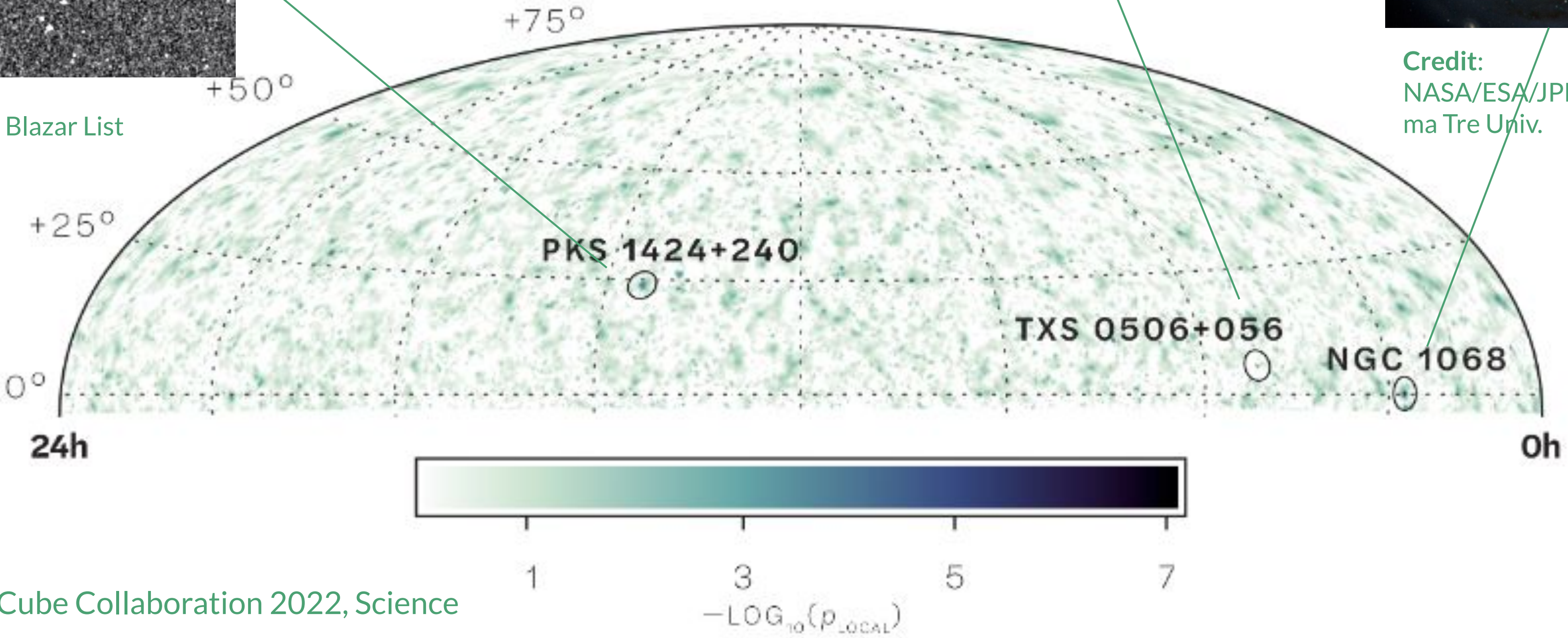
Credit:
NASA/DOE/Fermi
LAT Collaboration



Seyfert 2
(D$_L$ ~ 10.2 Mpc)



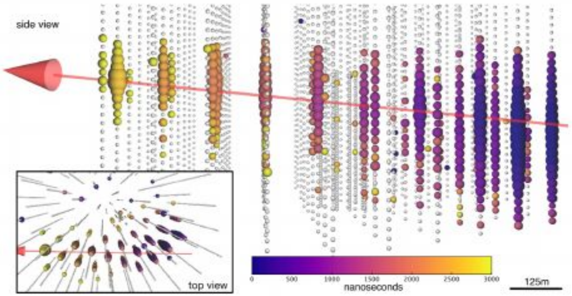
Credit:
NASA/ESA/JPL-Caltech/Roma Tre Univ.



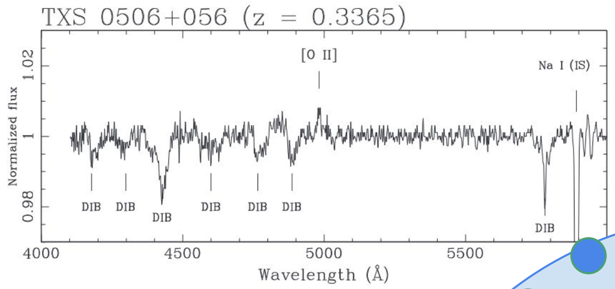
IceCube Collaboration 2022, Science

TXS 0506+056 / IC 170922A

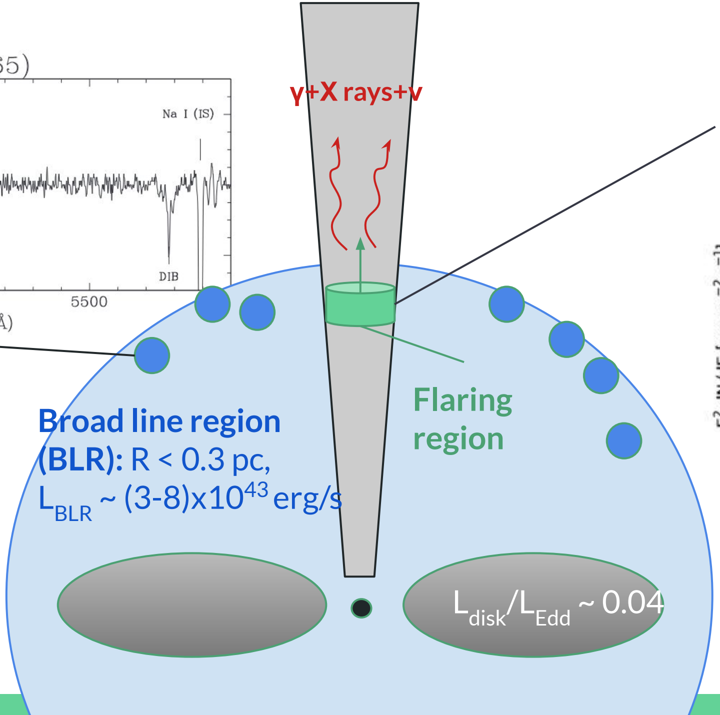
- IC 170922A (~ 290 TeV) detected during a 6 month-long flare
- Blazar at z = 0.3365 from weak emission lines
- Masquerading BL Lac with Esyn, pk < 4 eV [IBL] → hidden broad line region
  (Padovani et al. 2019, MNRAS; Georganopoulos & Marscher 1998; Giommi & Padovani 2013)

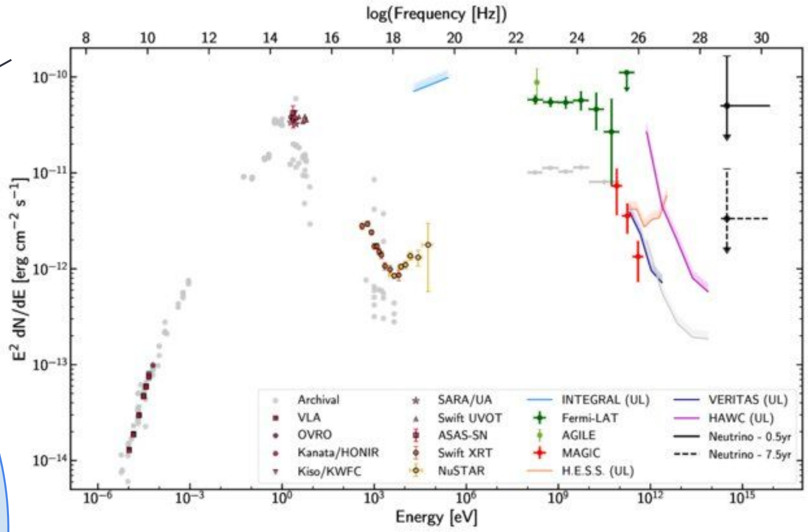


IceCube collaboration 2018, Science



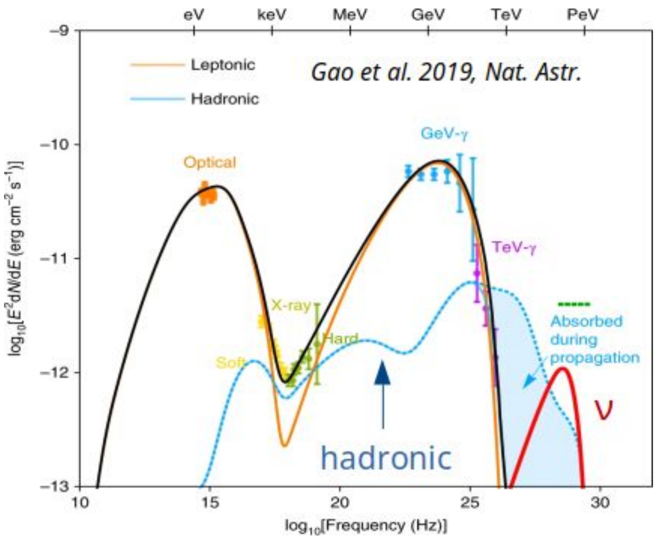
Paiano et al. 2018, ApJL

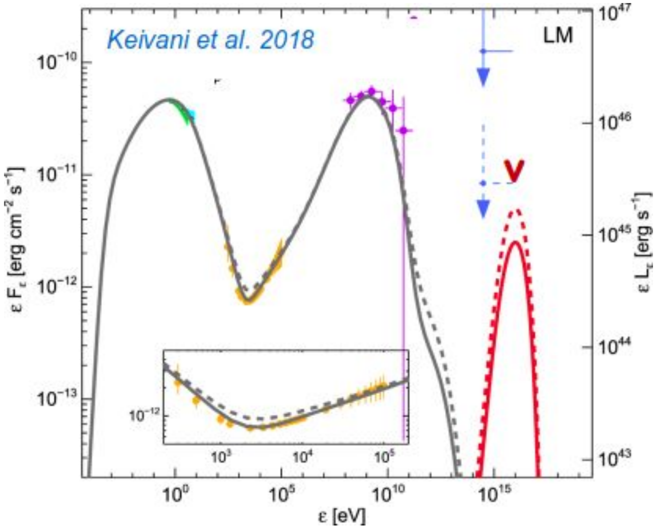




Modeling of the 2017 flare

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



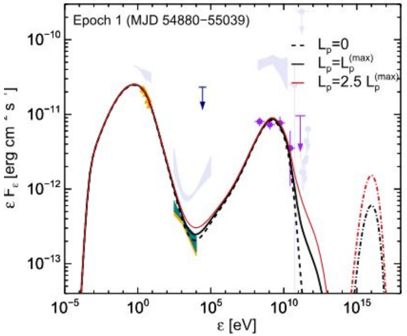


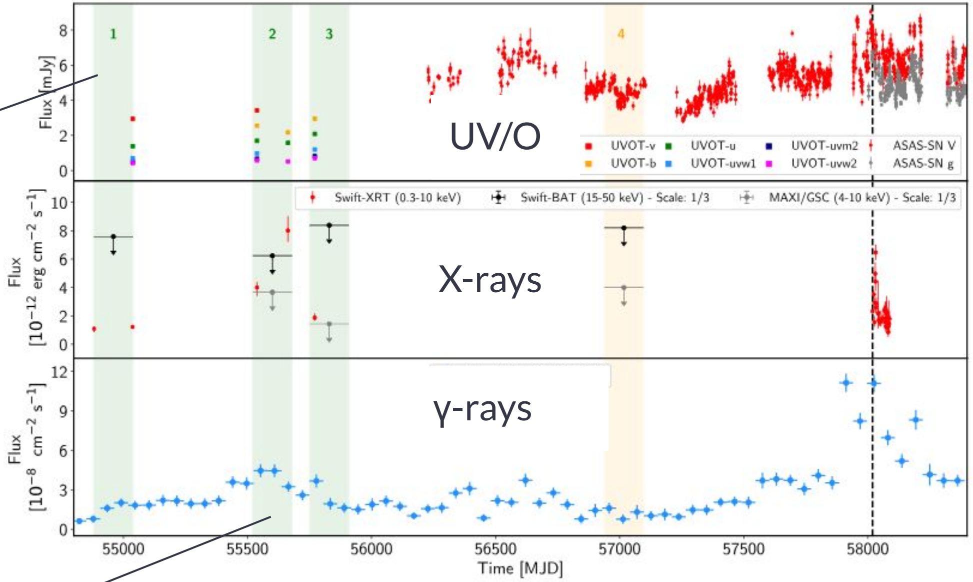
- Leptonic γ-rays → inverse Compton scat. radiation of accelerated electrons
- “Hidden” hadronic emission → **Hybrid model**
- Max. neutrino flux is set by the X-ray flux
- Max. ratio of neutrino-to-γ ray flux **Y ~ 0.03**
- Max. proton energies below EeV → **not an UHECR accelerator**

Check slide 106

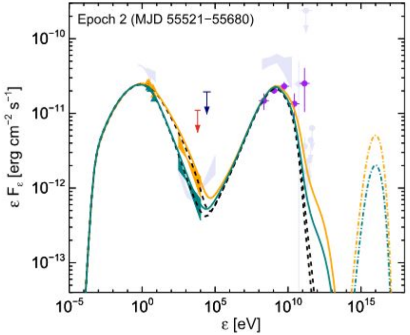
How many ν are expected from other epochs ?

