ACTIVE GALACTIC NUCLEI AS OBJECTS OF MULTI-MESSENGER ASTROPHYSICS

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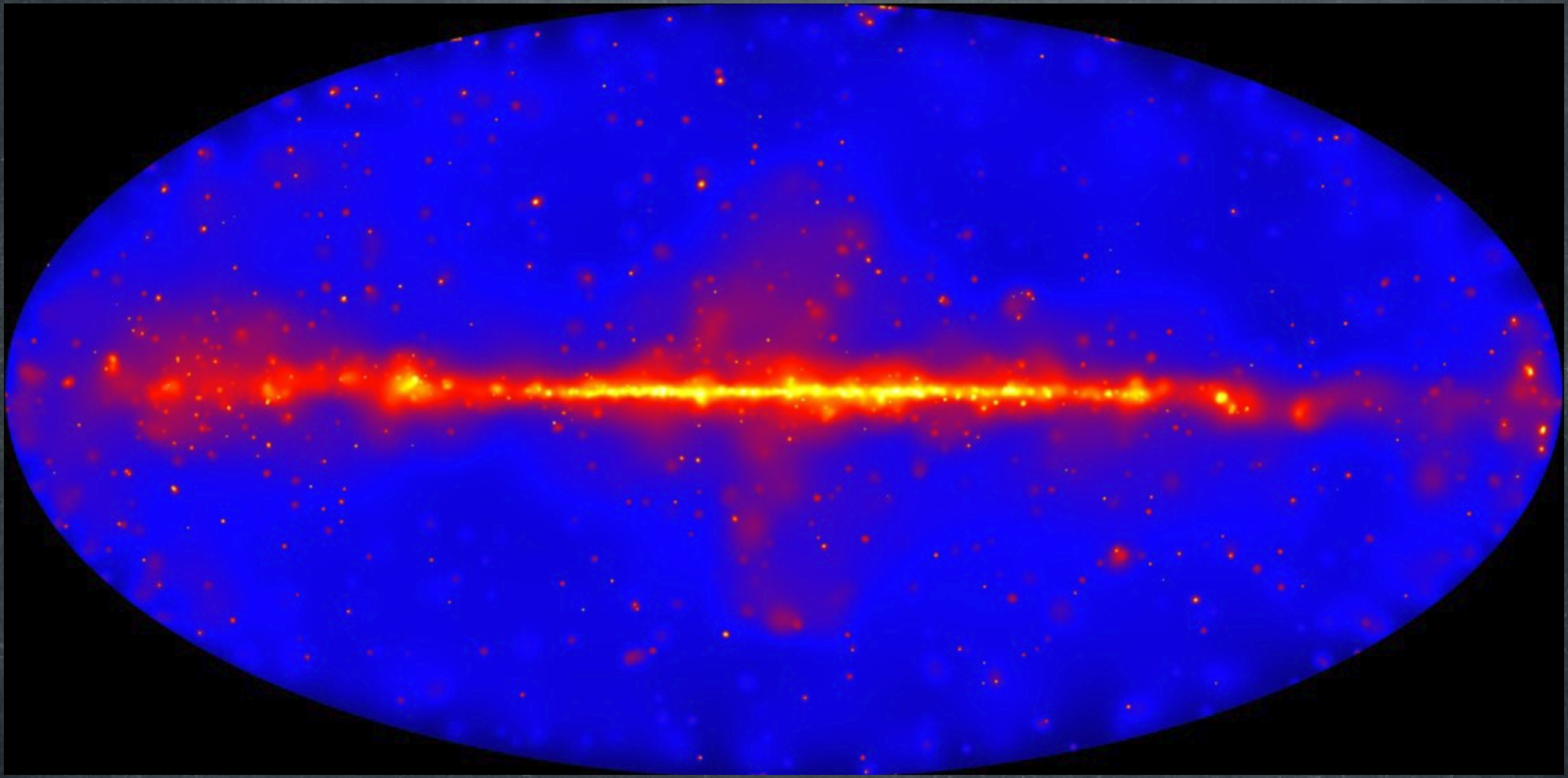
TALK OUTLINE

