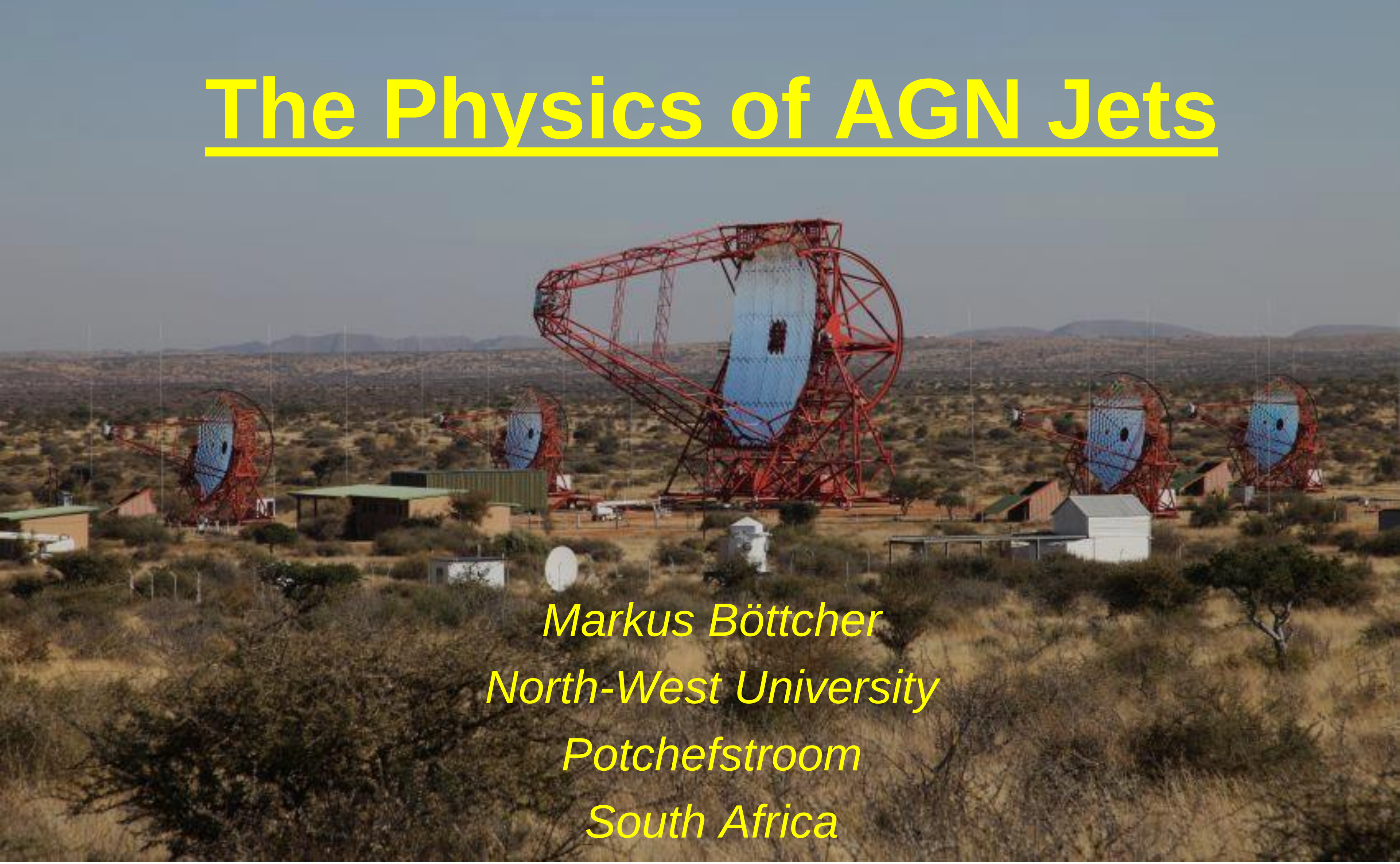
The Physics of AGN Jets



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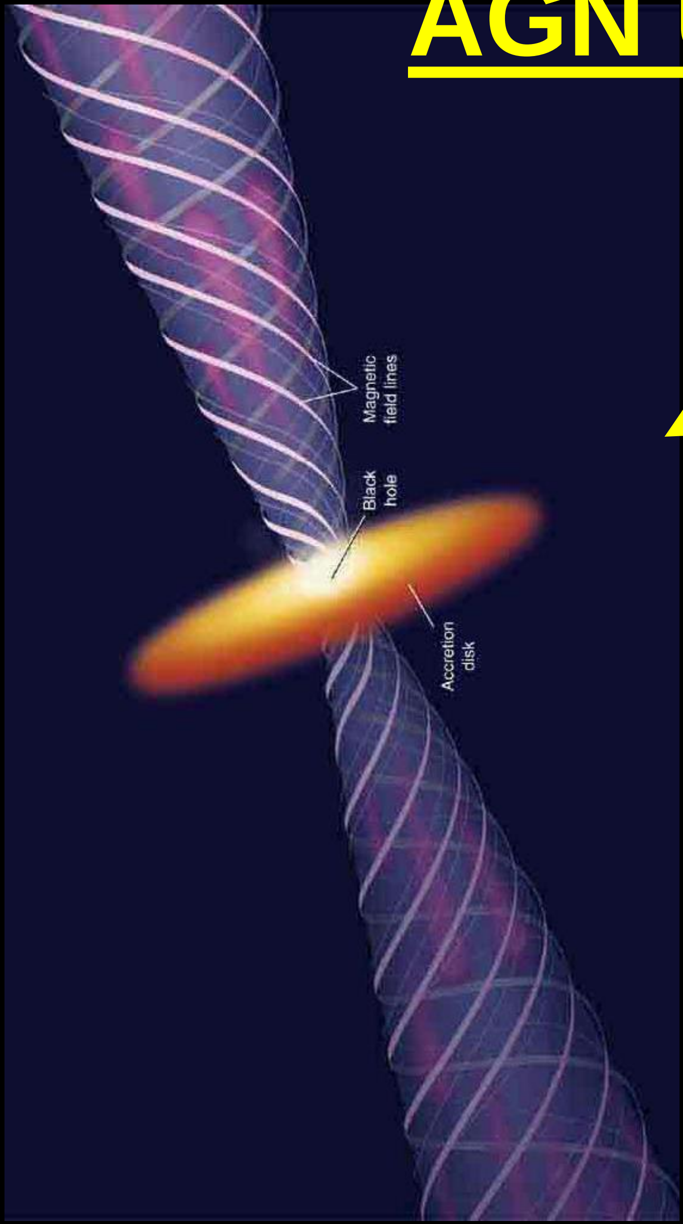
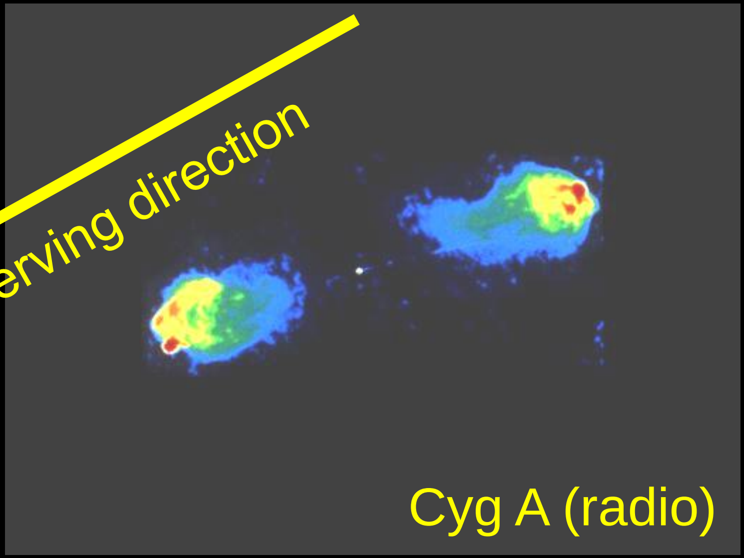
Active Galactic Nuclei (AGN)

Nuclei of galaxies with peculiar properties:

- Extremely bright nuclei
- Variability
- High-Energy (X-/γ-ray) emission
- Emission lines
- Polarization
- Relativistic outflows (jets)