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



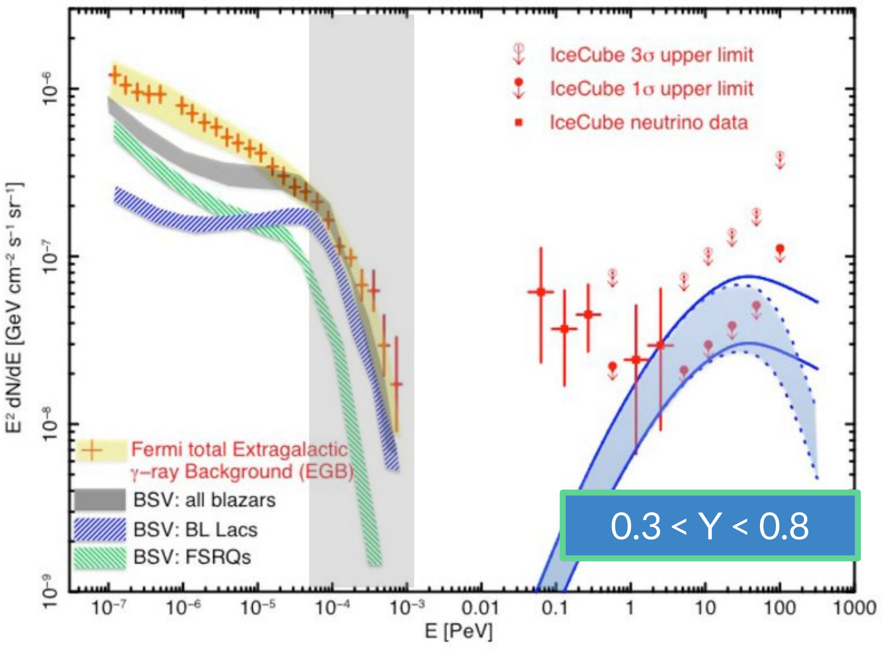


Epoch	$\dot{N}_{\nu_\mu+\bar{\nu}_\mu}$ (yr^{-1})
1	0.04
2[a]	0.2
2[b]	0.1
3	0.2
4	0.1
2017	0.1



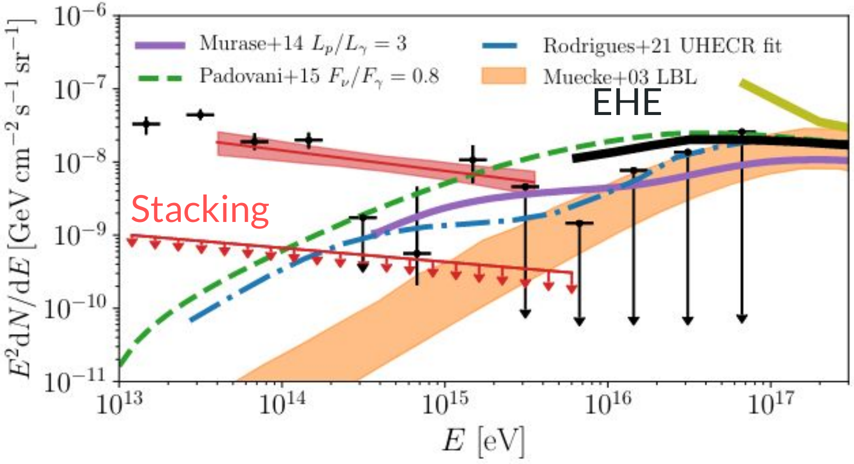
- Synchro-Compton model for all epochs (small changes in power-law index, power of e-)
- Model fails to explain the ν excess in Ep. 4
- Upper limit of **~ 0.4 - 2 muon ν in 10 yr** IceCube obs, **Y < 0.1**
- IceCube-170922A → **upper fluctuation** from average ν rate ?

Diffuse neutrino emission from blazars



Padovani, Petropoulou et al. (2016) MNRAS

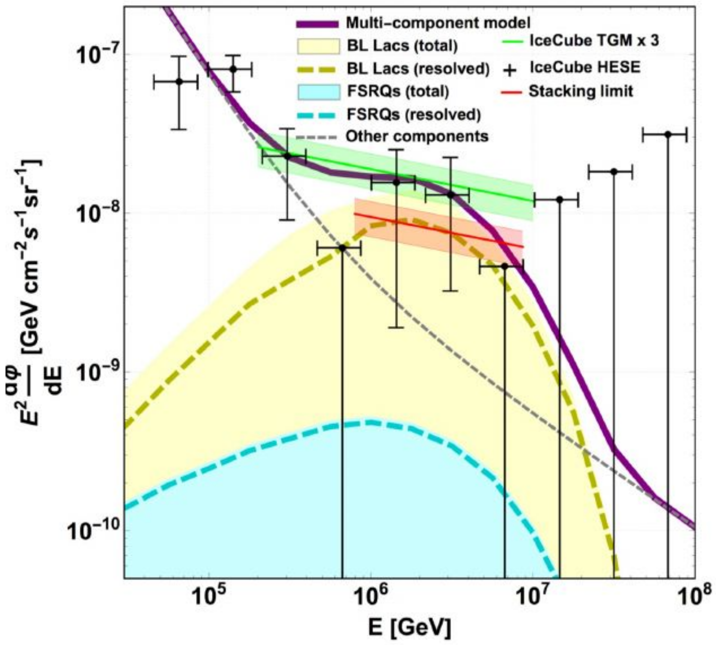
Oikonomou ICRC 21 (arXiv:2201.05623)



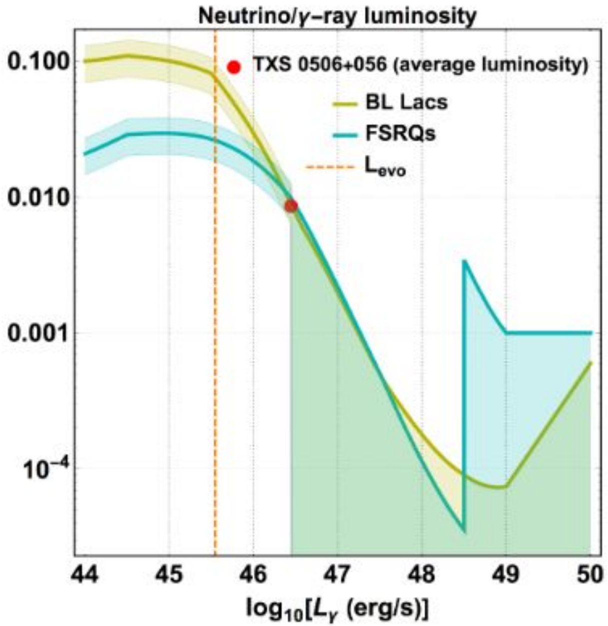
- Blazars (BL Lacs) explain 100% of EGB > 100 GeV and 10% of diffuse ν flux with Y ~ 0.8
- Absence of event clustering → blazar contribution <10-20% to diffuse ν flux
- Stacking limits (Fermi 3LAC) → blazar contribution <5-15% to diffuse ν flux
- IceCube 9yr extreme high-energy (EHE, > 5 PeV) limits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

Is Y universal in the blazar population?

Hypothesis: AGN blazars describe the diffuse ν flux



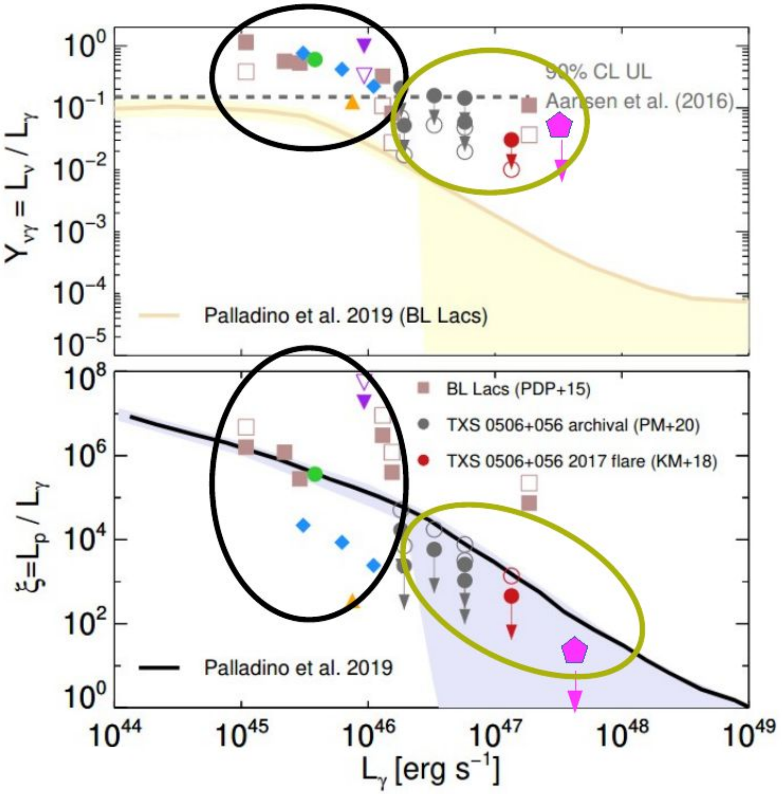
Palladino et al. (2019) ApJ



Findings:

- Unresolved BL Lacs describe the diffuse ν flux
- Baryonic loading ξ (=Lp/Lγ) and ratio Y (=Lν/Lγ) must evolve with with Lγ → **Data driven approach**

Is Y universal in the blazar population?



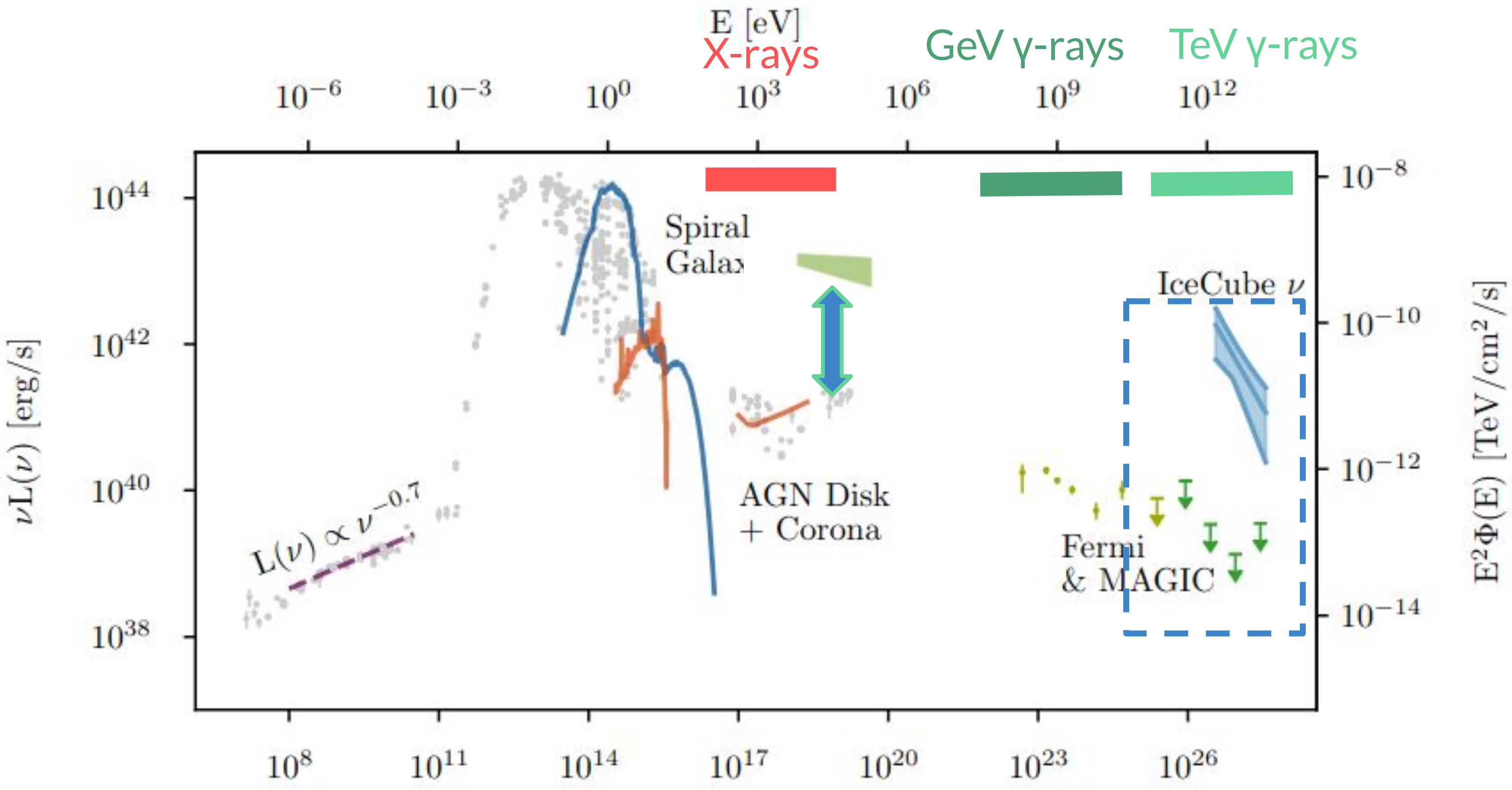
Results from hybrid models (upper limits) and cascade models (symbols) for different types of blazars: PKS 1502+106 (FSRQ, hexagon), TXS 0505+056 (masquerading BL Lac; circles), true BL Lacs (squares), and 3HSP J095507.9+35510 (extreme** BL Lac; other symbols)

Modeling of individual blazars hints to a **negative trend** of ξ (=Lp/Lγ) and Y (=Lν/Lγ) with Lγ!