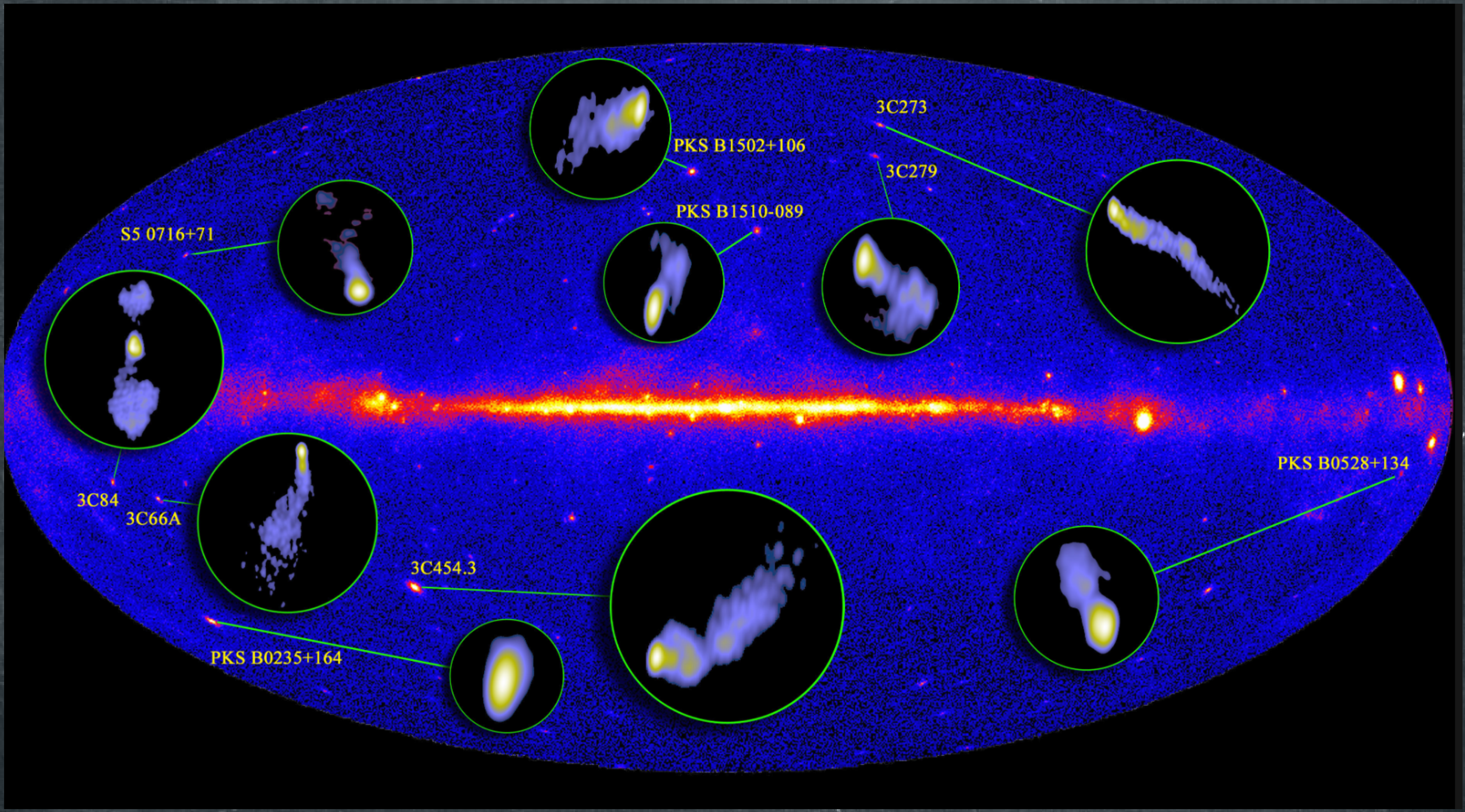
- Radio Loud AGNs - Blazars
- Models of non-thermal emission
- Blazars as multi-messenger sources
- IceCube neutrinos and TXS 0506+056