Types of radio-loud AGN and AGN Unification

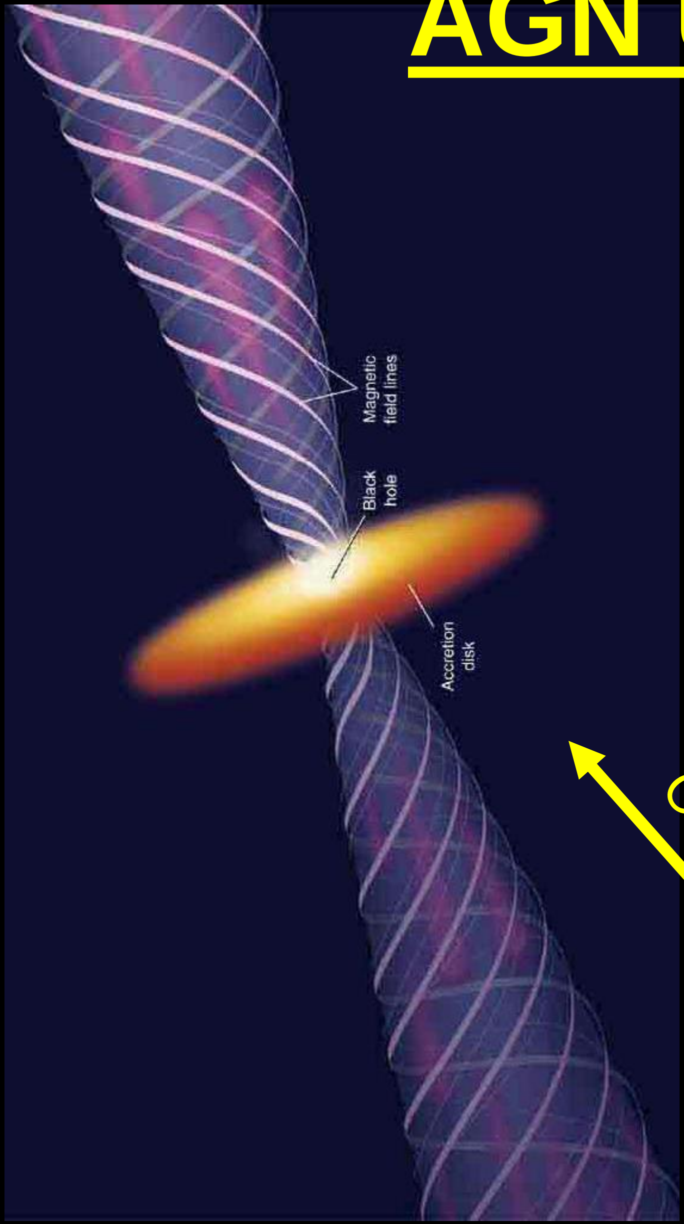




Radio Galaxy:

Powerful ***radio lobes*** at the end points of the jets, where kinetic jet power is dissipated.

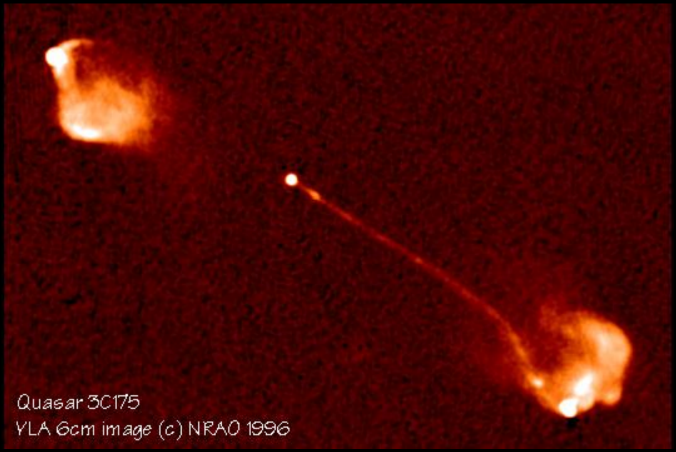
Types of radio-loud AGN and AGN Unification



Flat-Spectrum Radio Quasar or BL Lac object

Emission from the jet pointing towards us is Doppler boosted compared to the jet moving in the other direction (“counter jet”).

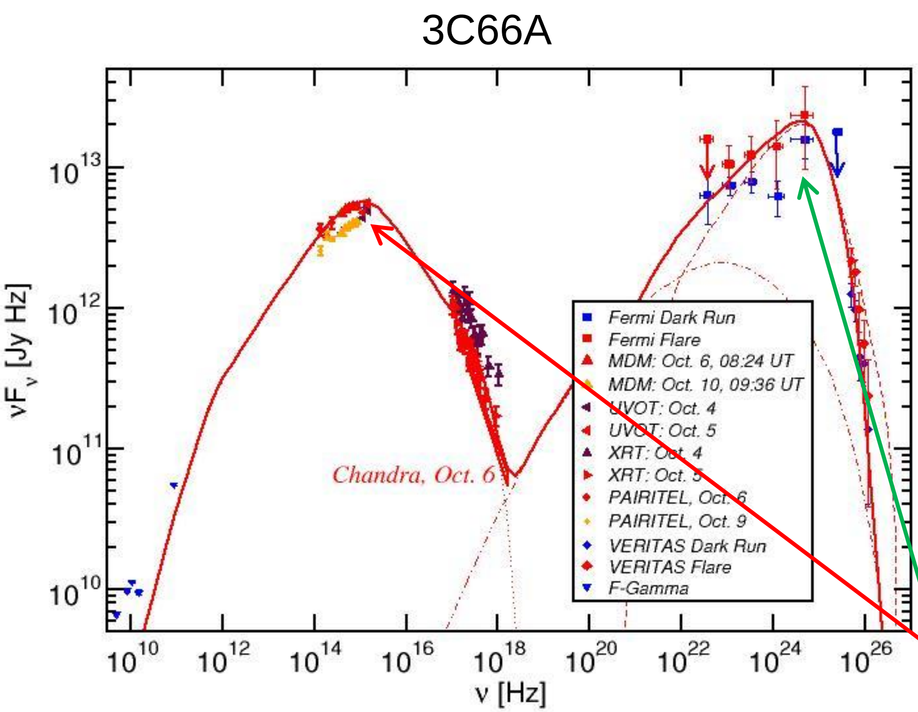
Observing direction

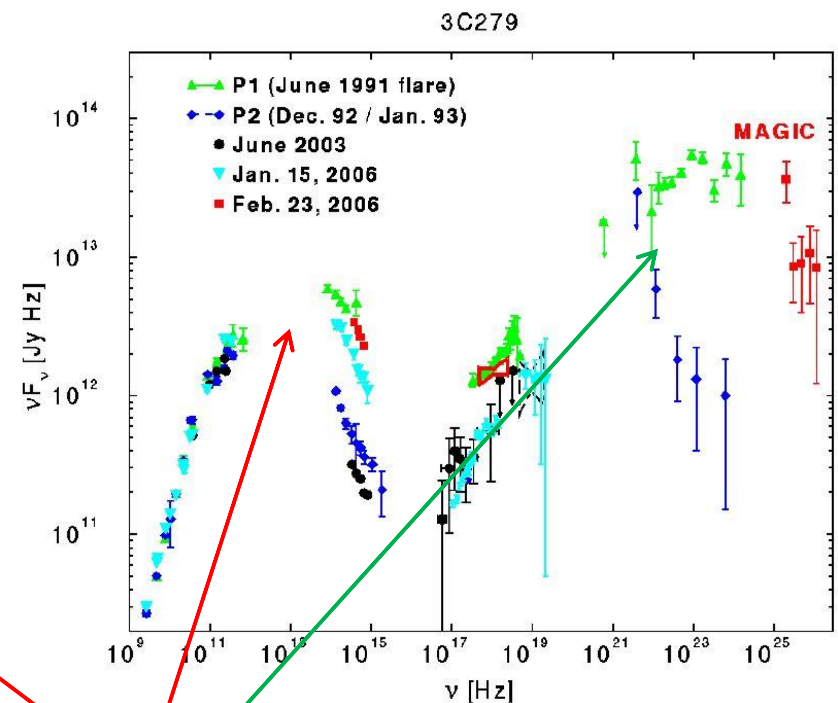


Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars with relativistic jets pointing close to our line of sight
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio knots often with superluminal motion
- Radio and optical (and X-ray?) polarization

Blazar Spectral Energy Distributions (SEDs)

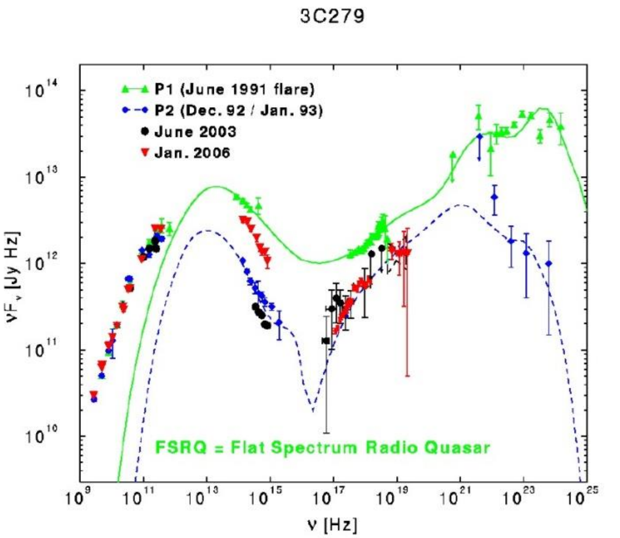




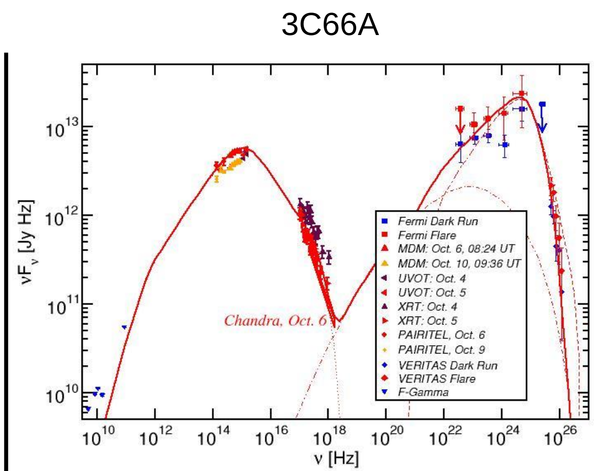
Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