** Modeling of a large sample of extreme BL Lacs from the 3HSP catalog is under way (Maria Rosaria Musone, Antonio Marinelli)

Petropoulou et al. (2020) ApJ

A multi-wavelength view of NGC 1068



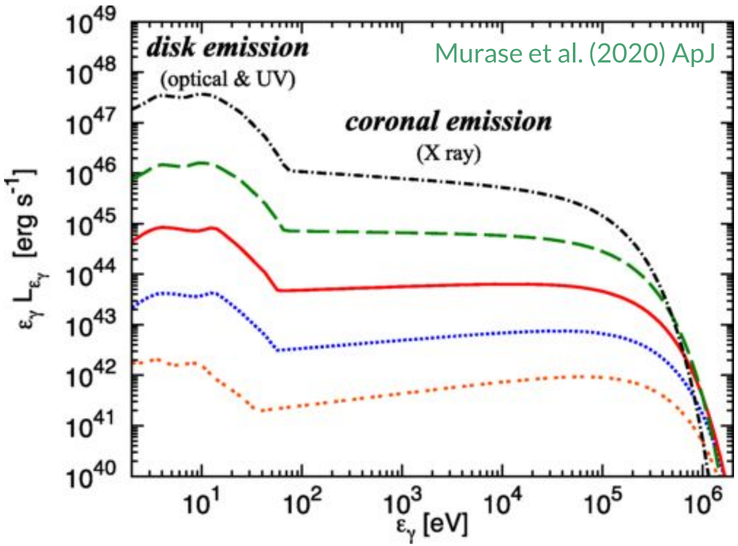
Padovani et al., 2024, Nat. Astronomy

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

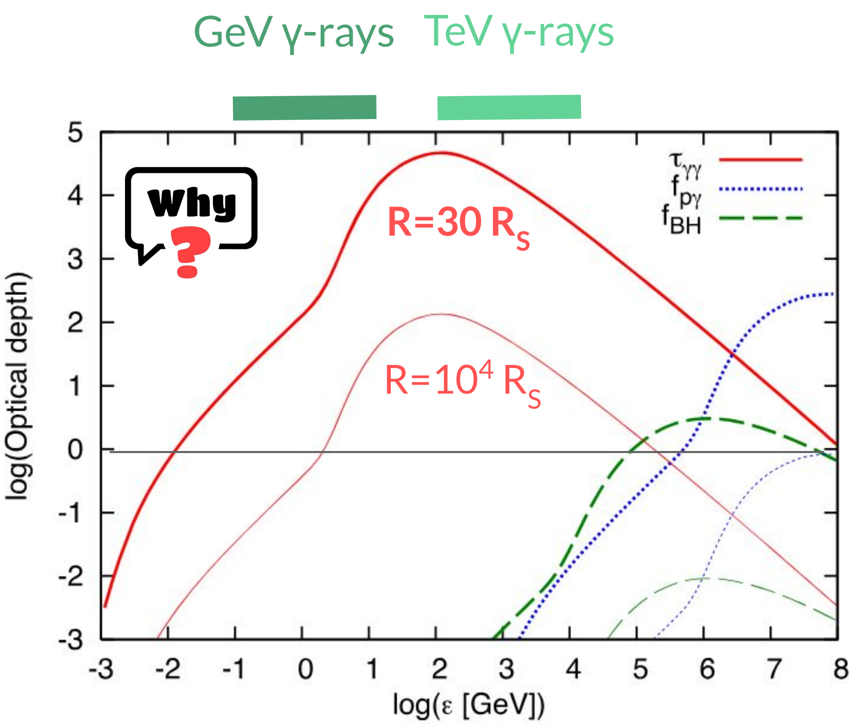
Check slide 52

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 et al. (2020) ApJ



Murase (2022) ApJ

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)
  - Diffuse shock acceleration (Inoue et al. 2019, 2020, Eichmann+2022)
  - Magnetic reconnection (Kheirandish+2021, Fiorillo+2024a, Karavola+2025)

+ Exercise

Common findings

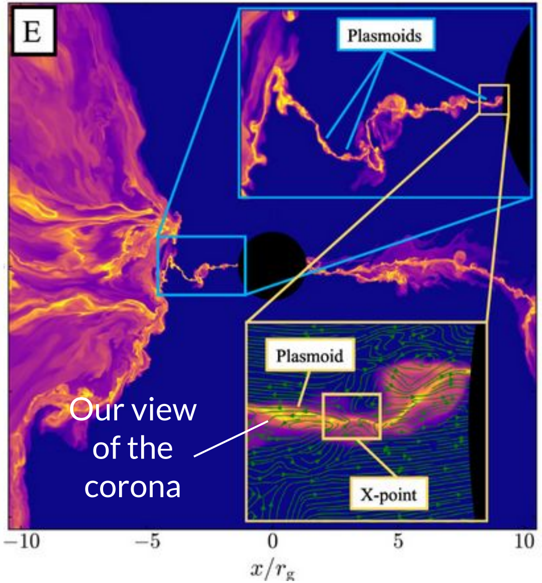
- Neutrino production site:
  - inner disk and/or corona
  - opaque to TeV γ-rays → constraints on coronal size
- GeV γ-rays: starburst
- MeV γ-rays: hadronic cascade

Different findings

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

Corona powered by reconnection

Fiorillo et al., 2024a, ApJL



Ripperda et al. (2022)

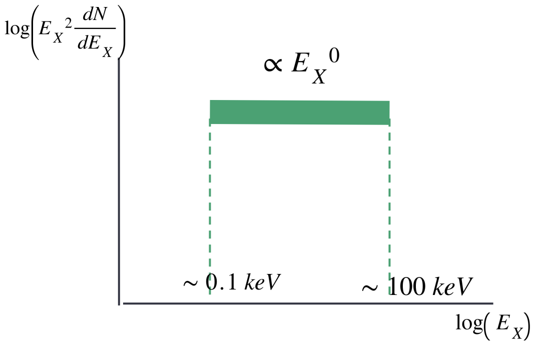
Poynting flux

Comptonized X-ray luminosity	Relativistic proton luminosity
$L_X = \eta_X S_P A$	$L_p = \eta_p S_P A = \frac{\eta_p}{\eta_X} L_X.$
+	+
Corona spectrum	Proton spectrum

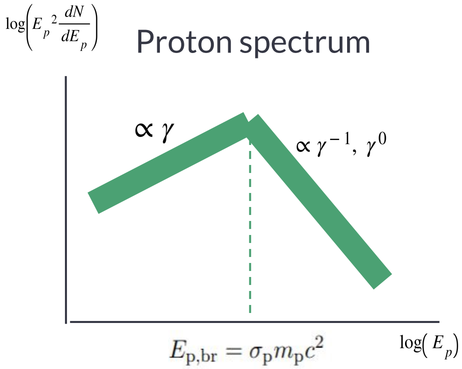
p-γ collisions

Neutrino spectrum

Corona spectrum



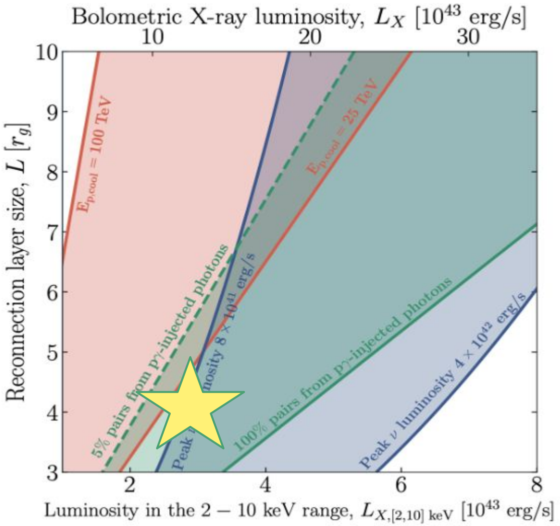
Proton spectrum

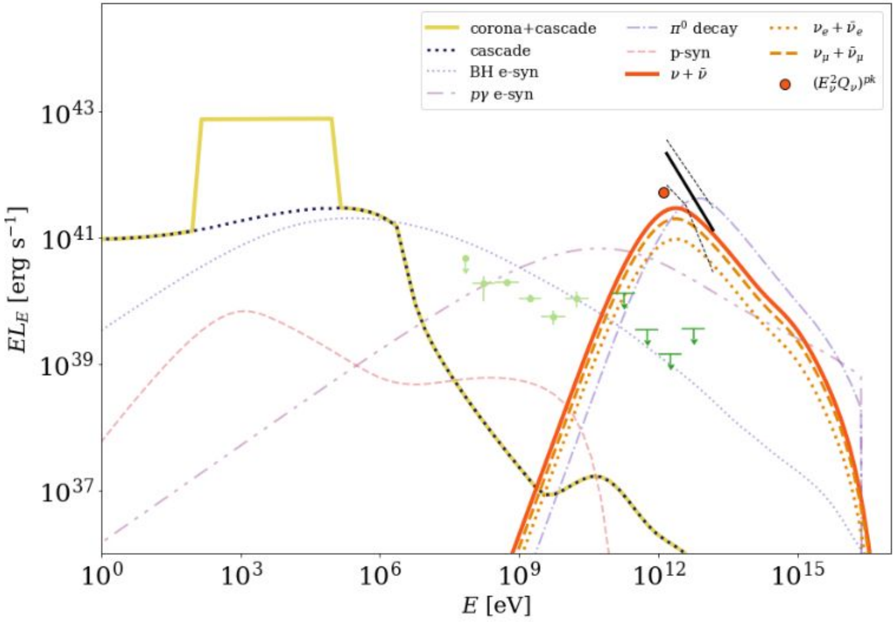


For particle acceleration check : Werner & Uzdensky 2017, Chernoglazov et al. 2023, Zhang et al. 2021, 2023

Fiorillo et al., 2024, ApJL

Results for NGC 1068





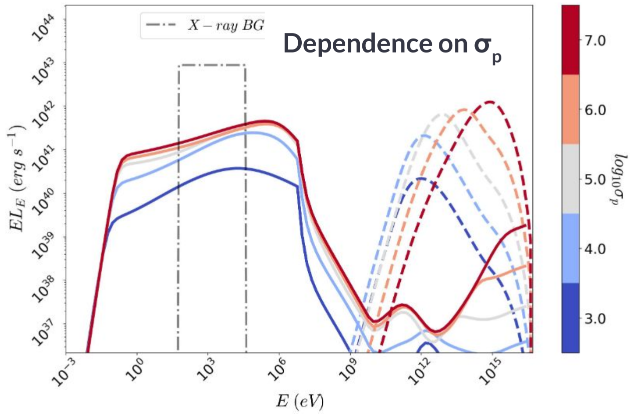
- Compact corona: L ~ (3-10)*R_g
- Pair dominated corona: $n_{ee}/n_p \sim 10^{6-7}$