THE GeV GAMMA-RAY SKY

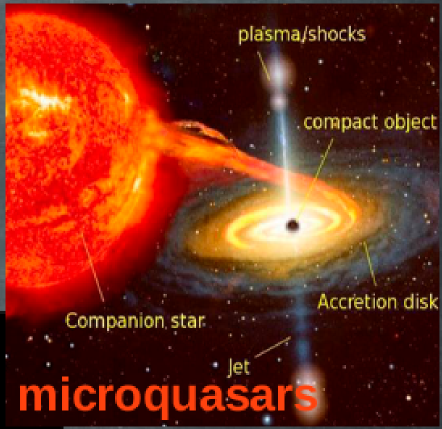


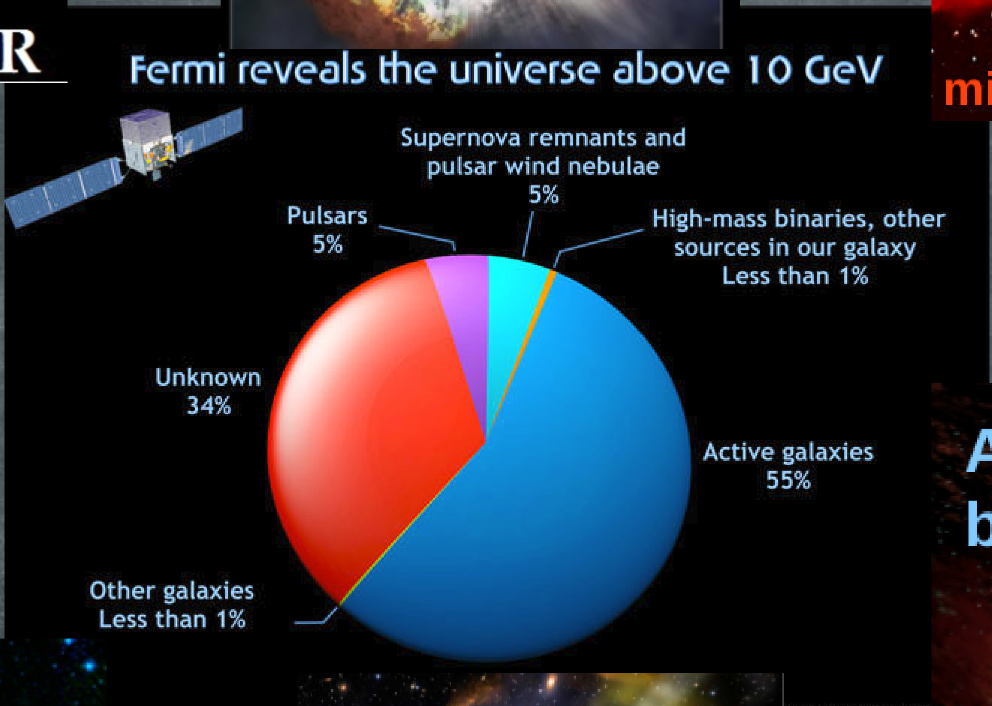
Fermi Telescope (>2010) - What are these sources?