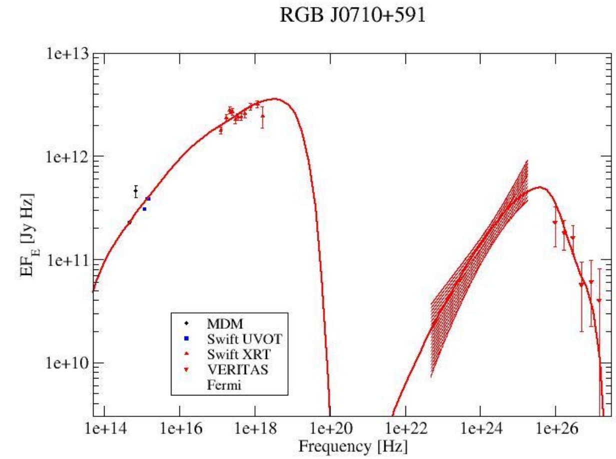
Blazar Classification



(Hartman et al. 2000)



(Abdo et al. 2011)



(Acciari et al. 2009)

<u>Low-Synchrotron Peaked (LSP): Quasars (FSRQs)/ Low-frequency peaked BL Lac Objects (LBLs)</u>

Low-frequency component from radio to optical/UV,

$\nu_{sy} \leq 10^{14}$ Hz

High-frequency component from X-rays to γ-rays, often dominating total power

<u>Intermediate-Synchrotron Peaked (ISP): Intermediate BL Lacs (IBLs):</u>

Peak frequencies at IR/Optical and GeV gamma-rays,

10^{14} Hz $< \nu_{sy} \leq 10^{15}$ Hz

Intermediate overall luminosity

Sometimes γ-ray dominated

<u>High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):</u>

Low-frequency component from radio to UV/X-rays,

$\nu_{sy} > 10^{15}$ Hz

often dominating the total power

High-frequency component from hard X-rays to high-energy gamma-rays

Flux and Polarization Variability

Multi-wavelength variability on various time scales (months – minutes)

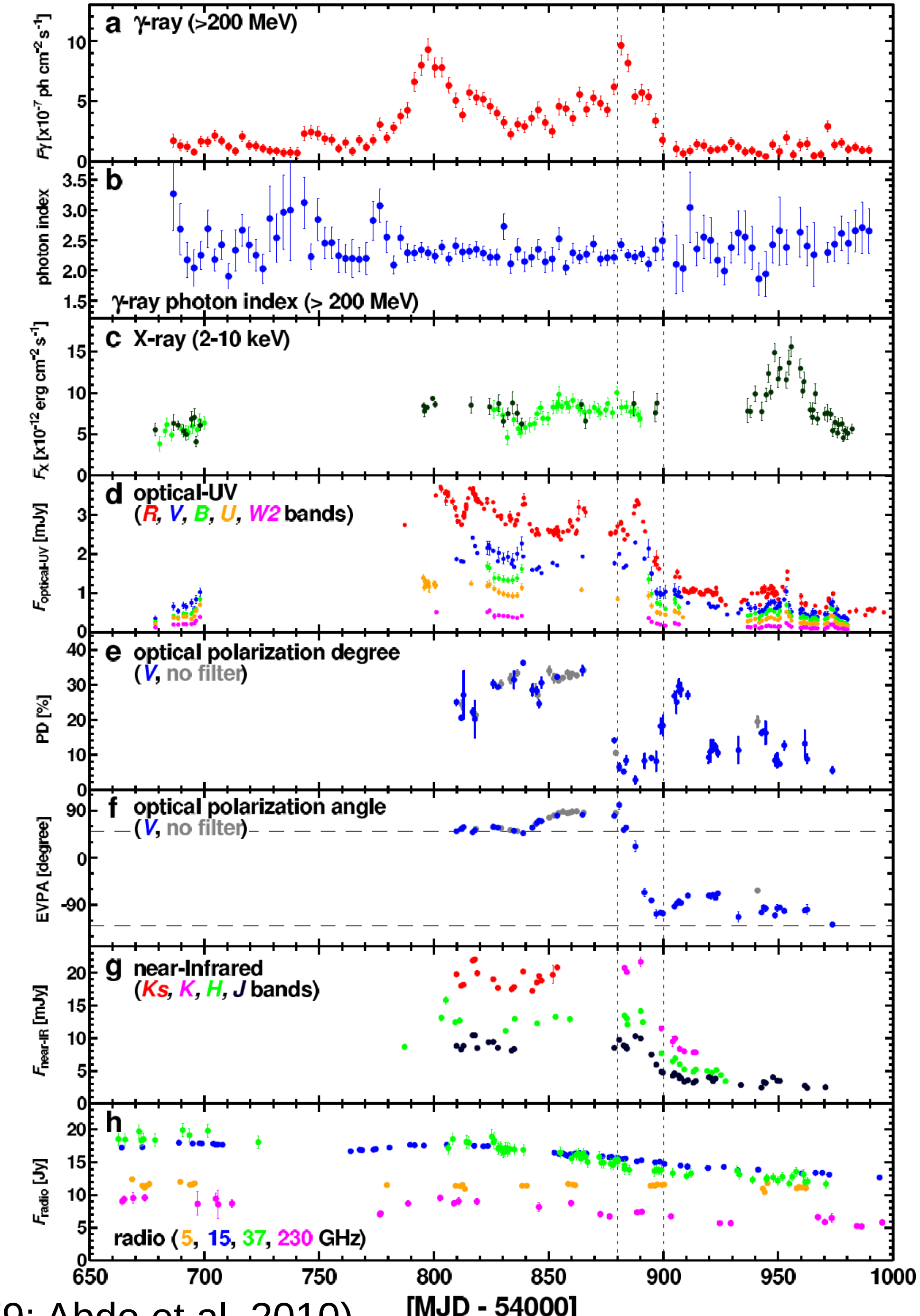
Sometimes correlated, sometimes not

Observed optical polarization degrees

Π_{opt} <~ 30 %

Both degree of polarization and polarization angles vary.

Swings in polarization angle sometimes associated with high-energy flares!



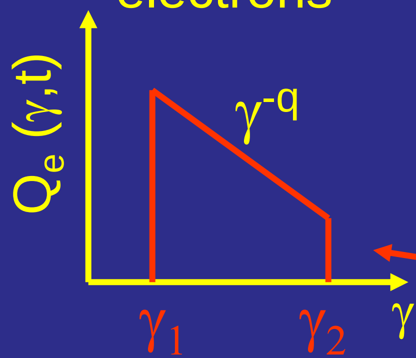
(3C279: Abdo et al. 2010)

Open Physics Questions

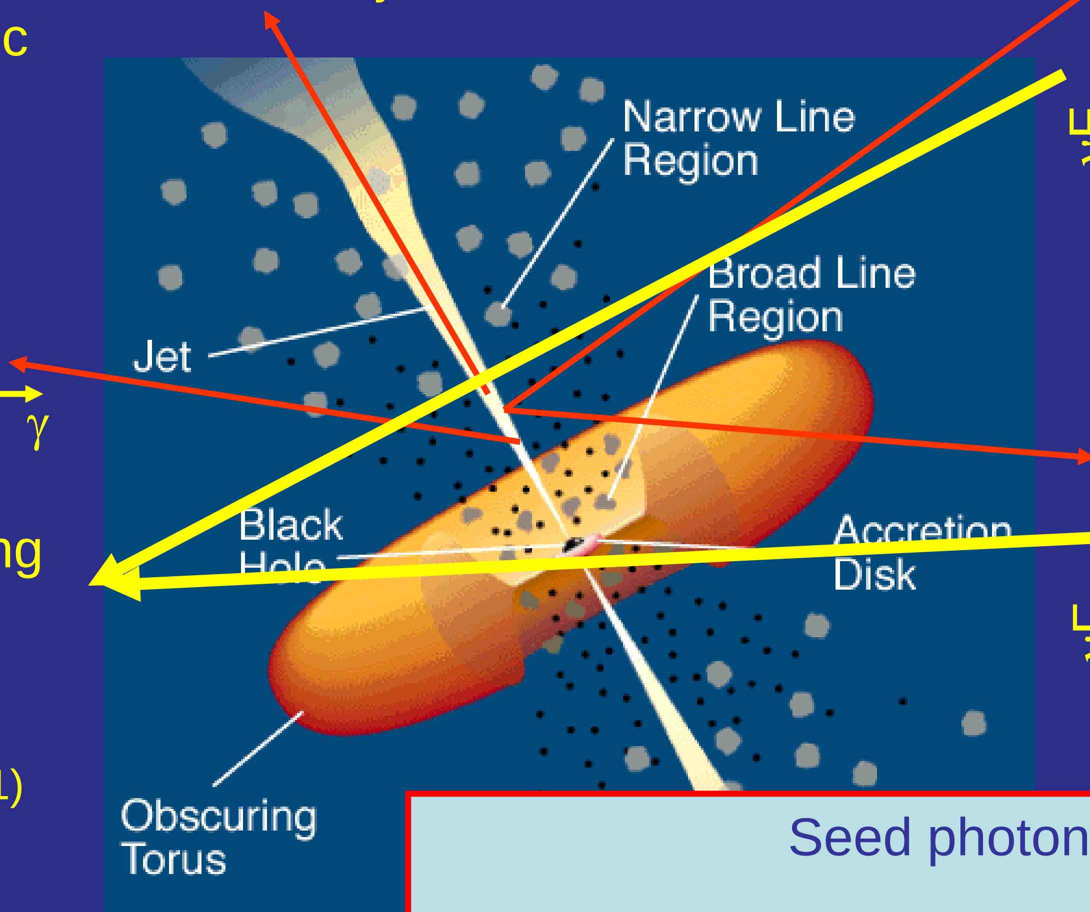
- Source of Jet Power (Blandford-Znajek / Blandford-Payne?)
- Physics of jet launching / collimation / acceleration – role / topology of magnetic fields
- Composition of jets (e^--p or e^+-e^- plasma?) – leptonic or hadronic high-energy emission?
- Mode of particle acceleration (shocks / shear layers / magnetic reconnection?) - role of magnetic fields
- Location of the energy dissipation / gamma-ray emission region