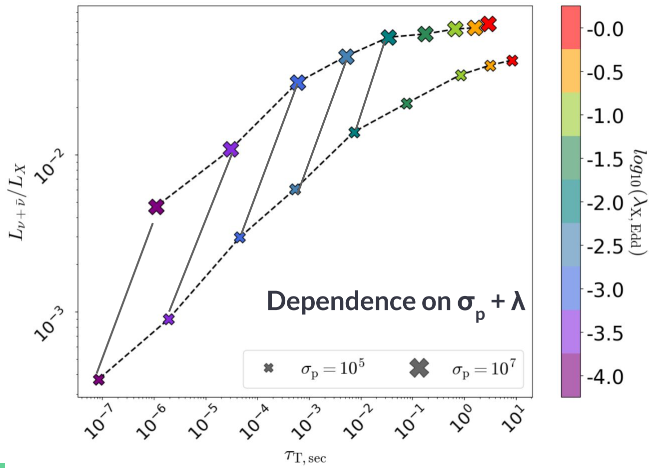
- Highly magnetized corona: $\sigma_e \sim 10^2$ and $\sigma_p \sim 10^5$
- Non-thermal-to-thermal proton fraction: ~1
- Not an UHECR accelerator

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

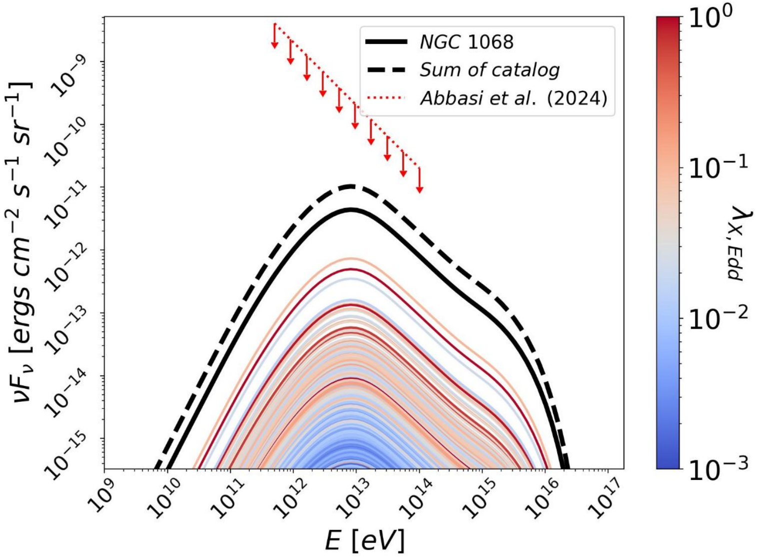
Extending to other AGN

Karavola et al., 2025, JCAP





Stacking signal from ~ 700 AGN
(Swift/BAT-70M catalog; Ricci+2017, ApJ)



Key Parameters:

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

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

$$\nu F_{\nu,i} = \nu L_{\nu,1068} \frac{L_{X,i}}{L_{X,1068}} \frac{\nu L_{\nu,i}}{L_{X,i}} (4\pi D_i)^{-2}$$

Neutrino-to-X-ray luminosity ratio is not a constant!

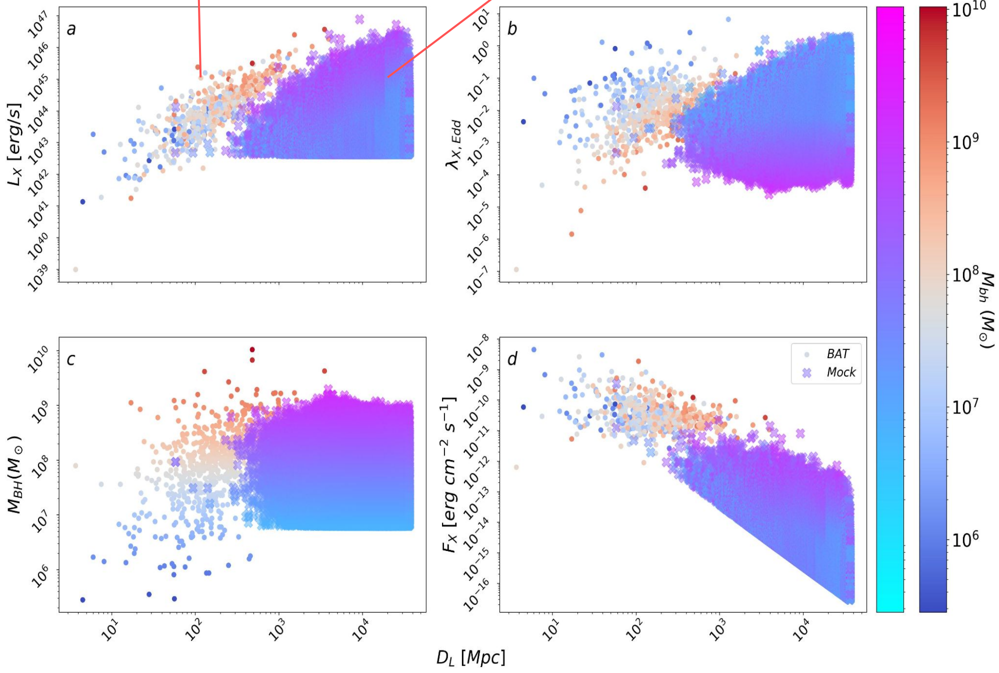
Diffuse ν emission from non-jetted AGN

Karavola et al., in prep.

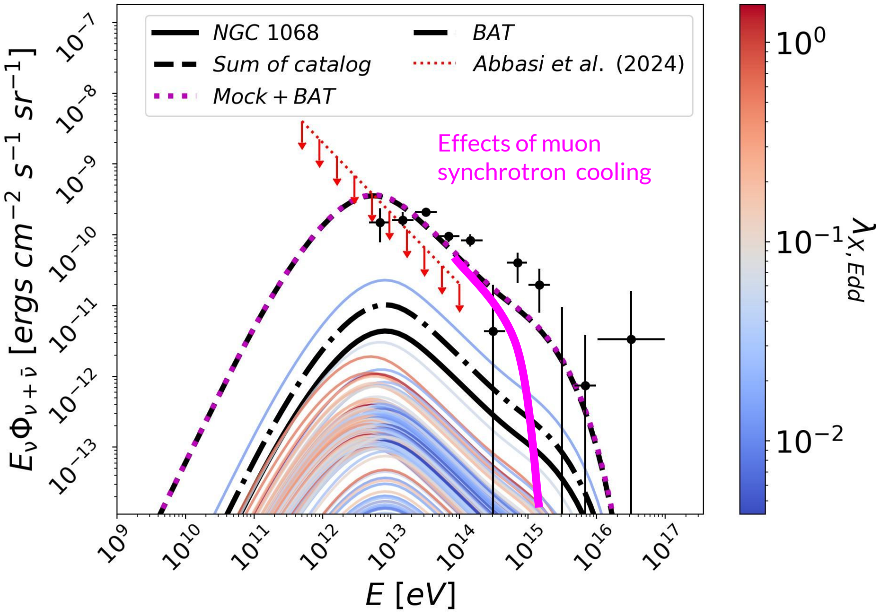
PRELIMINARY

Swift/BAT-70M catalog (Ricci+2017, ApJ)

Mock AGN catalog (Georgakakis, Ruiz, LaMassa 2020)

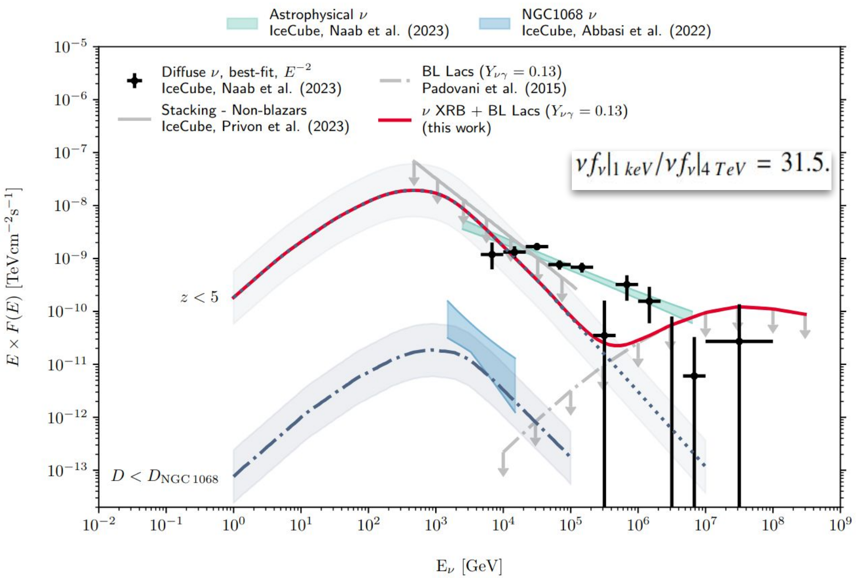


Main hypothesis: all coronae with σ_p=10^5



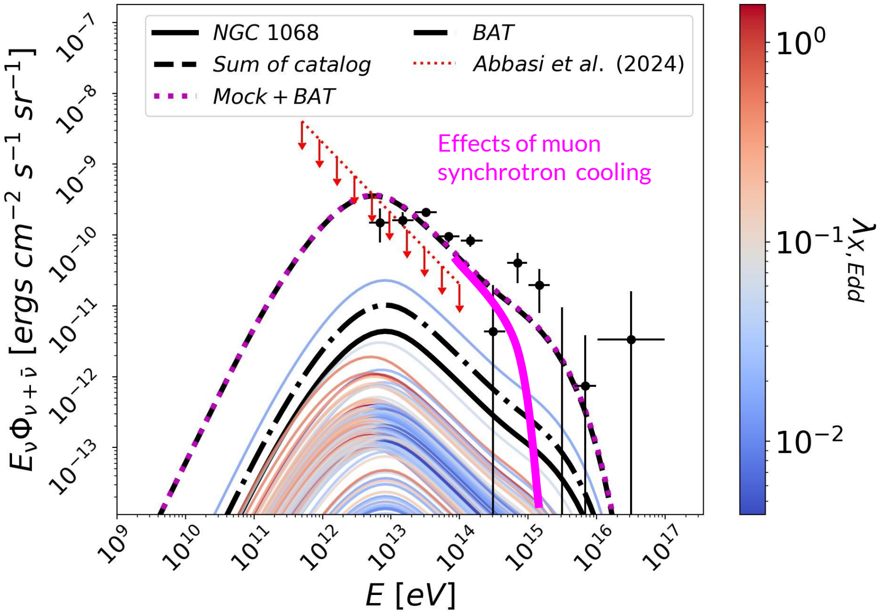
Diffuse emission from AGN

Data driven approach



Padovani et al. (2024) MRNAS

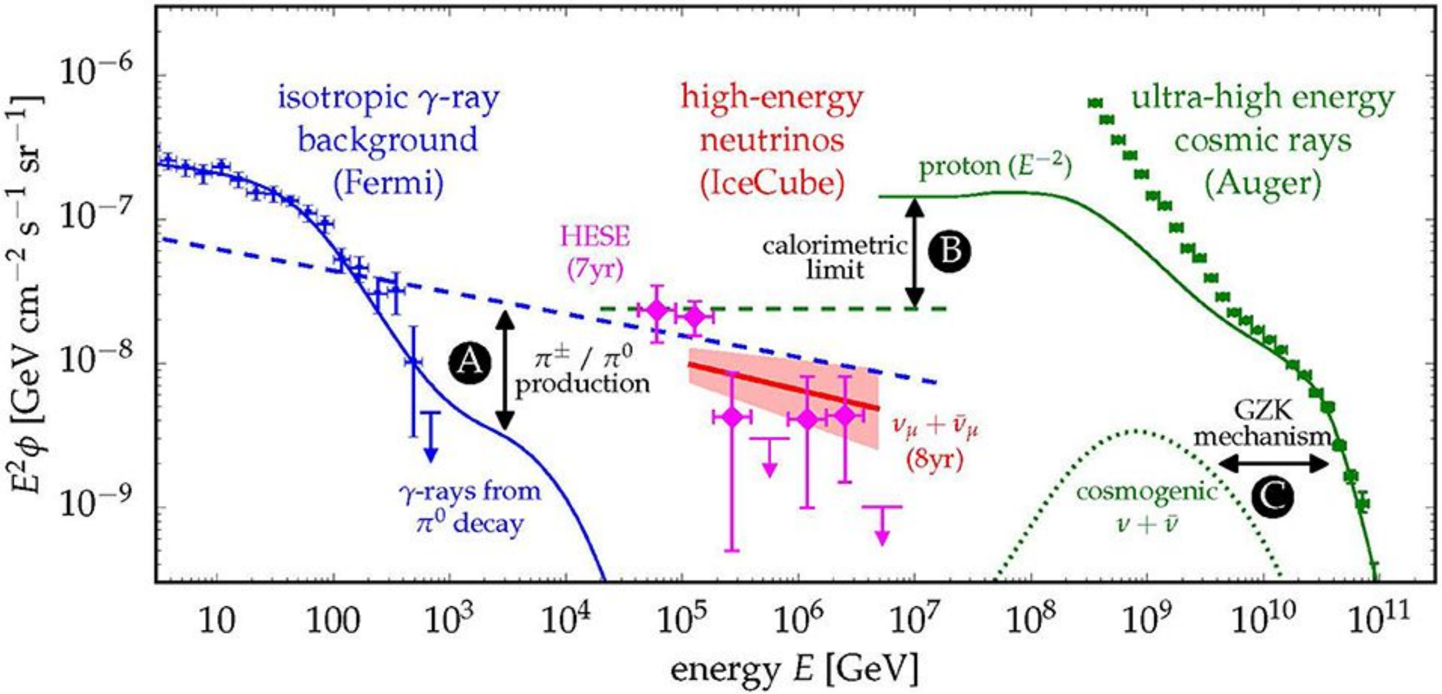
Physically driven approach



Karavola et al., in prep.