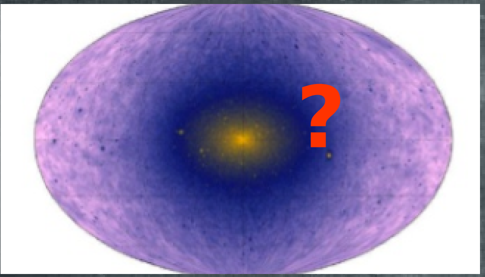
GAMMA – RAY vs RADIO



High-latitude GeV sources are Active Galactic Nuclei

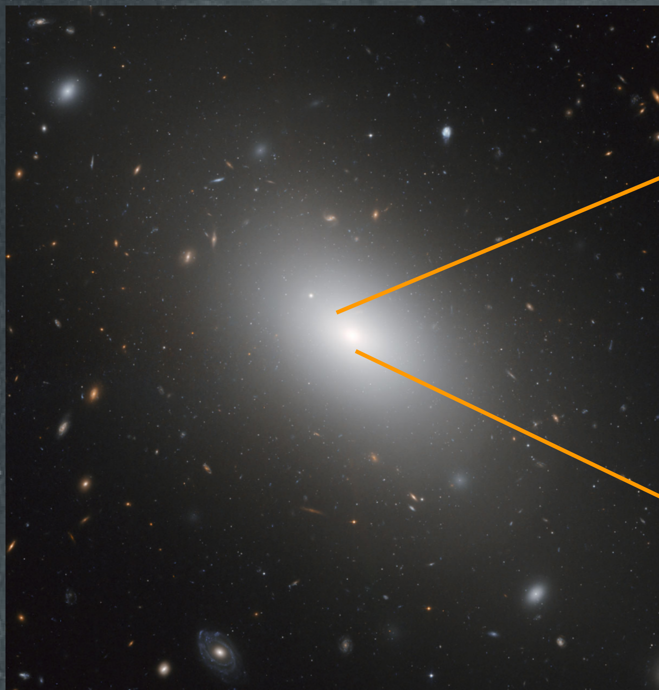






Goddard Space Flight

WHAT IS AN AGN?