Leptonic Blazar Model

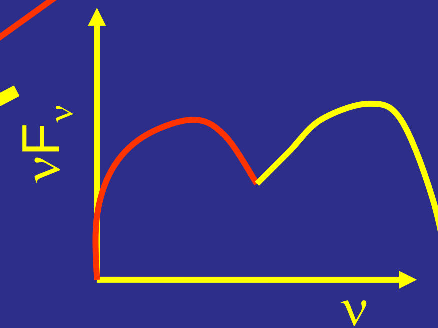
Injection, acceleration of ultrarelativistic electrons



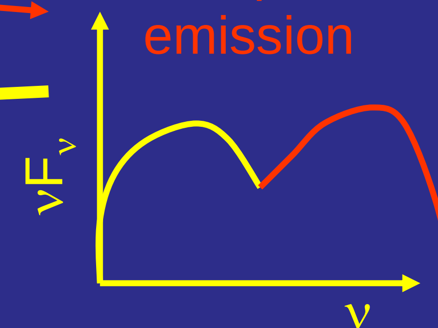
Relativistic jet outflow with $\Gamma \approx 10$



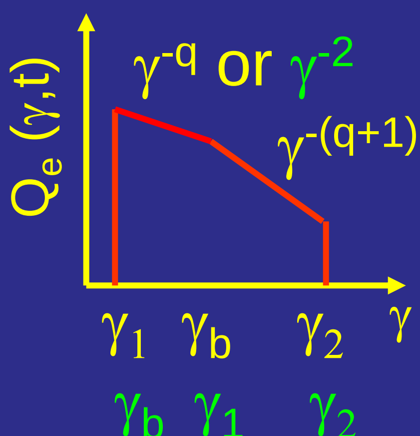
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



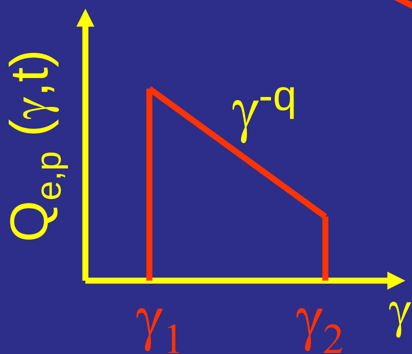
γ_b:
$\tau_{cool}(\gamma_b) = \tau_{esc}$

Seed photons:

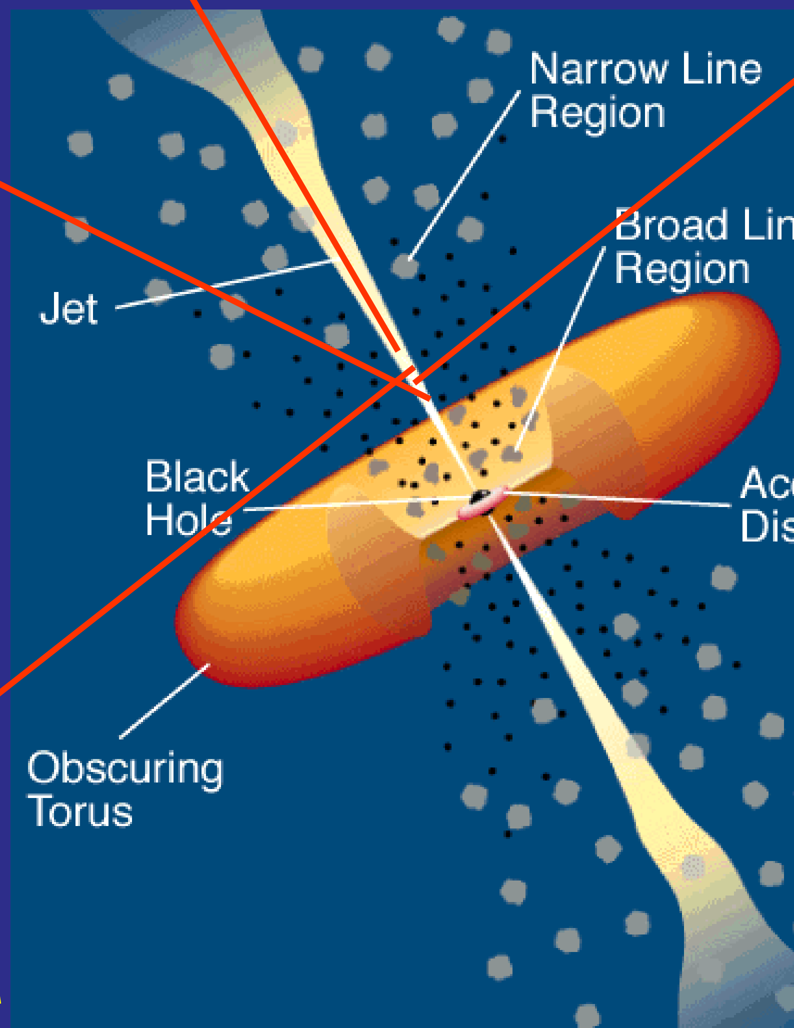
Synchrotron (within same region [SSC] or external sources, e.g., accretion disk, BLR, dust torus (EC = External Compton)

Hadronic Blazar Models

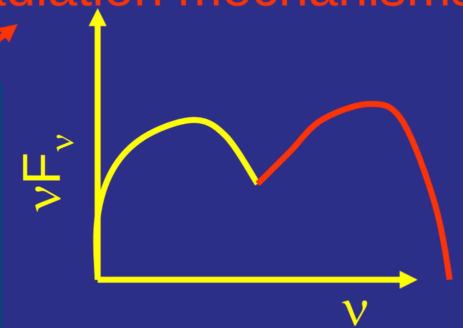
Injection, acceleration of ultrarelativistic electrons and protons



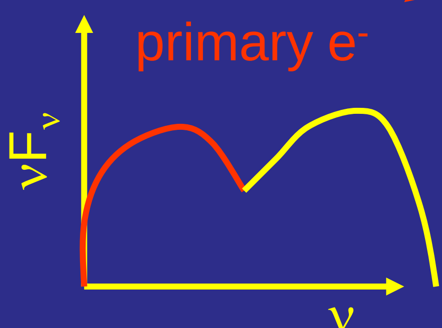
Relativistic jet outflow with $\Gamma \approx 10$



Proton-induced radiation mechanisms



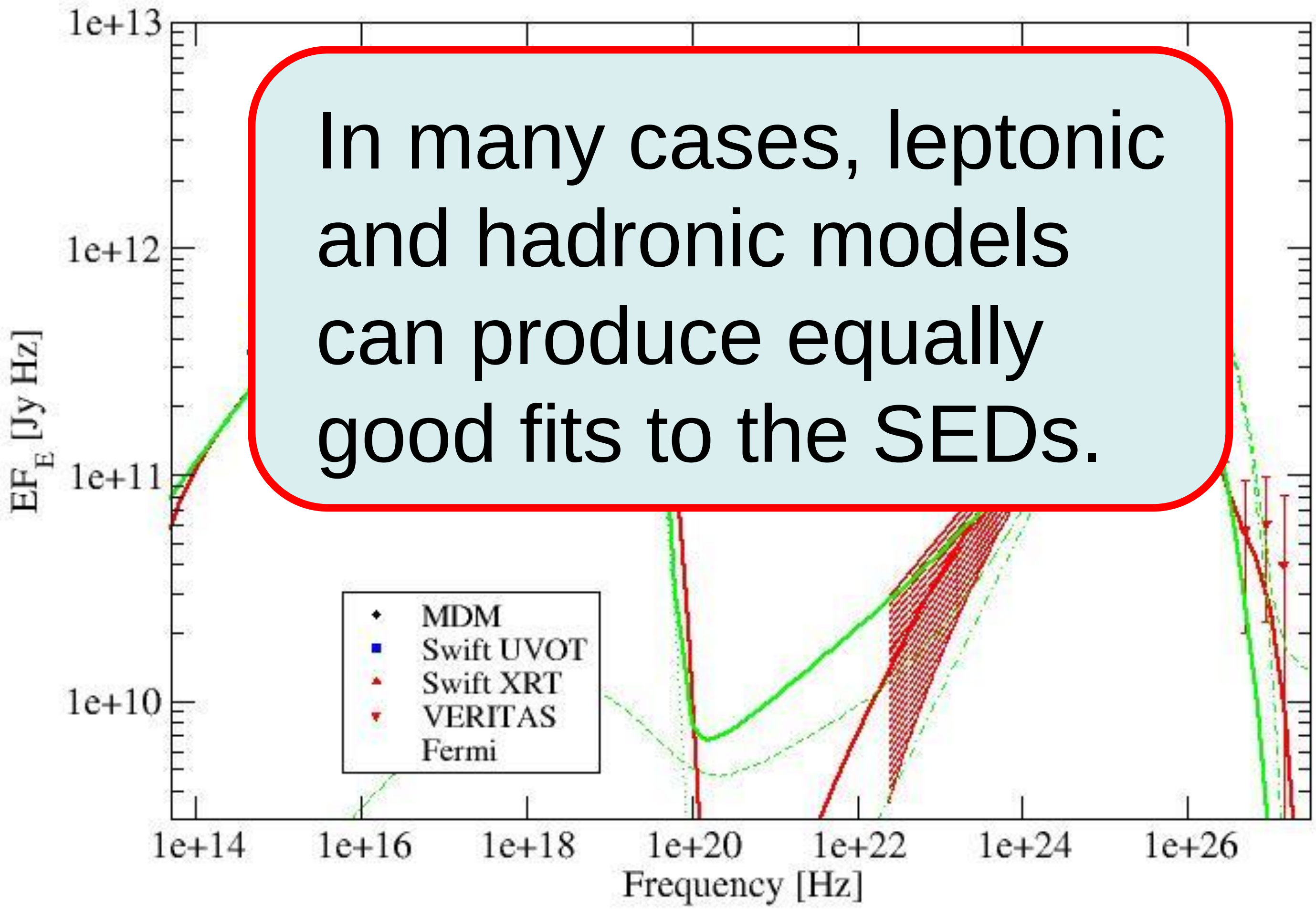
Synchrotron emission of primary e^-



- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu_\mu}$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Lepto-Hadronic Model Fits to Blazar SEDs