The multi-messenger picture

Energy production rates are comparable to a few ~10^{43} erg Mpc^{-3} yr^{-1} → Common sources?



Halzen & Kheirandish, 2019, Frontiers

Key questions

What is the driving particle acceleration mechanism?

Where in the jet are the flares produced?

Where in the jet are neutrinos being produced?

Can data-driven approaches reveal the conditions in the emitting region(s) of AGN jets?

What is the disk-corona-jet connection?

Summary - 2+3

- 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 rel. 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.
- Usual numerical approach: PDE solvers for non-linear and non-stationary physical problems
- Sources of diffuse neutrino flux and UHECRs remain unknown.

Useful References

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Useful References

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2. Malcolm S. Longair, *High Energy Astrophysics*, Cambridge, UK: Cambridge University Press, 2011
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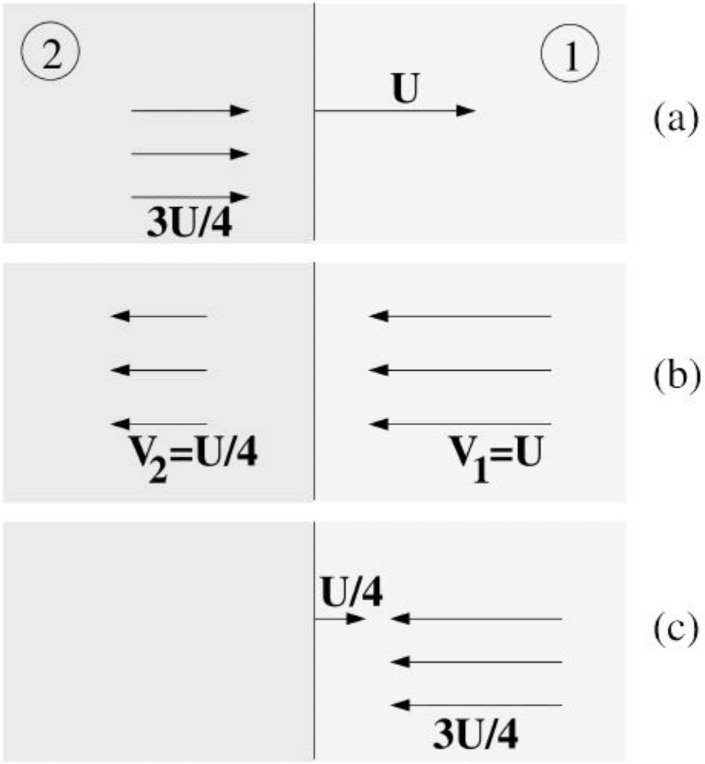
5. Palladino A., Fedynitch A., Rasmussen R.~W., Taylor A.~M., 2019, JCAP, 2019, 004. doi:10.1088/1475-7516/2019/09/004
6. Laha S., Ricci C., Mather J. C., Behar E., Gallo L., Marin F., Mbarek R., et al., 2025, FrASS, 11, 1530392. doi:10.3389/fspas.2024.1530392

Backup

Fermi shock acceleration: basics



$$r = \frac{(\gamma+1)M_1^2}{(\gamma_1-1)M_1^2+2} \to \frac{\gamma+1}{\gamma-1}$$

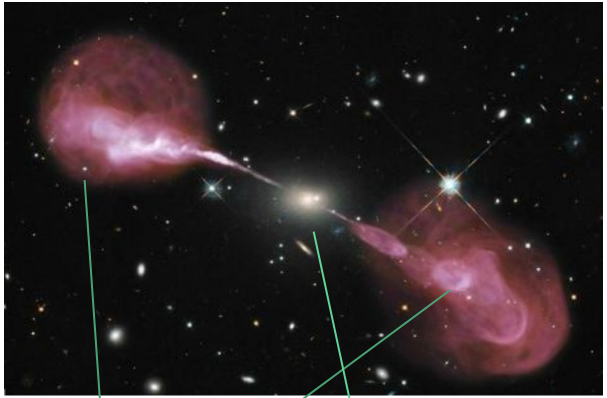
$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\frac{v_1 - v_2}{c}$$

$$N(E) \propto \left(\frac{E}{E_0}\right)^{-\alpha} \quad \text{with} \quad \alpha = \frac{3}{r-1} + 1 = \frac{r+2}{r-1}$$

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\frac{\ln(1-U/c)}{\ln(1+U/c)}} \approx \left(\frac{E}{E_0}\right)^{-1} \Rightarrow N(E)dE \propto E^{-2}dE\,,$$

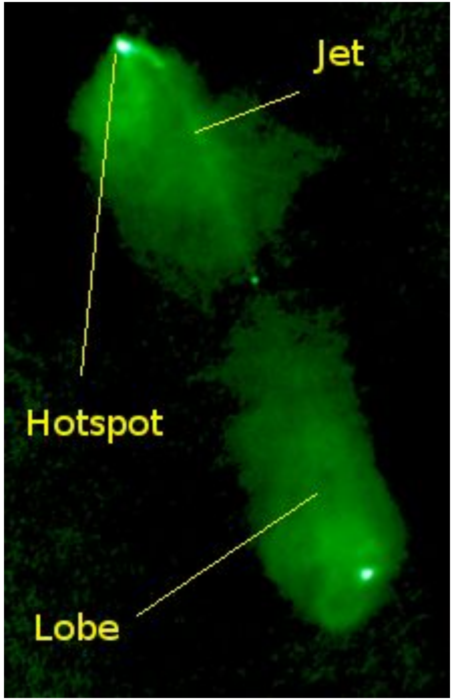
Radio galaxies

Hercules A

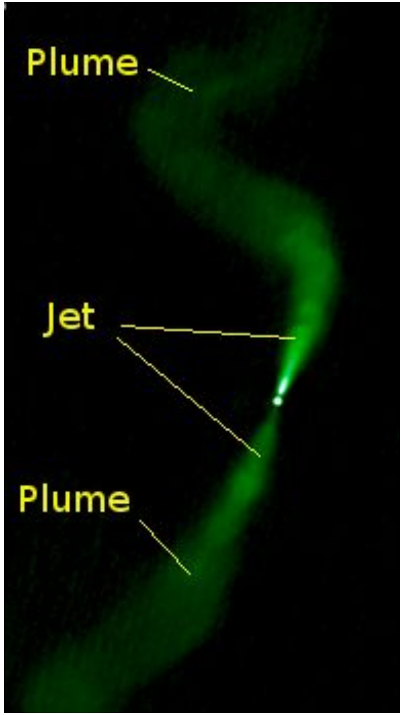


Radio jets
(~500 kpc)

Host galaxy in
optical light



FRII radio galaxy 3C98.



FRI radio galaxy 3C31

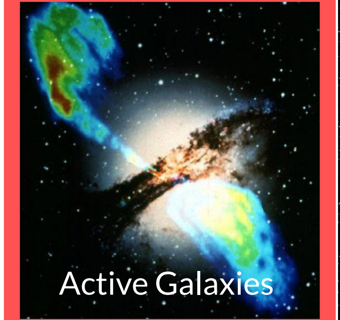
Opacity ~ Efficiency

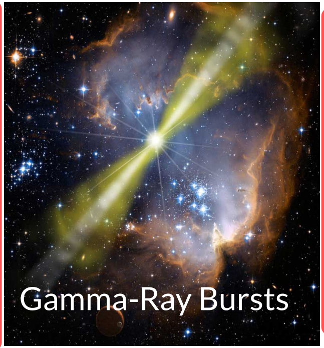
Opacity = cross section * target density * length

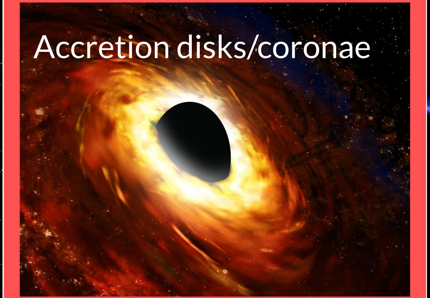
$$\tau = \int dl \int d\Omega \int d\varepsilon \, n_t(\varepsilon, \Omega) \; \sigma(\gamma_{rel}) \; c \, \beta_{rel} \left(1 - \vec{\beta}_p \cdot \vec{\beta}_t\right) \; \sim L \, \sigma \, n_t$$

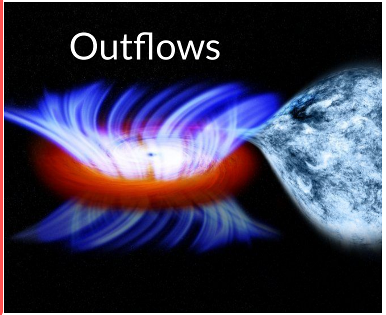
More photon content

More gas content









Comparing the opacity for pγ and γγ processes

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

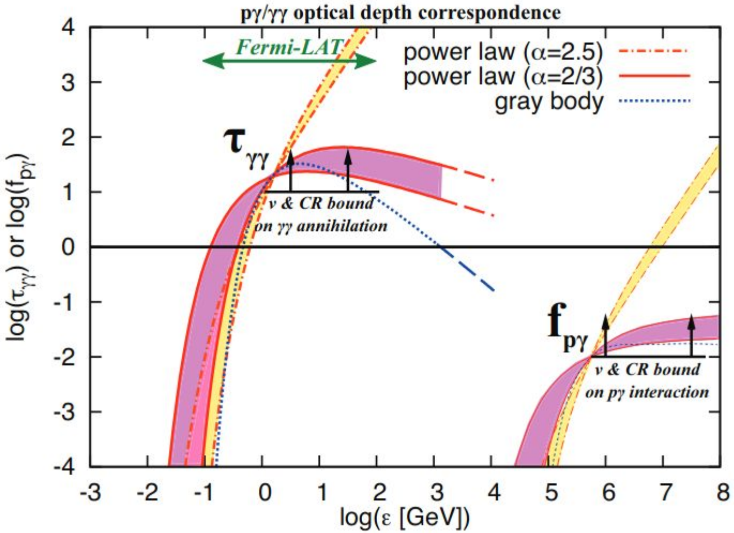
$$\varepsilon_t \approx \delta\, \varepsilon'_t \approx 70\, keV \left(\frac{\delta}{10}\right)^2 \left(\frac{E_\nu}{10\, TeV}\right)^{-1}$$

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

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

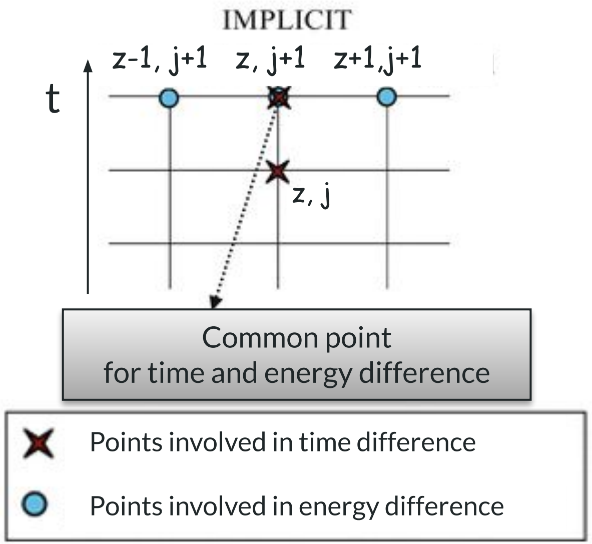
$$\frac{f_{p\gamma}}{\tau_{\gamma\gamma}} \approx \frac{\eta_{p\gamma}}{\eta_{\gamma\gamma}} \frac{\hat{\sigma}_{p\gamma}}{\sigma_{\gamma\gamma}} \approx \frac{1}{300} \frac{\eta_{p\gamma}}{\eta_{\gamma\gamma}}$$