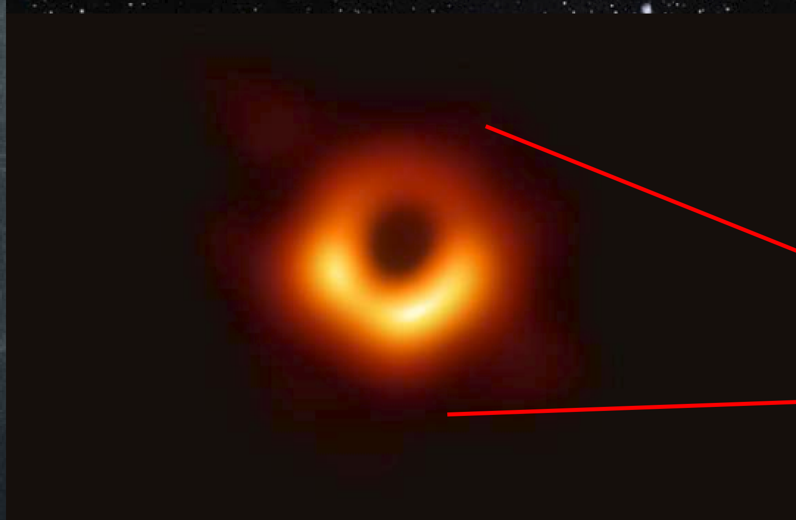


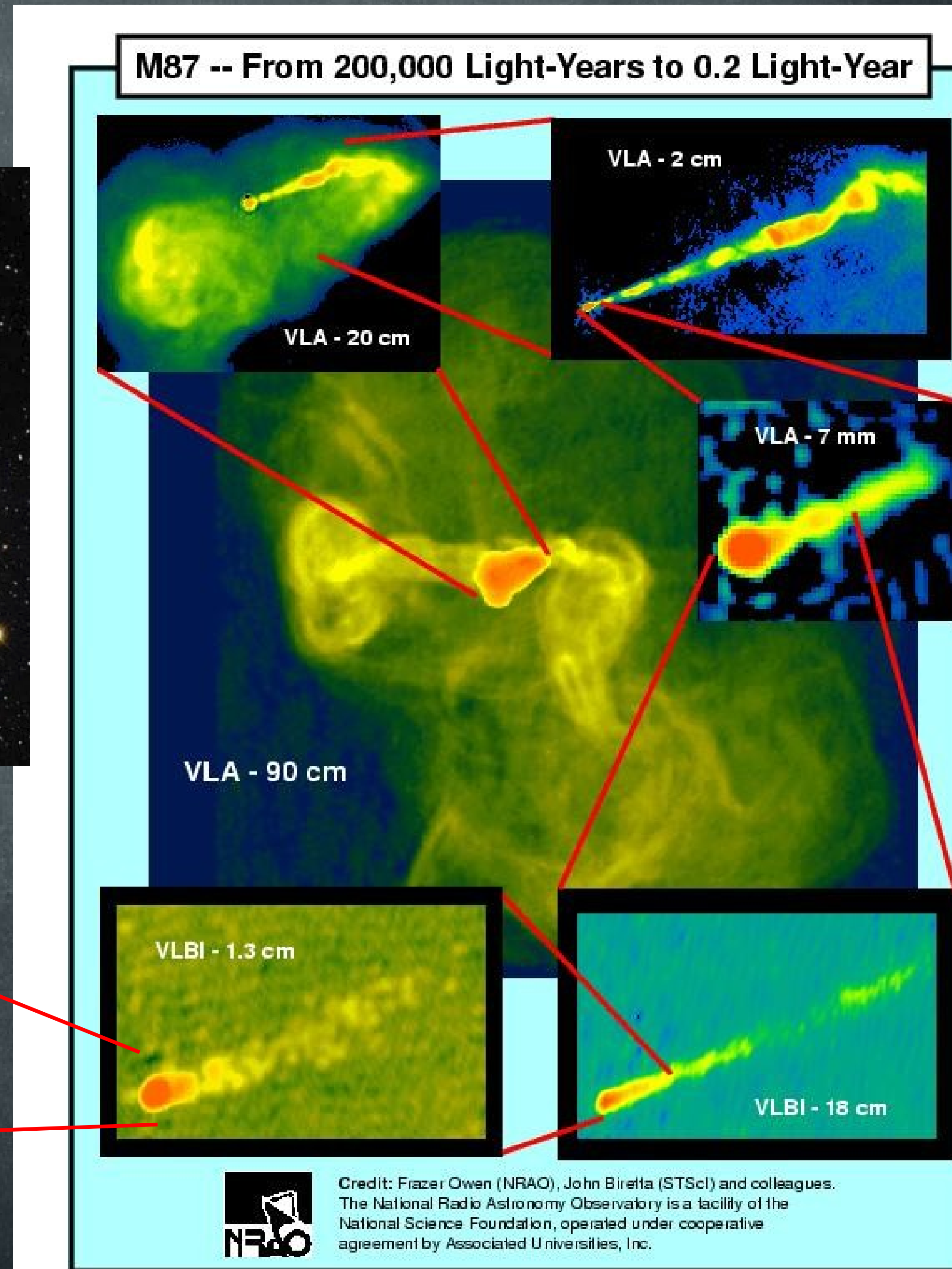
~100 kpc

~100 μpc

Manifestations of a supermasive black hole in the center of a galaxy

RADIO GALAXY
M87

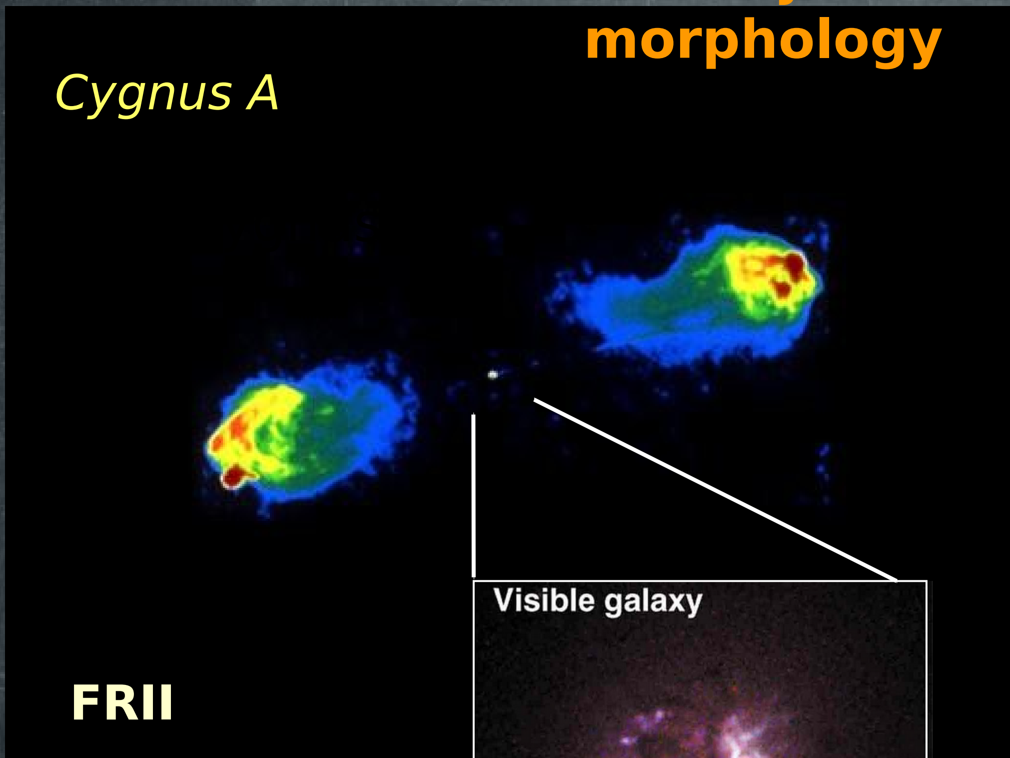


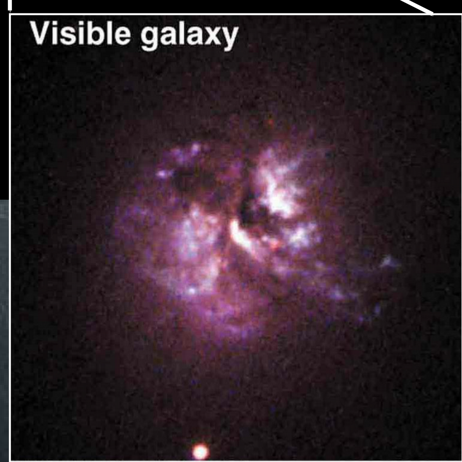