RGB J0710+591 (HBL)

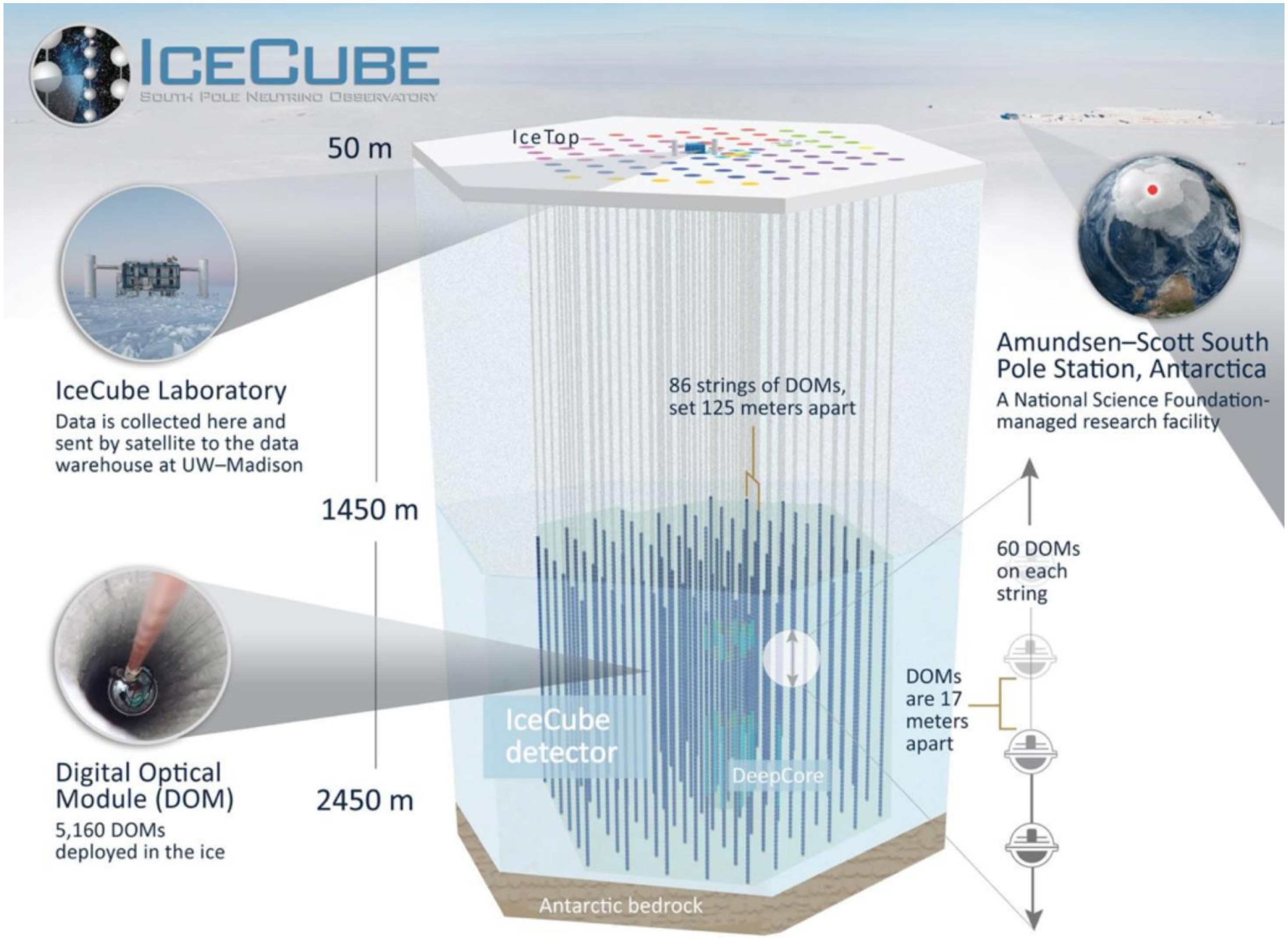


In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

Possible Diagnostics to distinguish:

- Neutrinos
- Variability
- Polarization

The IceCube Neutrino Detector at the South Pole



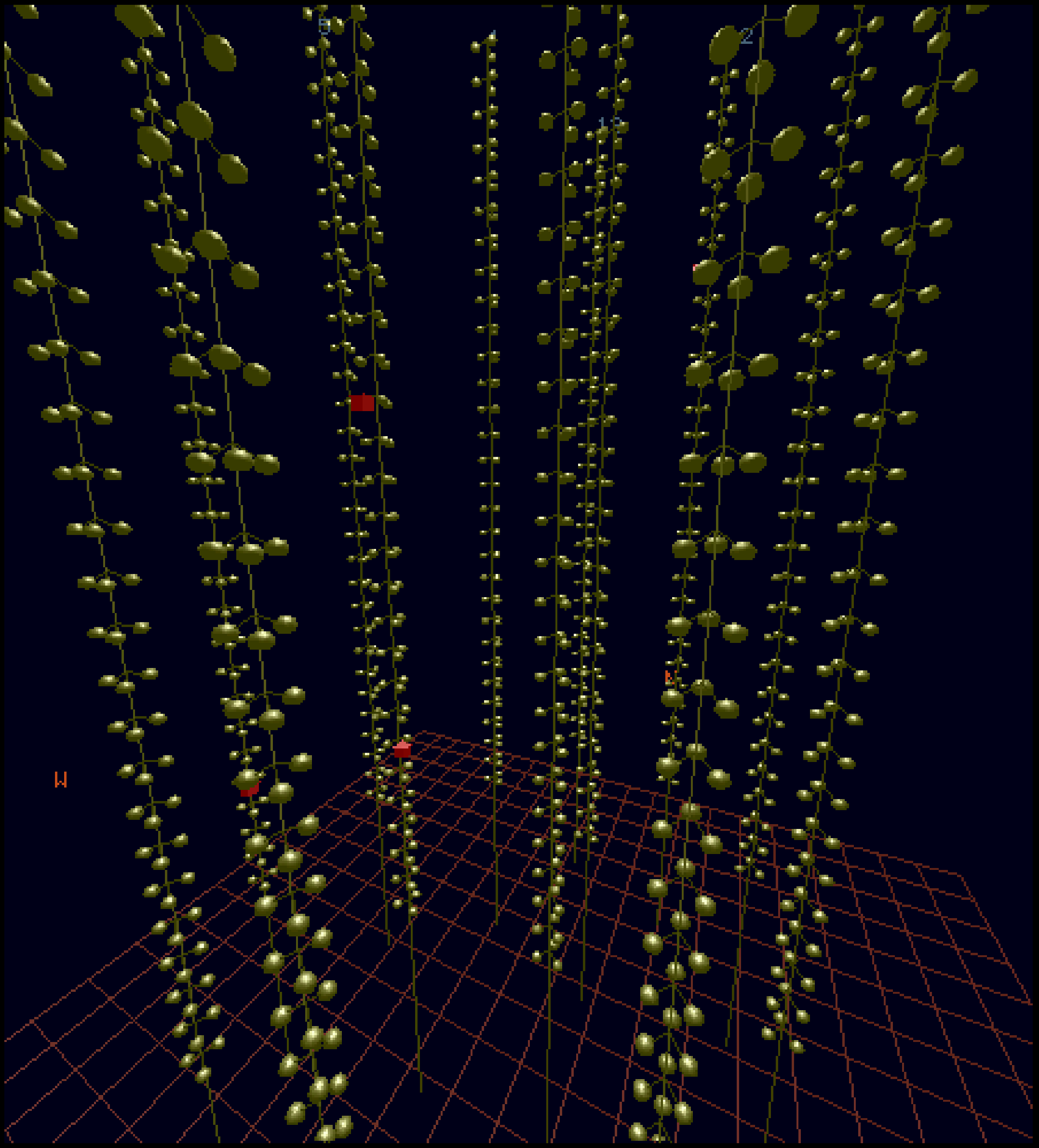
Fully operational since 2010.