Independent of beaming effects



Murase, Guetta, Ahlers (2016)

Numerical scheme for solving PDEs



PDE for particle species *i*

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

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

(Euler's Method)

(Fluxes at mid-points)

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

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

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

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

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

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

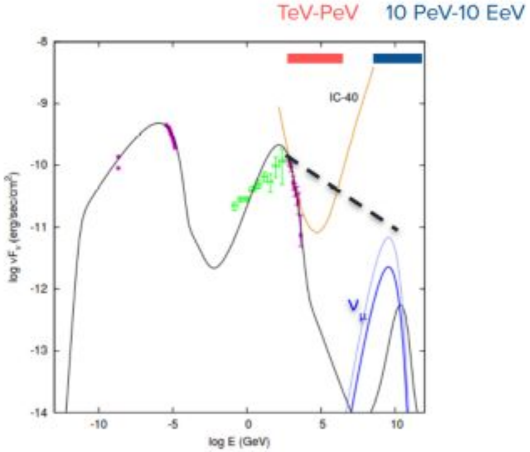
Tridiagonal matrix
(Thomas, L. H. 1949)

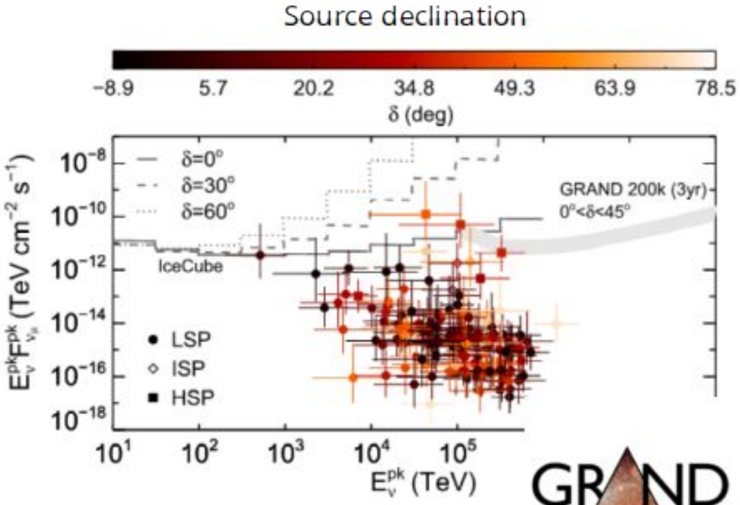
Chang & Cooper (1970)

Proton-synchrotron (PS) models

Dimitrakoudis, MP, Mastichiadis 2014

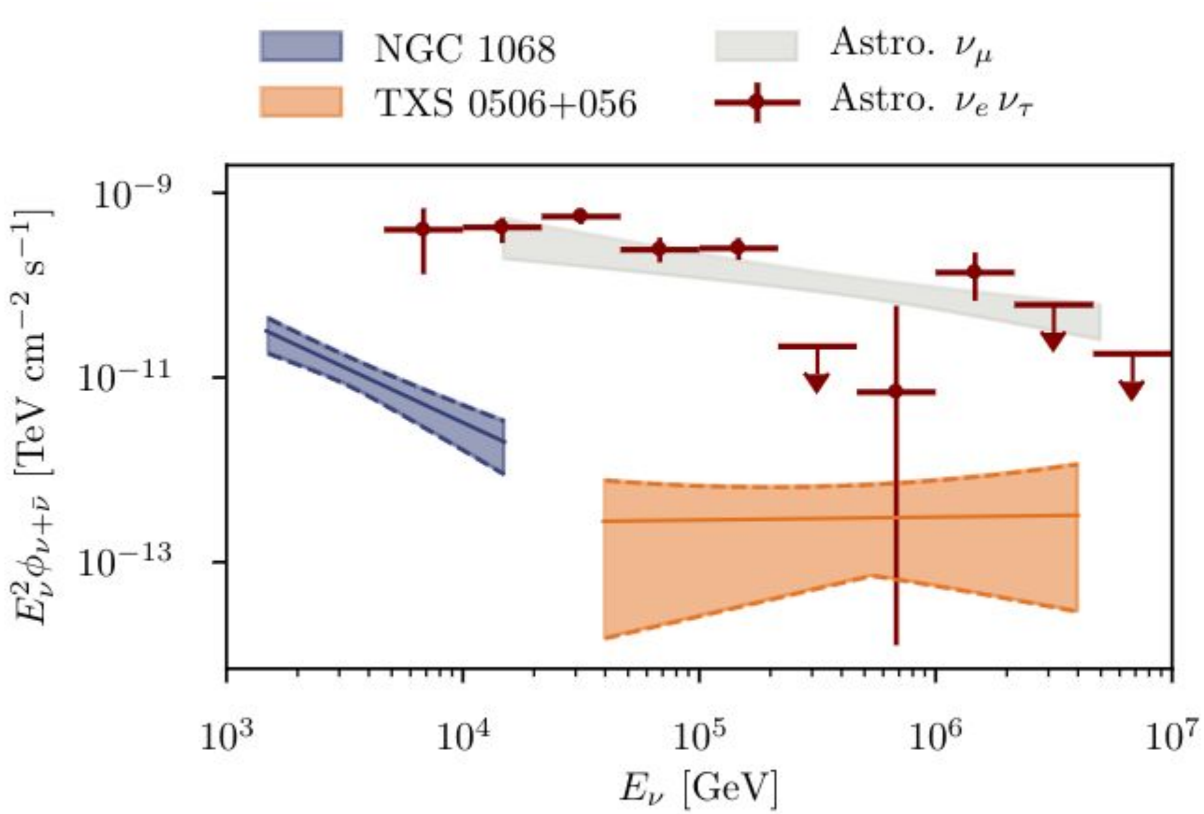
Liodakis & MP 2020, ApJL





- (0.1-10) EeV neutrinos + UHECR protons
- $Y_{\nu\gamma}=L_\nu/L_\gamma \ll 1$
- Minimum jet power = (1-100)*Eddington luminosity
- Search for ~EeV neutrinos with future neutrino experiments (e.g. GRAND)

Highlights



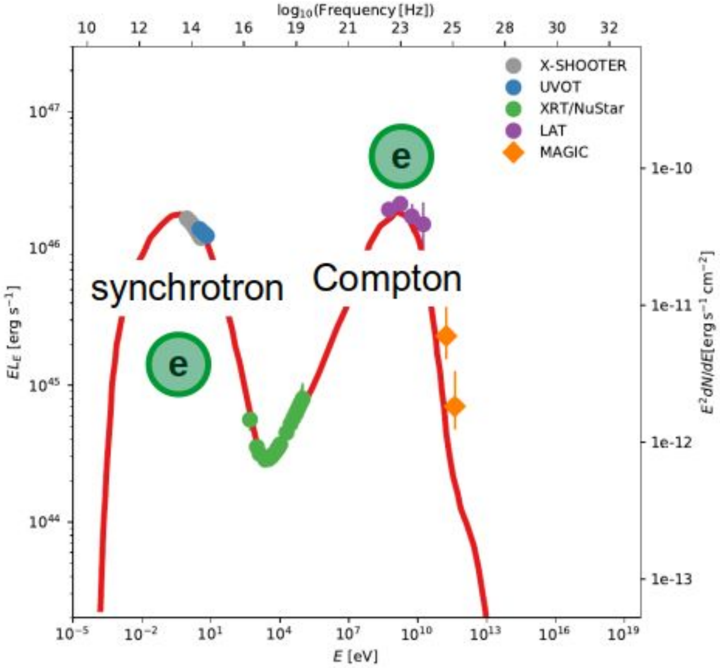
- Are neutrino spectra of non-jetted and jetted AGN *different*, and why?
- Are *all* jetted AGN neutrino emitters, or only those sharing common properties with TXS 0506+056?
- Can we explain the diffuse flux with a *combination* of jetted and non-jetted AGN?

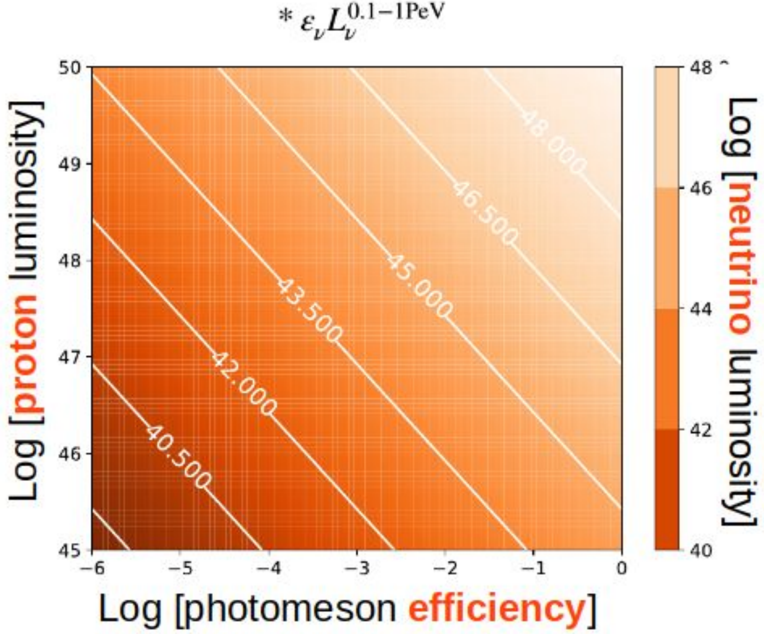
IceCube Collaboration 2022, Science

What sets the max ν luminosity ?

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

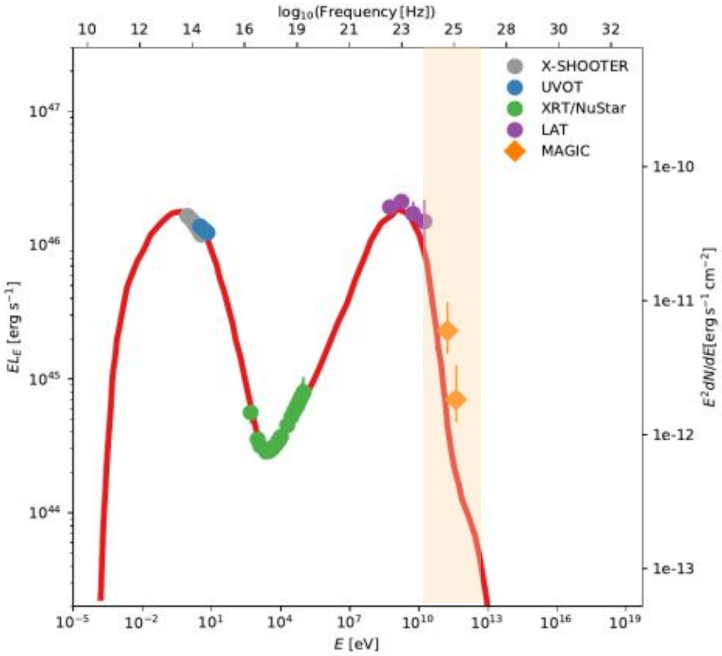
Check slide 52

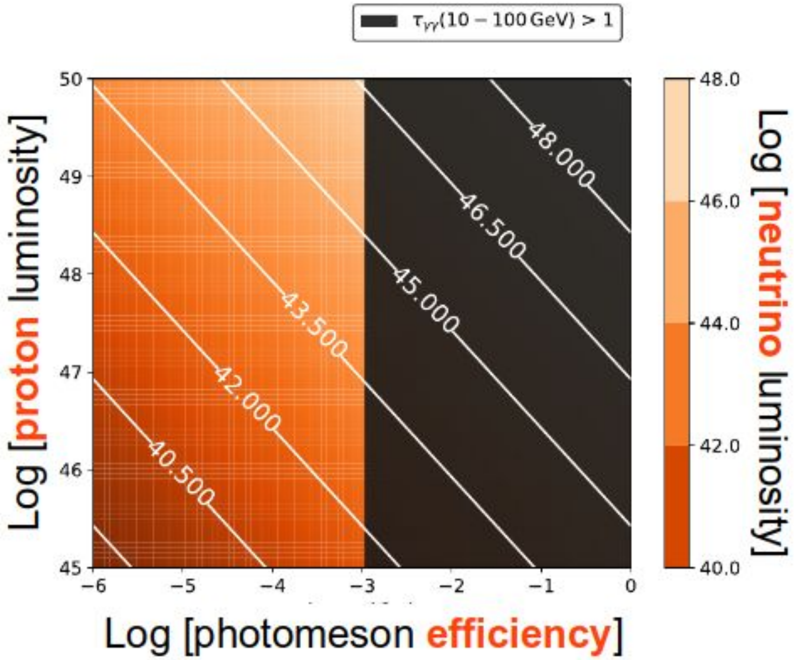




Murase, Oikonomou, Petropoulou (2018), ApJ

What sets the max ν luminosity ?