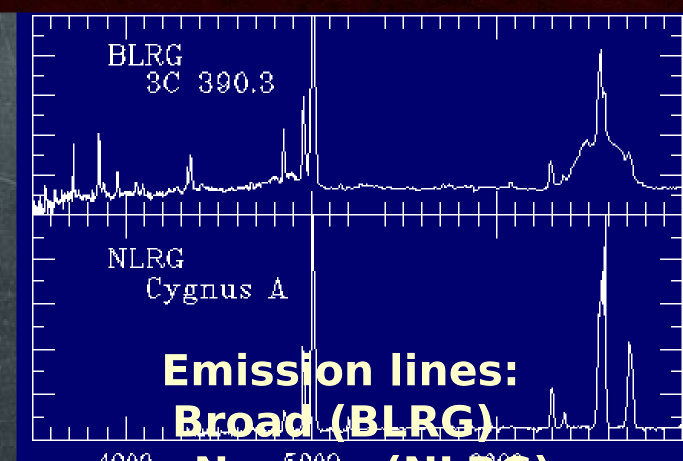
RADIO GALAXIES

Galaxies (mostly ellipticals) hosting an active nucleus

Core - jet - lobes morphology

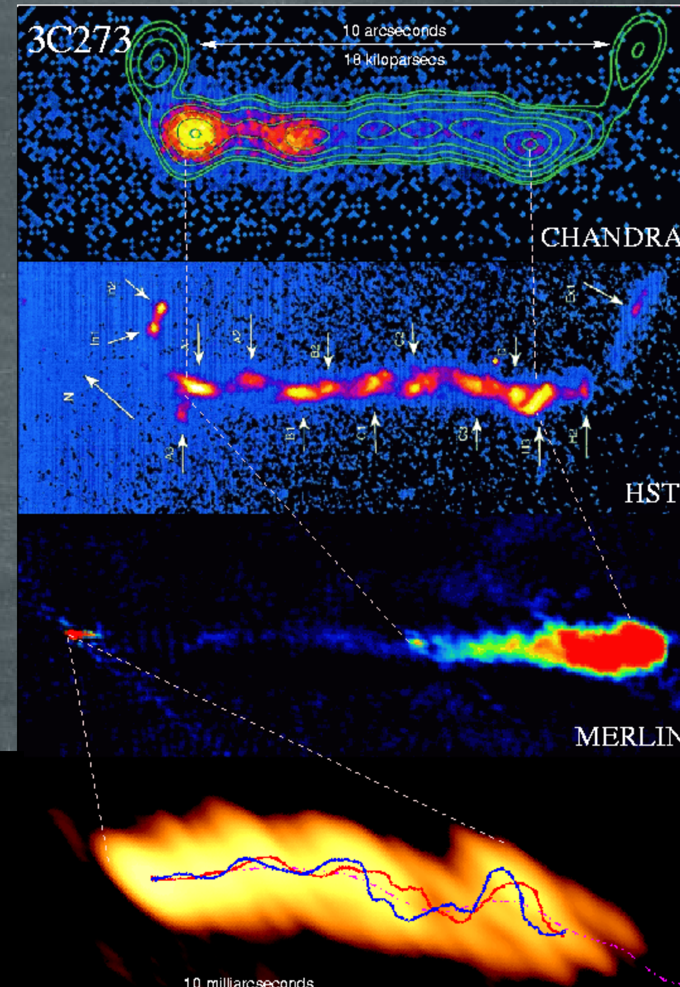


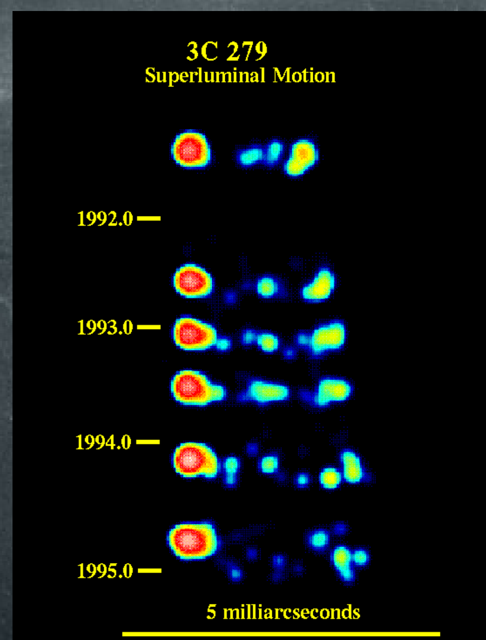


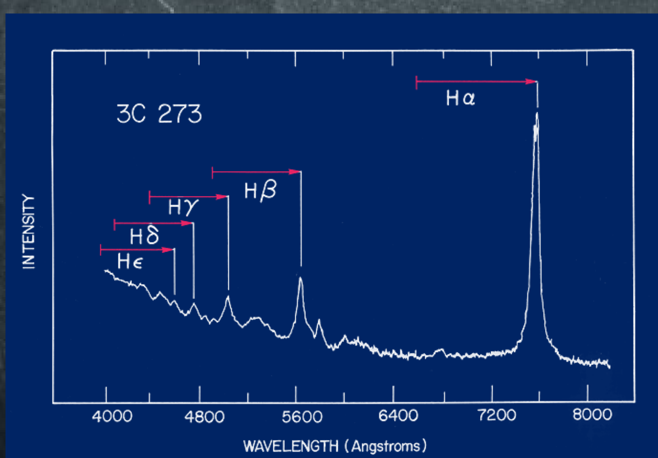


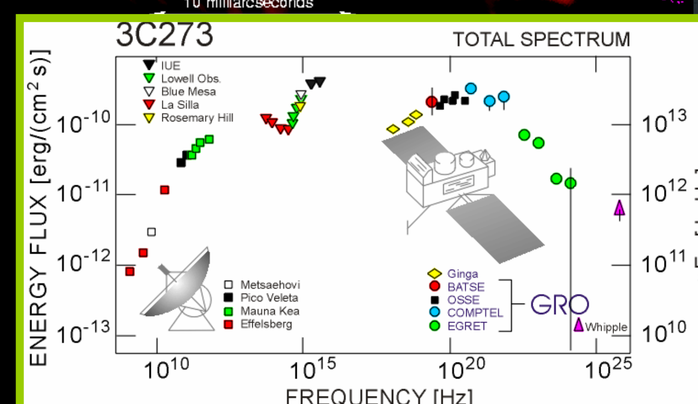
QUASARS

- Star-like appearance
- High redshift → high luminosity
- Strong, broad, emission lines
- Continuum and emission line variability
- Broad spectral energy distribution (SED) from radio to γ-rays
- Superluminal motion