High-Energy Neutrino Detectors

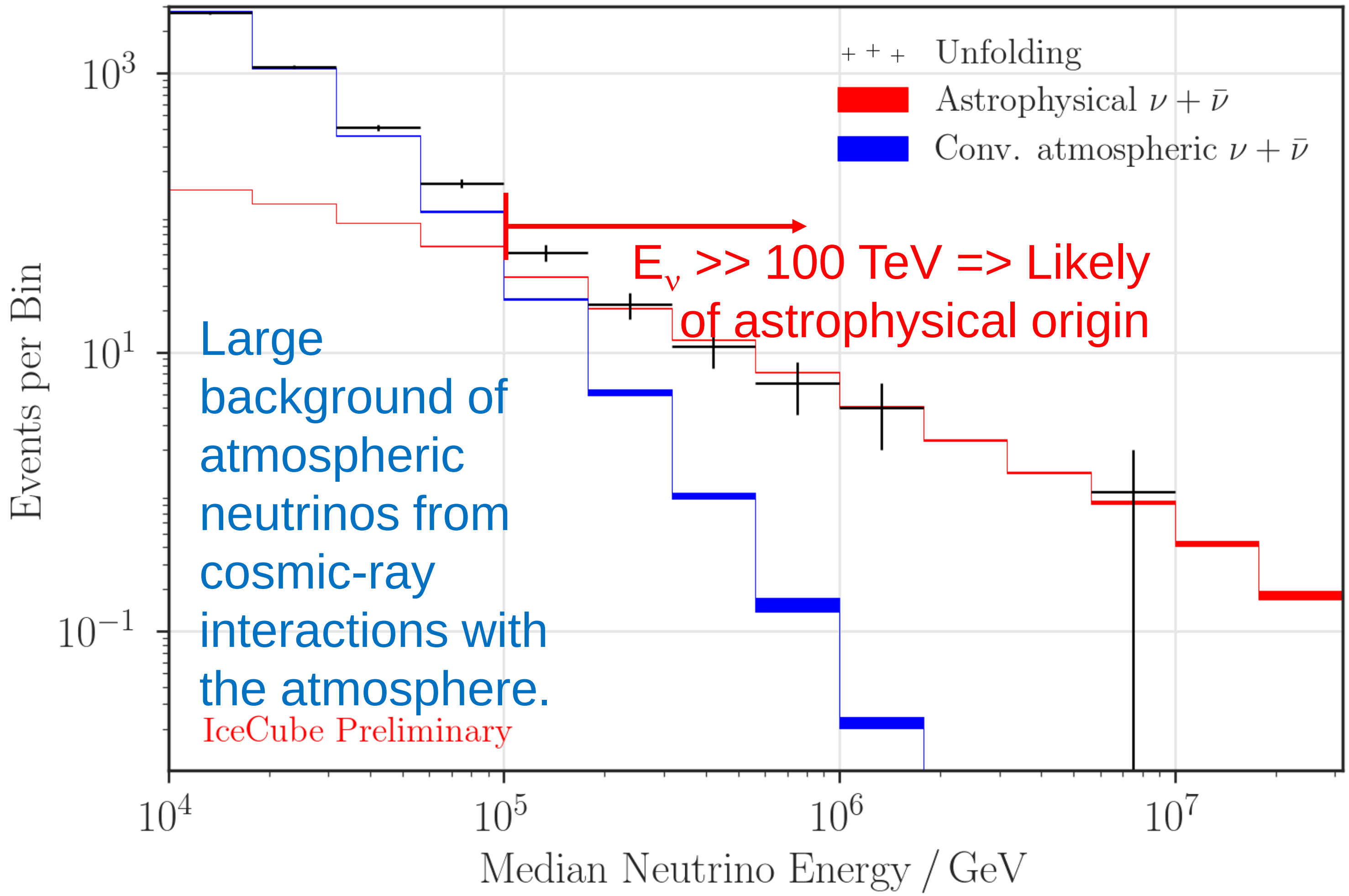
IceCube:

$E_\nu \sim$ 100 TeV – few PeV

ν-matter scattering, followed by particle cascades in ice/water $\rightarrow$ Cherenkov light detection.

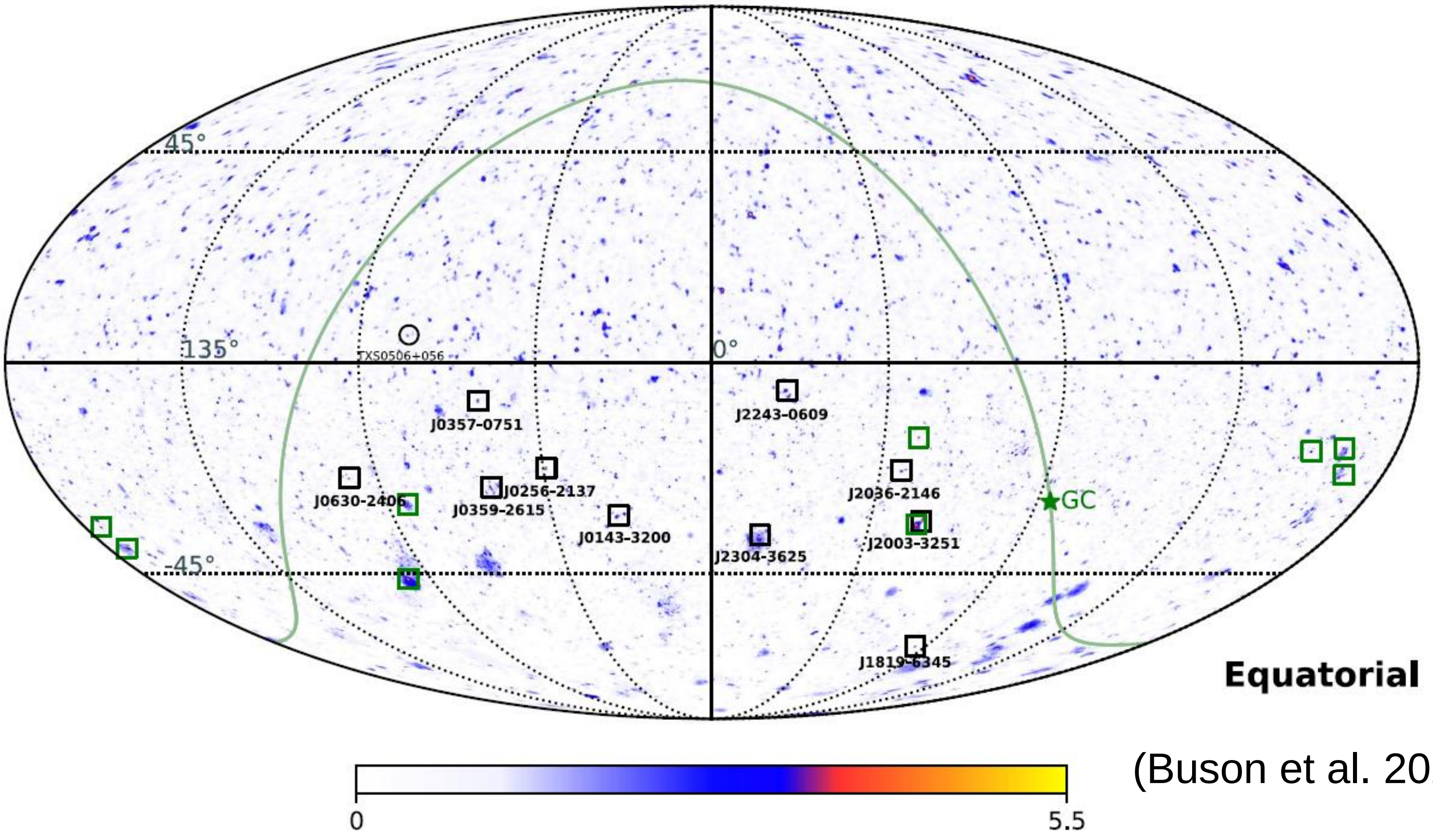


The IceCube Neutrino Spectrum



First evidence for astrophysical neutrinos published in 2013.

Origin of IceCube-Detected Neutrinos



(Buson et al. 2022)

Significant correlation of IceCube neutrinos with **blazars** (chance coincidence p = $6 \cdot 10^{-7}$) – but can not be responsible for all IceCube neutrinos (e.g., Murase et al. 2018)