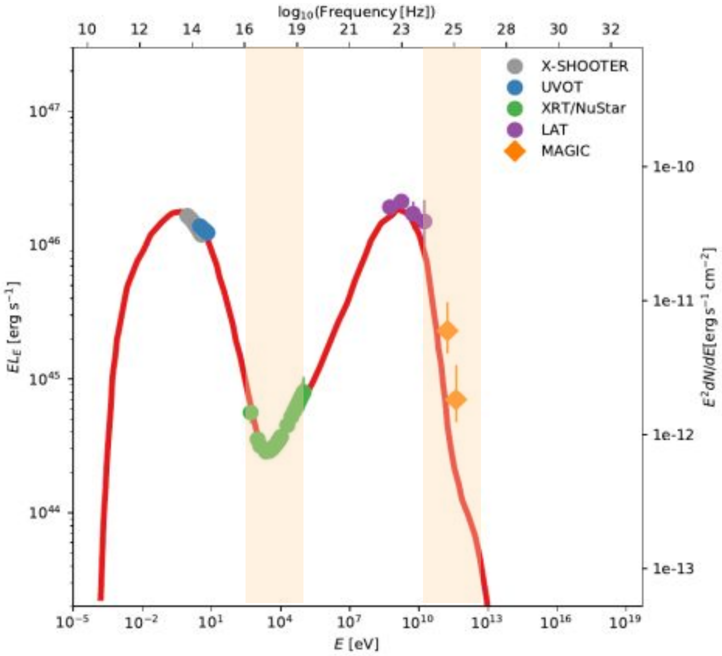


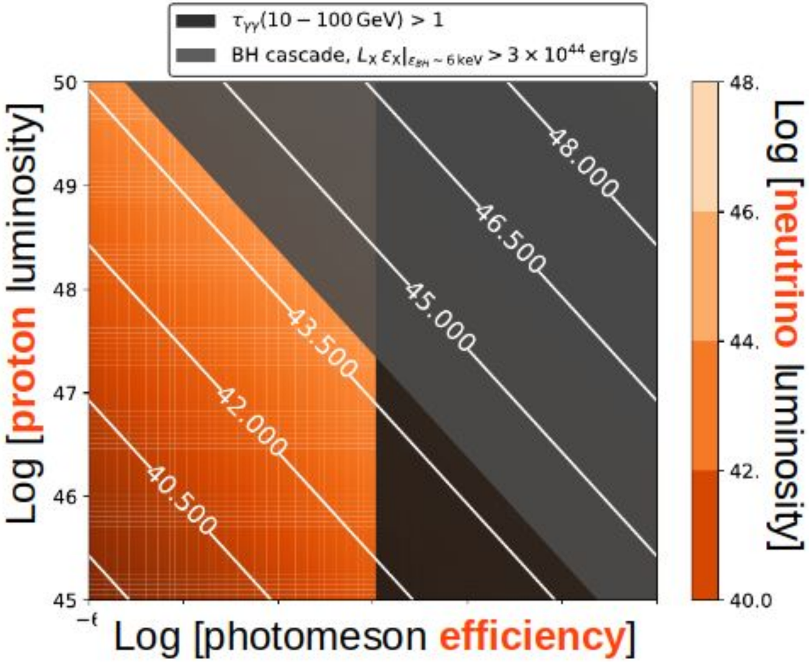


- Optical depth for attenuation of 10 - 100 GeV γ - rays must be low ($\tau_{\gamma\gamma}$ < 1)
- PeV γ-rays are attenuated in source by the synchrotron jet photons

What sets the max ν luminosity ?

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



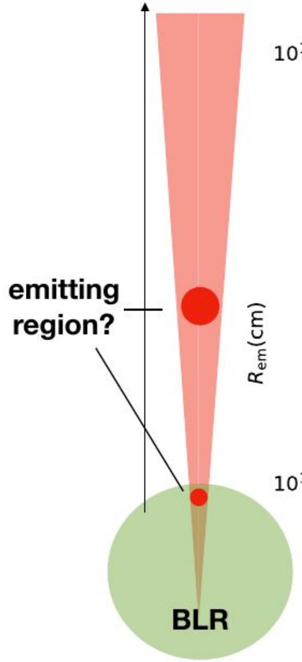


- Synchrotron emission by Bethe-Heitler pairs must not overshoot X-rays

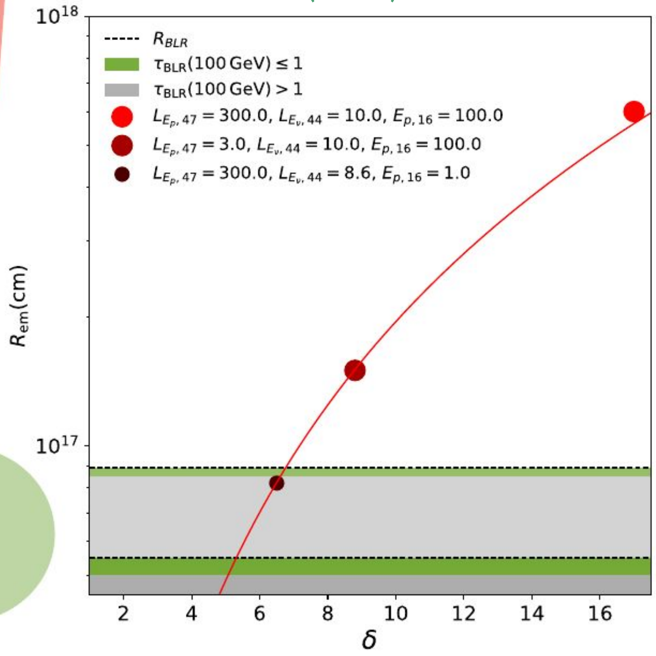
$$\varepsilon_\nu L_{\varepsilon_\nu}^{0.1-1\ \mathrm{PeV}} \sim \varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon_{\mathrm{syn}}^{\mathrm{BH}}} \sim \frac{1}{4} g[\beta] f_{p\gamma}\, \varepsilon_p L_p \leq 3\times 10^{44}\ \mathrm{erg/s}$$

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

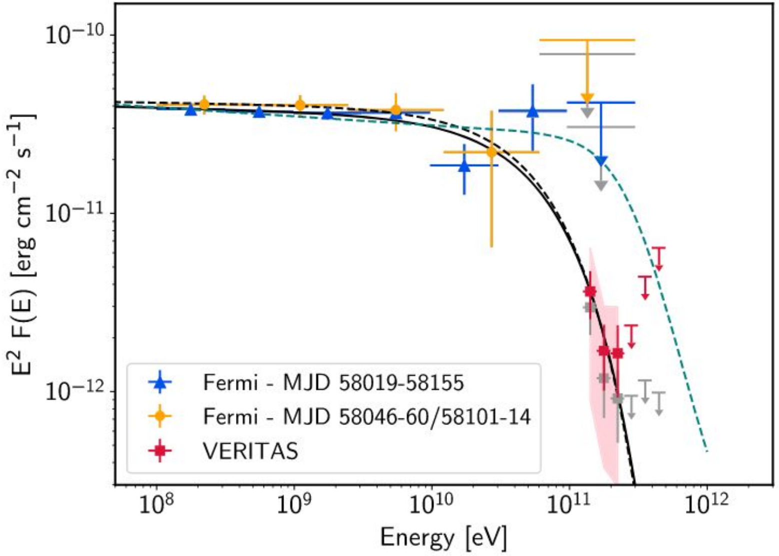
Where is the flaring region located ?



Padovani et al. (2019)



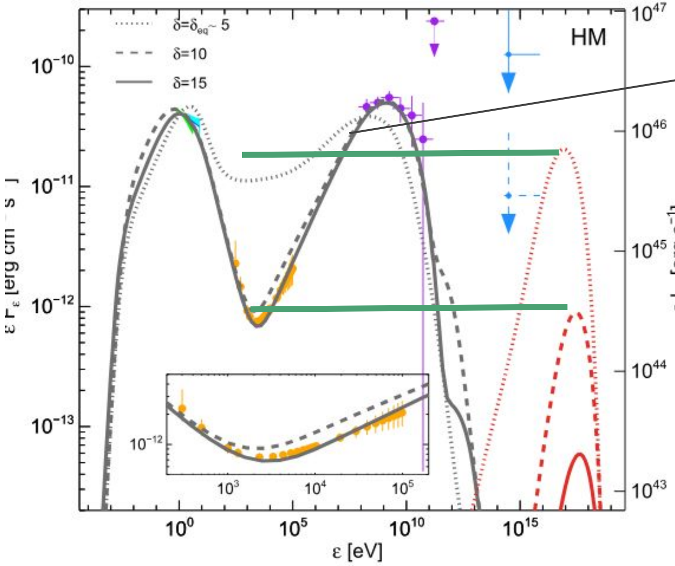
Veritas Collaboration (2018)



- 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

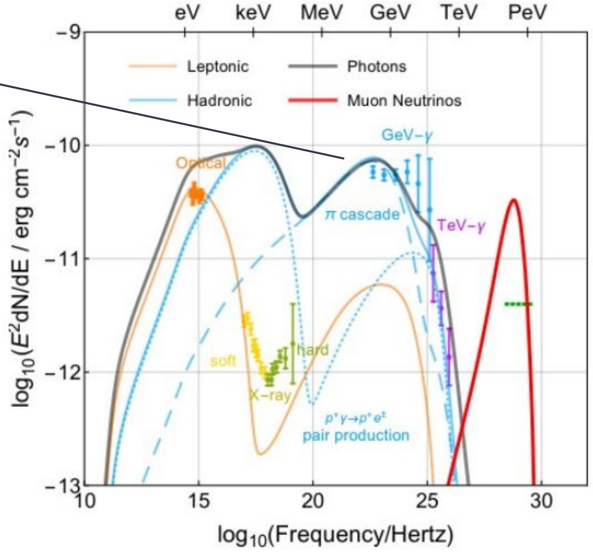
Why the p-SYN model does not work ?

Keivani et al. (2018) ApJ



Cascade emission

Gao et al. (2019) Nat. Ast.



- Proton-synchrotron models predict EeV neutrinos with low luminosities
- Lower Doppler factors → higher opacities → higher cascade emission → model overshoots X-ray data

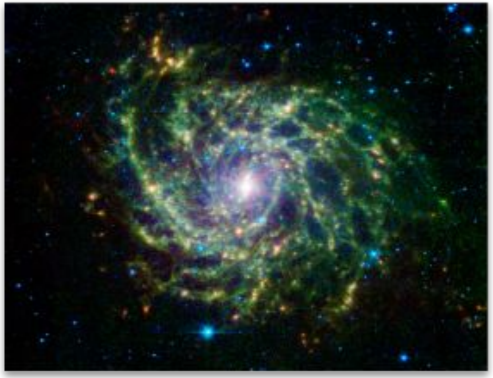
Hunting for extragalactic neutrinos ...