Photo-pion induced neutrino production in relativistic jets

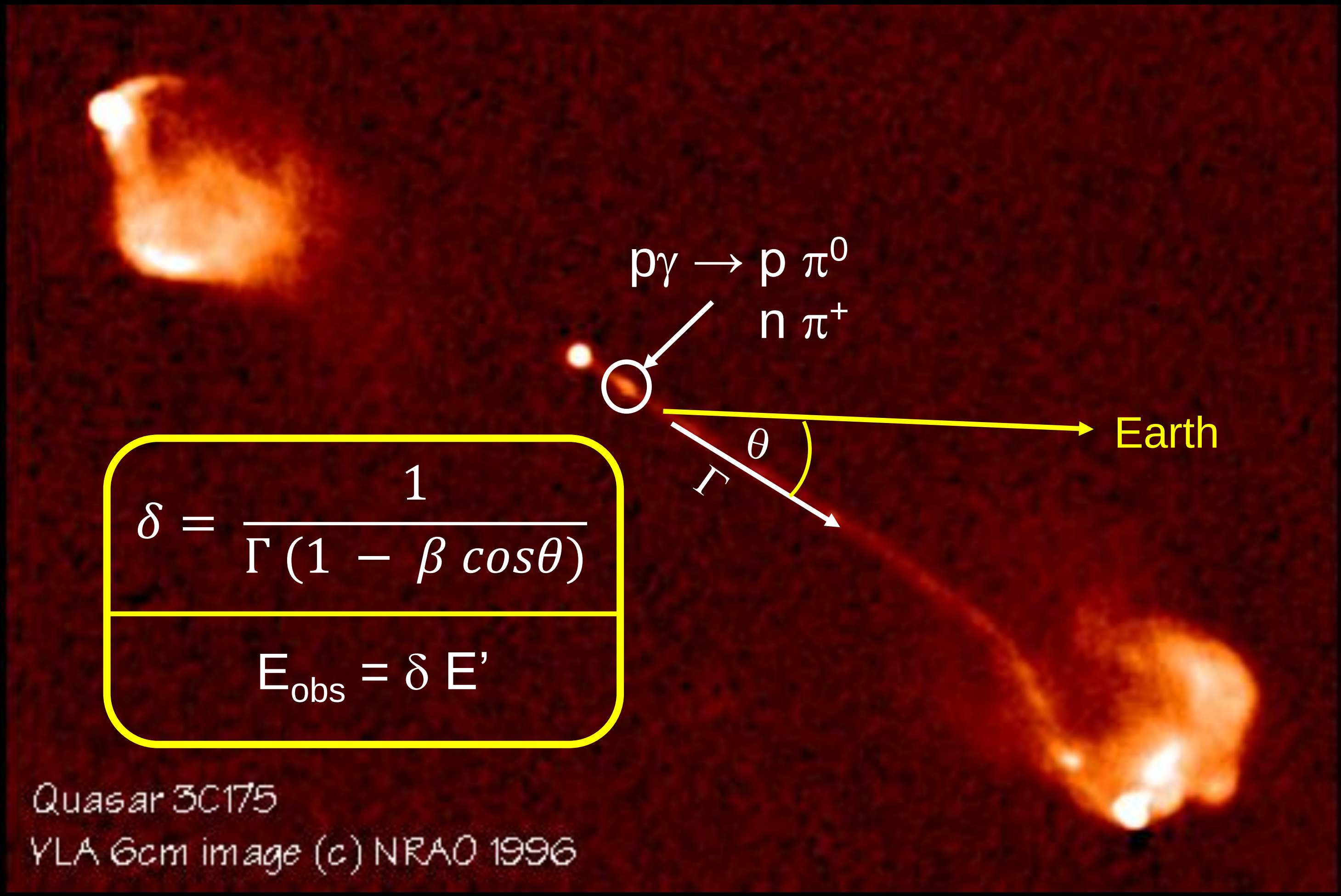
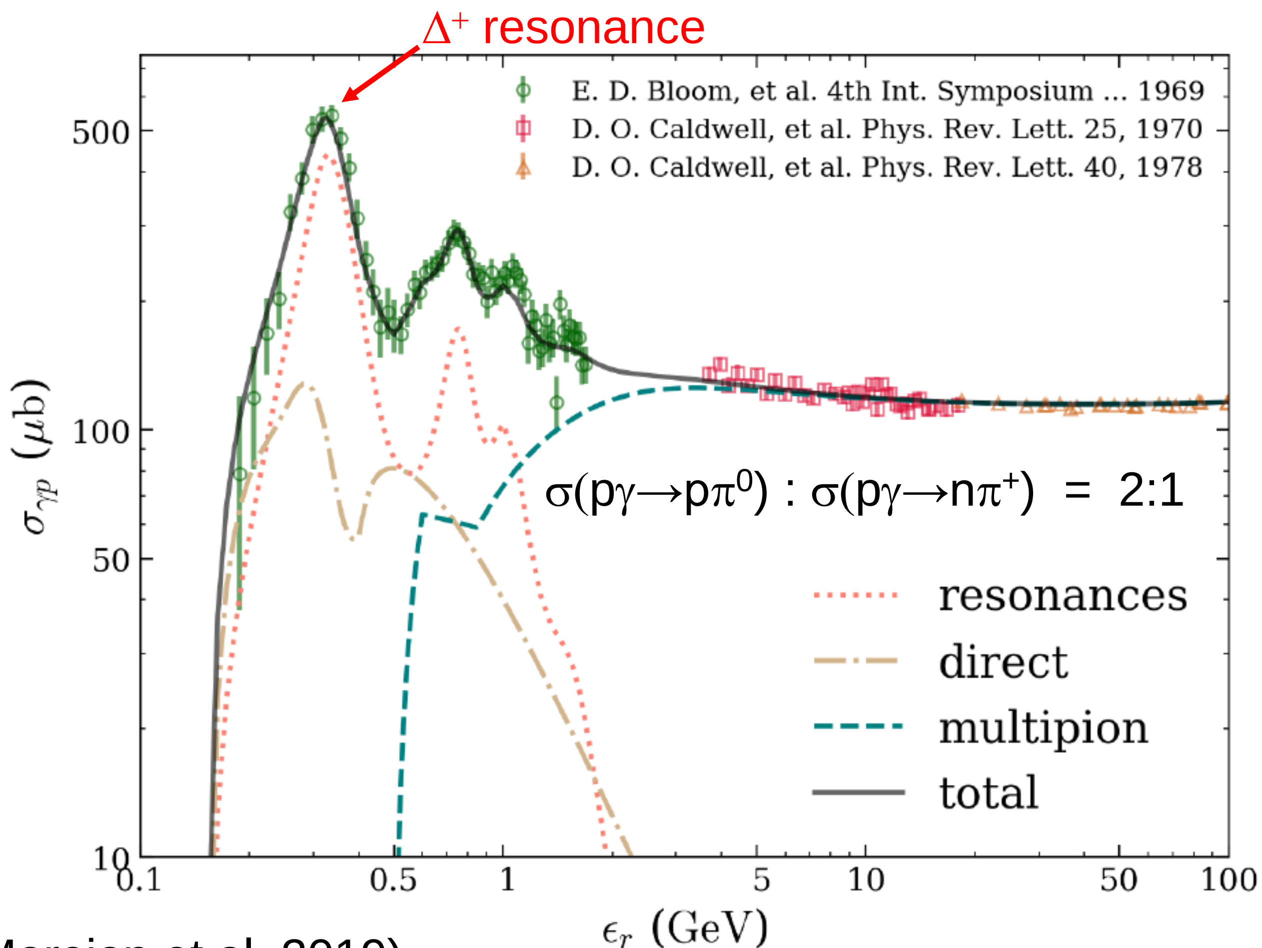


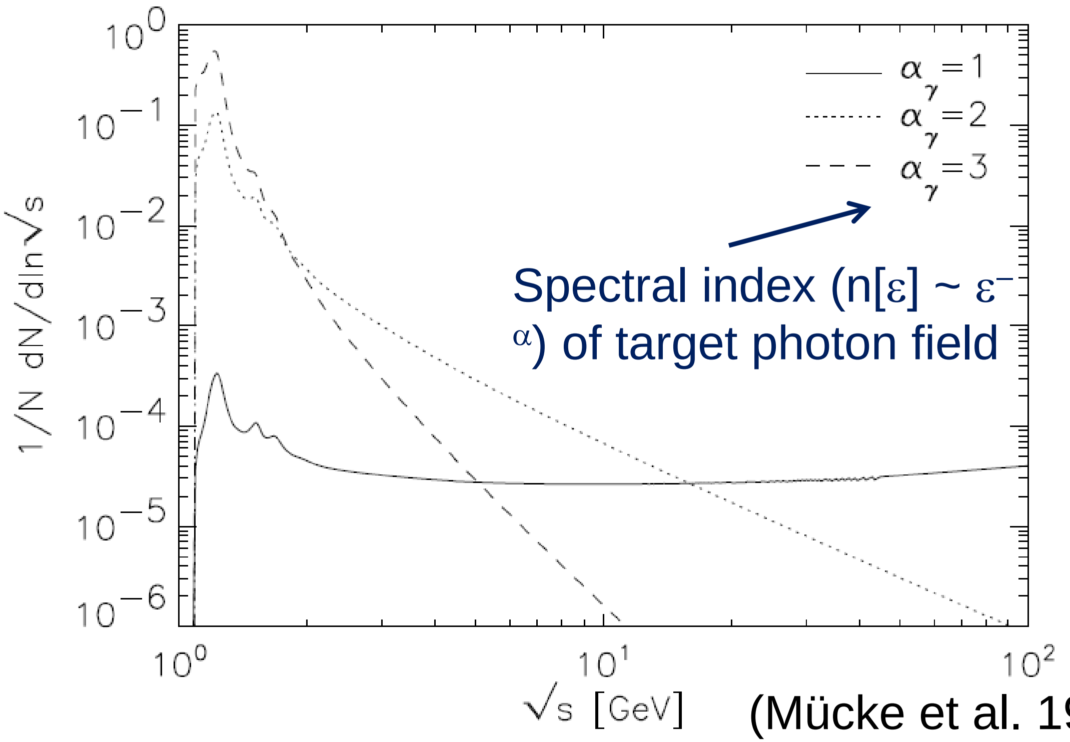
Photo-Pion Production Cross Section



(Morejon et al. 2019)

Photo-Pion Production

Interaction Probability



(Mücke et al. 1999)

Center-of-Momentum energy

For realistic target photon fields, most interactions occur near threshold (at Δ^+ resonance).

Photo-pion production - Energetics

At Δ^+ resonance:

$$s = E'_p E'_t (1 - \beta_p' \mu) \sim E'_p E'_t \sim E_{\Delta+}{}^2 = (1232 \text{ MeV})^2$$

and $E'_\nu \sim 0.05 E'_p$

$\Rightarrow$ To produce IceCube neutrinos (~ 100 TeV $\rightarrow E_\nu = 10^{14} E_{14}$ eV):

(i.e., $E'_\nu = 10 E_{14} \delta_1^{-1}$ TeV)

Need protons with $E'_p \sim 200 E_{14} \delta_1^{-1}$ TeV

and target photons with $E'_t \sim 1.6 E_{14}^{-1} \delta_1$ keV => X-rays!

Photo-pion production – Origin of Target Photons

To produce IceCube neutrinos (~ 100 TeV → $E_\nu = 10^{14} E_{14}$ eV):

Need protons with	$E'_p \sim 200\, E_{14}\, \delta_1^{-1}$ TeV
and target photons with	$E'_t \sim 1.6\, E_{14}^{-1}\, \delta_1$ keV

(At least) two possible scenarios for target photons:

a) Co-moving with the emission region

⇒ $E_t^{obs} \sim 16\, E_{14}^{-1}\, \delta_1^2/(1+z)$ keV

⇒ Observed as hard X-rays

⇒ Doppler boosted into observer's frame

⇒ Stringent constraints on co-moving energy density

⇒ Typically large proton power requirements!

b) Stationary in the AGN frame

⇒ $E_t^{obs} \sim 160\, E_{14}^{-1}/(1+z)$ eV

⇒ Observed as UV / soft X-rays

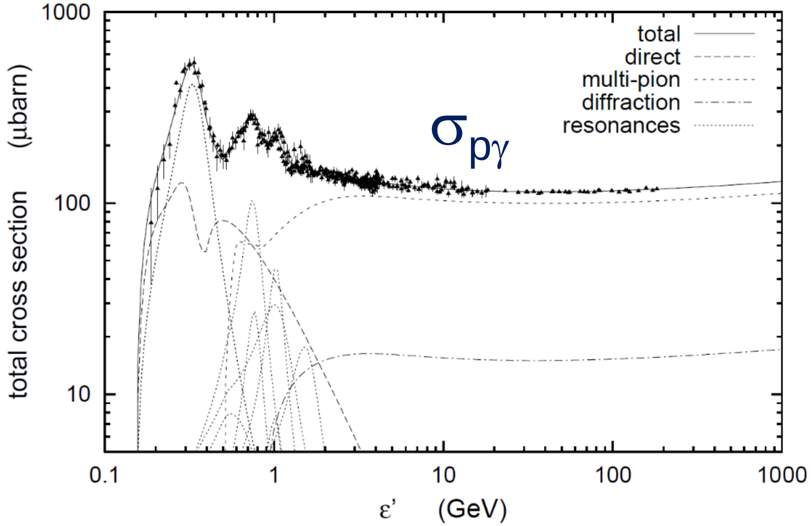
⇒ Doppler boosted into co-moving frame

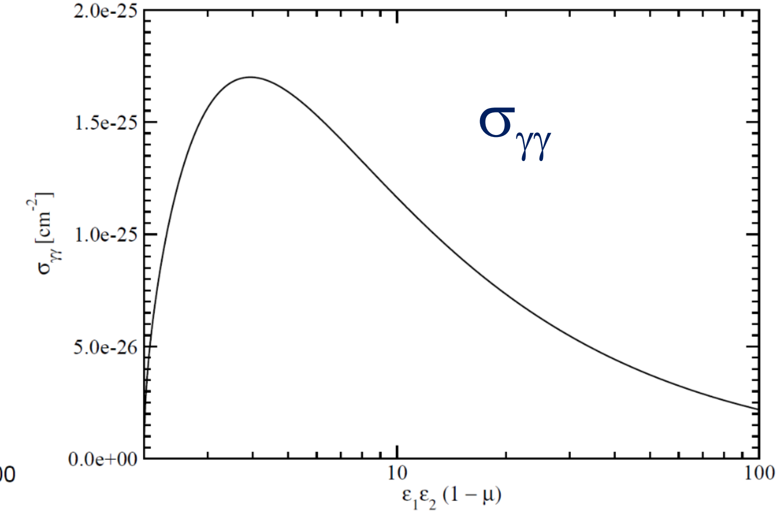
⇒ Strongly relaxed constraints on energy density

⇒ Much lower proton power requirements!

The pγ Efficiency Problem

- Efficiency for protons to undergo pγ interaction ~ $\tau_{p\gamma} = R\,\sigma_{p\gamma}\,n_{ph}$
- Likelihood of γ-ray photons to be absorbed ~ $\tau_{\gamma\gamma} = R\,\sigma_{\gamma\gamma}\,n_{ph}$



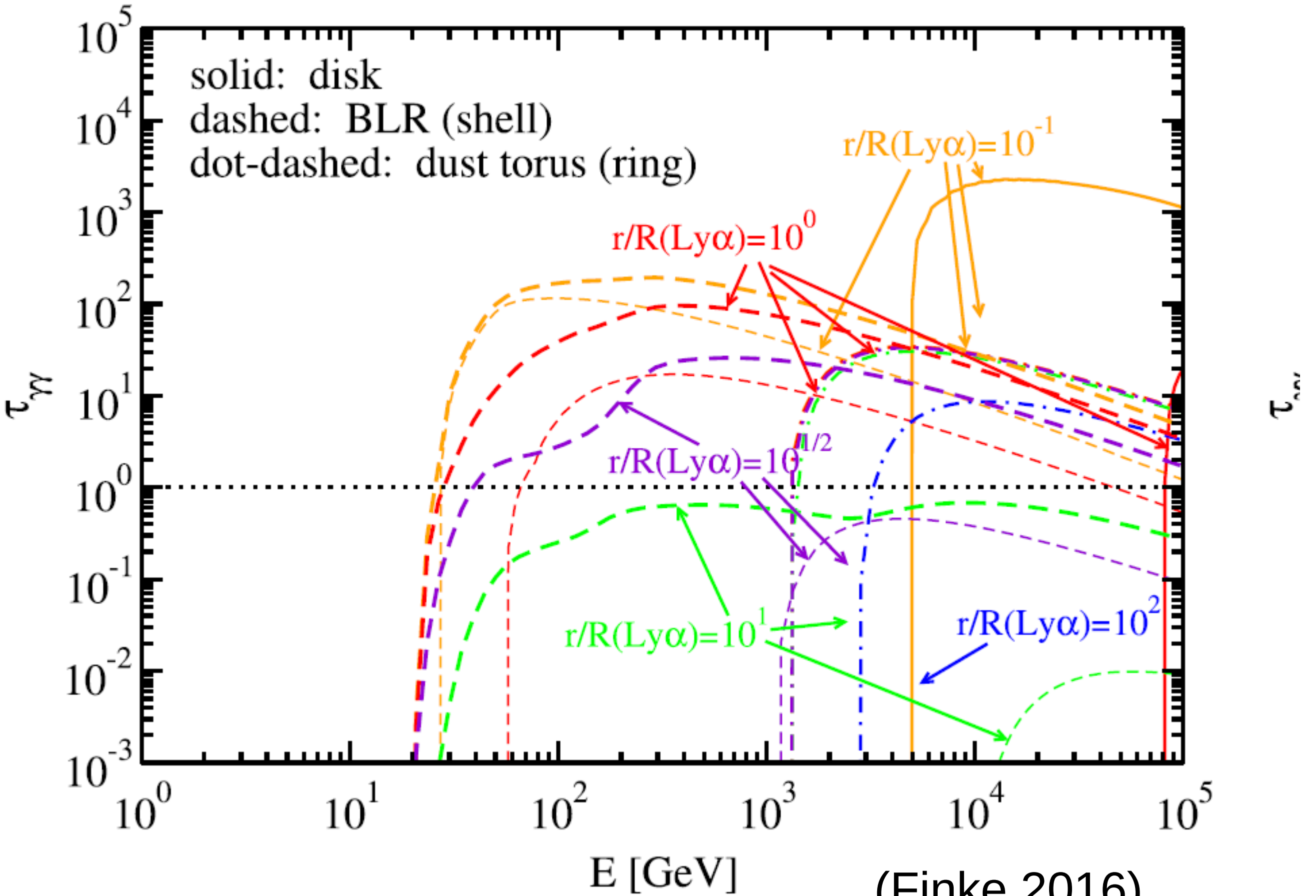


$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \approx \frac{1}{300}$$

at $E_\gamma \sim \frac{2\,m_e^{\,2}\,c^4}{E_t} \sim 3 \times 10^{-5}\,E_\nu\,/(1+z) \sim 3\,E_{14}/(1+z)$ GeV

⇒ Photons at E_γ ~ GeV are heavily absorbed.
⇒ Cascade emission at lower energies.
⇒ Expect correlation with X-rays / soft γ-rays and VHE γ-rays.

Example: BLR Target Photon Field



(Finke 2016)

Opacity decreases towards multi-TeV energies

=> H.E.S.S. follow-up program on potential IceCube neutrino counterpart blazars

Summary

1. Many open questions concerning jet acceleration / collimation / composition / …

2. VHE γ-ray observations of blazars may probe PeV cosmic-ray acceleration in AGN jets through

   a) Characteristic spectral signatures

   b) Characteristic variability signatures

   c) Correlation of VHE γ-ray activity (not necessarily Fermi-LAT GeV γ-ray activity!) with IceCube neutrino alerts.

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