Jetted AGN

Steady but variable

(e.g. Eichler 1979, Mannheim, Stanev, and Biermann 1992, Halzen & Zas 1997, Atoyan & Dermer 2001, 2003, Murase et al. 2014, Petropoulou et al. 2015, +++; see also review Murase & Stecker 2023)

Non-jetted AGN, Starbursts



Steady*

* accretion disk emission is variable

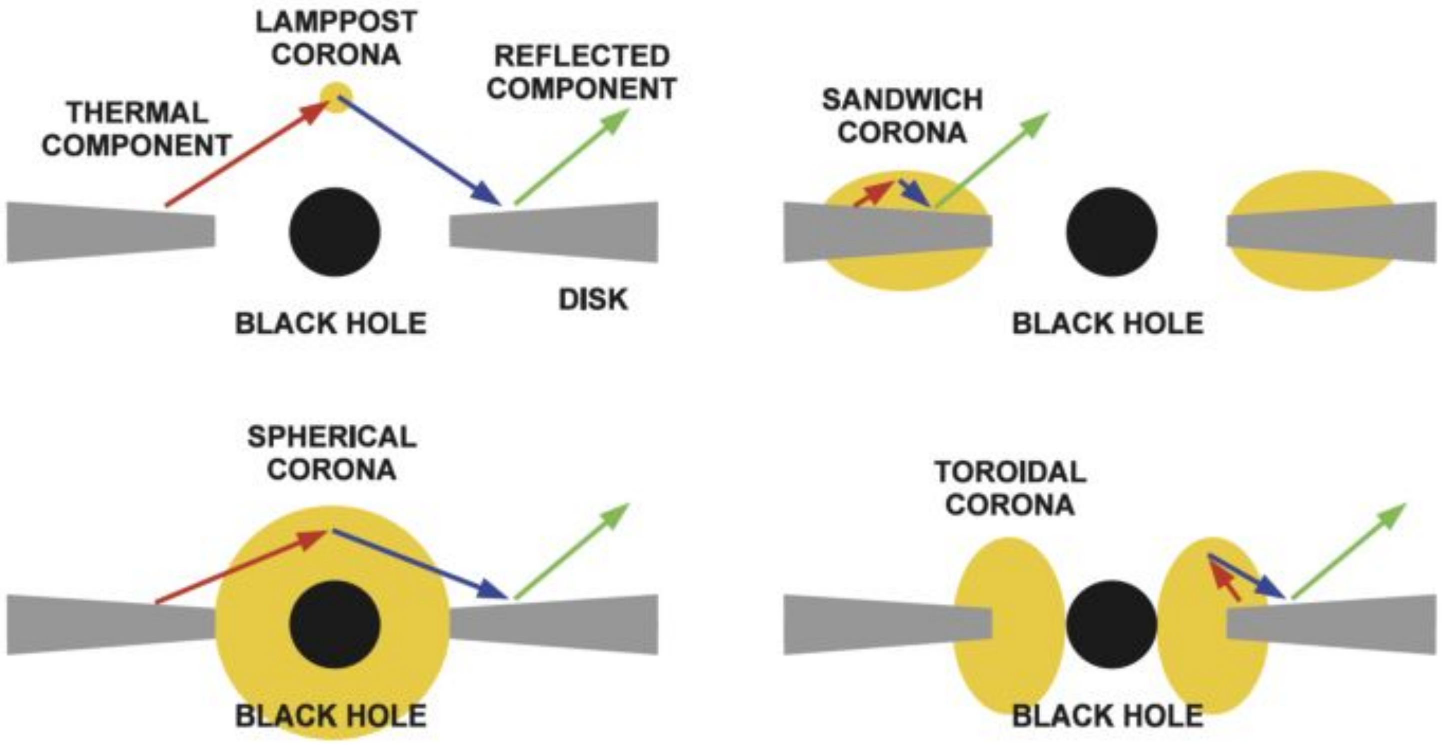
(e.g. Loeb and Waxman 2006, Stecker 2007, Tamborra et al. 2014, Bechtol et al. 2017, Peretti et al. 2020; see also review Murase & Stecker 2023)

GRBs, TDEs

Transients

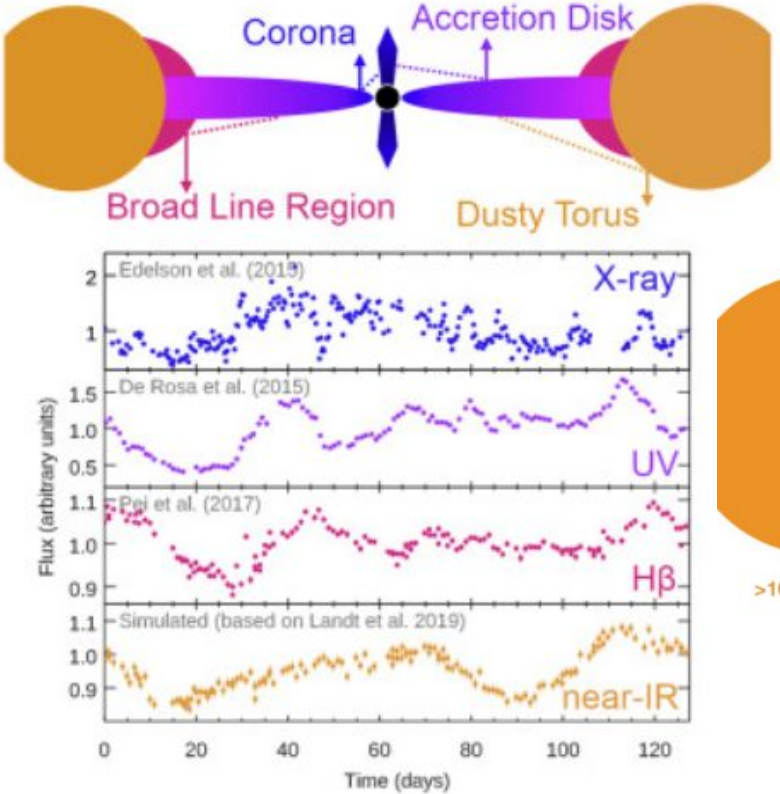
(e.g. Waxman & Bahcall 1999, Murase 2008, Petropoulou et al. 2014, Bustamante et al. 2017, Stein et al. 2021, +++)

AGN coronae

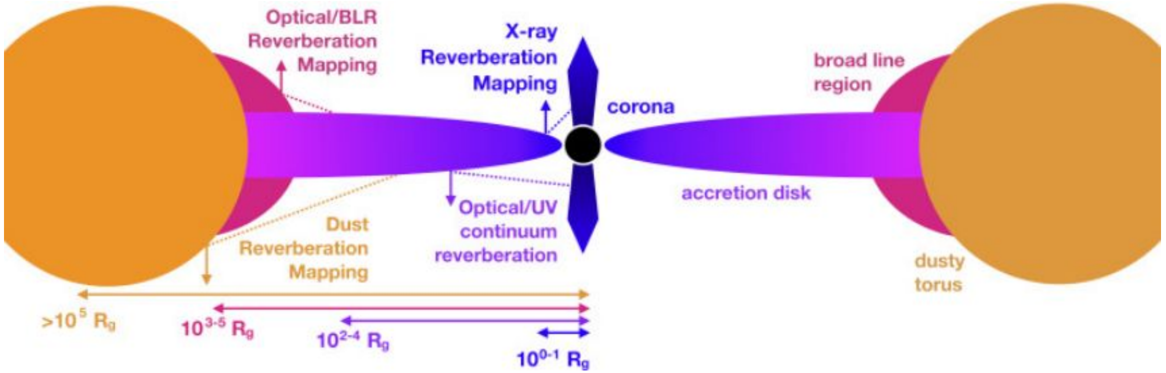


LAMPPOST CORONA
THERMAL COMPONENT
REFLECTED COMPONENT
DISK
BLACK HOLE
SANDWICH CORONA
BLACK HOLE
SPHERICAL CORONA
BLACK HOLE
TOROIDAL CORONA
BLACK HOLE

AGN coronae



Corona
Accretion Disk
Broad Line Region
Dusty Torus
Edelson et al. (2019)
X-ray
De Rosa et al. (2015)
UV
Pei et al. (2017)
Hβ
Simulated (based on Landt et al. 2019)
near-IR
Flux (arbitrary units)
Time (days)

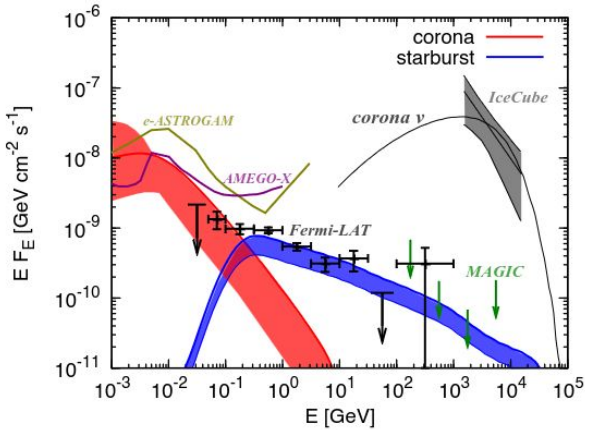


Optical/BLR Reverberation Mapping
X-ray Reverberation Mapping
corona
broad line region
accretion disk
Dust Reverberation Mapping
Optical/UV continuum reverberation
dusty torus
>10^5 R_g
10^3-5 R_g
10^2-4 R_g
10^0-1 R_g

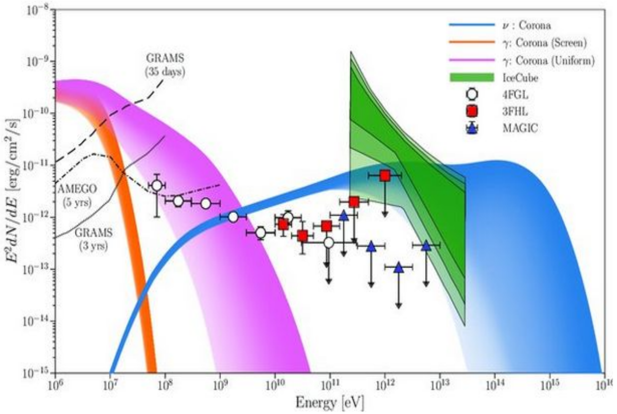
NGC 1068 models: pick your flavor

Different hypotheses

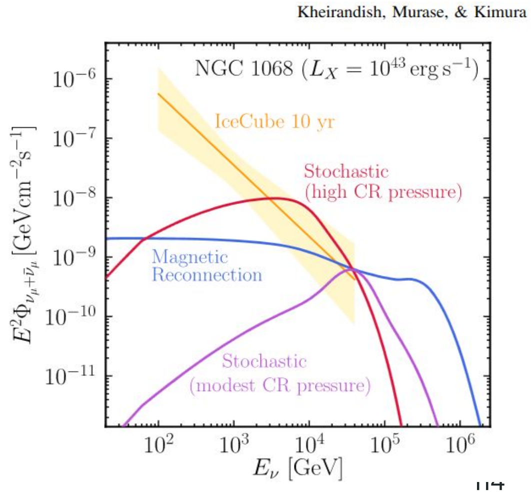
- CR acceleration:
  - Generic mechanism → power law
  - Stochastic acceleration in turbulence (Murase+2020, Murase 2022, Eichmann+2022, Fiorillo+2024b)
  - Diffuse shock acceleration (Inoue et al. 2019, 2020, Eichmann+2022)
  - Magnetic reconnection (Kheirandish+2021, Fiorillo+2024a, Karavola+2025)



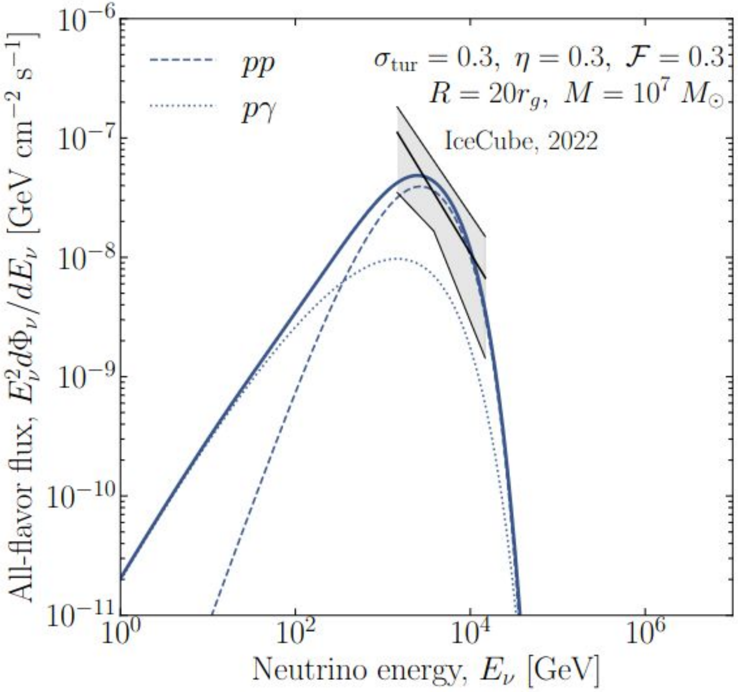
Ajello, Murase, McDaniel, 2023

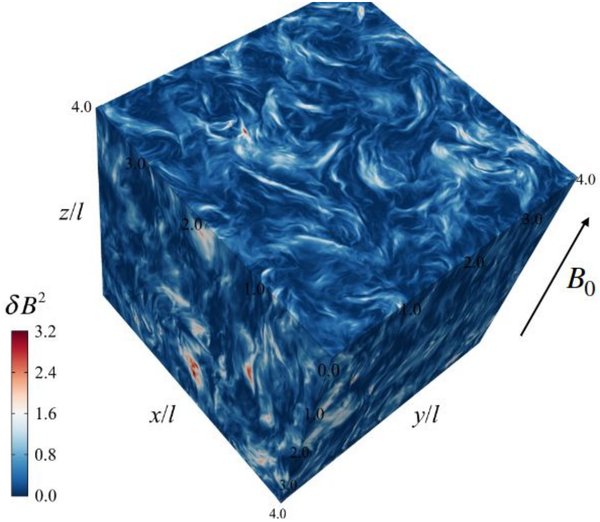


Inoue et al. 2019



Proposal No. 2: strong turbulence





Main results

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

For particle acceleration, see: Comisso & Sironi 2019

Fiorillo et al., 2024b, in prep.