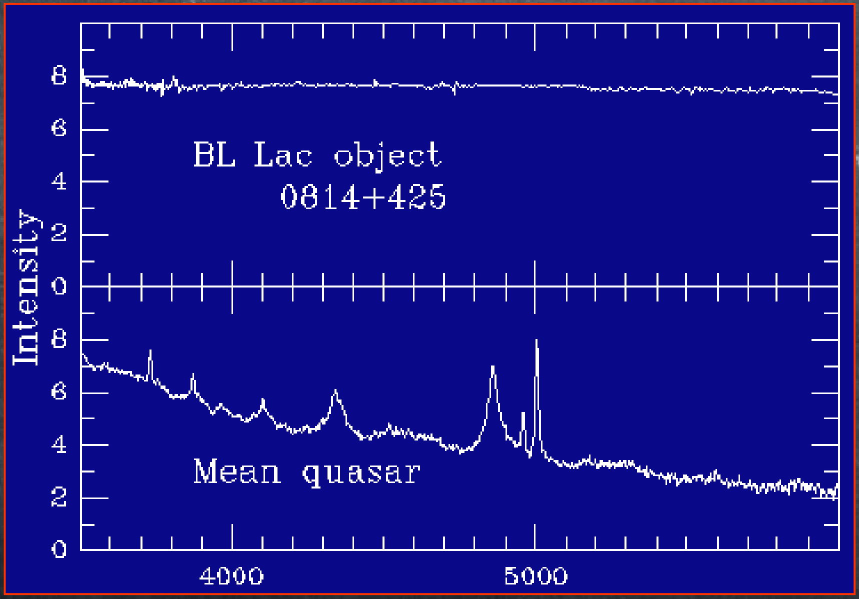




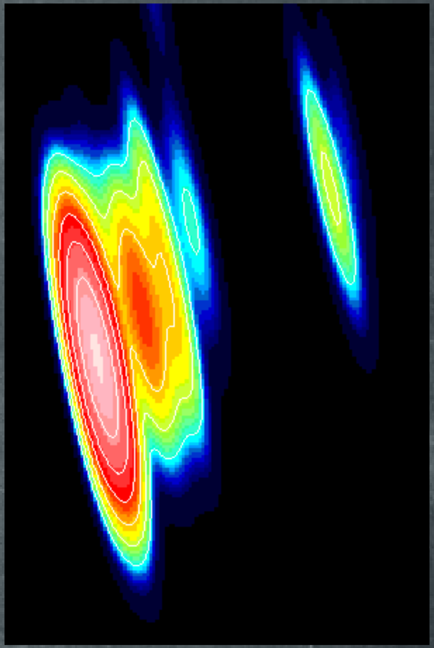


BL Lac OBJECTS

- Star-like appearance
- Low redshift → low luminosity
- No emission lines
- Non-thermal continuum (radio to gamma-rays)
- Fast variability
- High polarization
- Superluminal motion

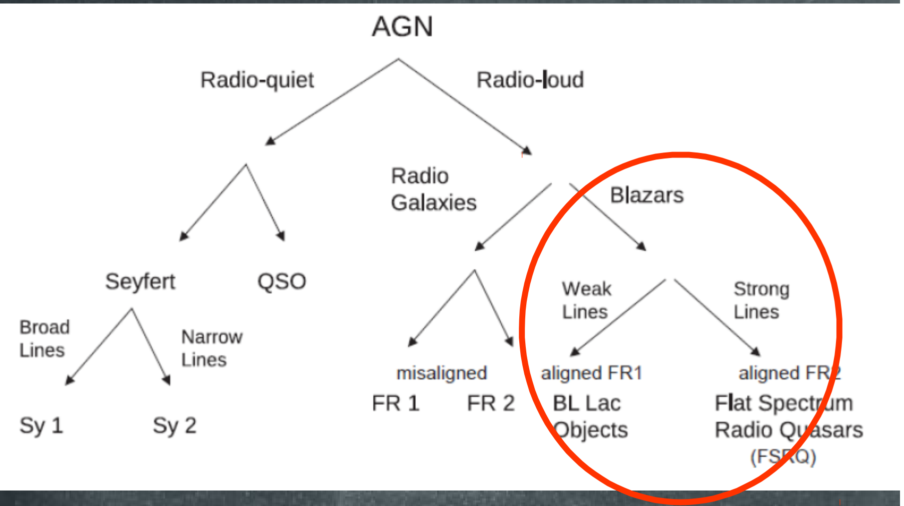


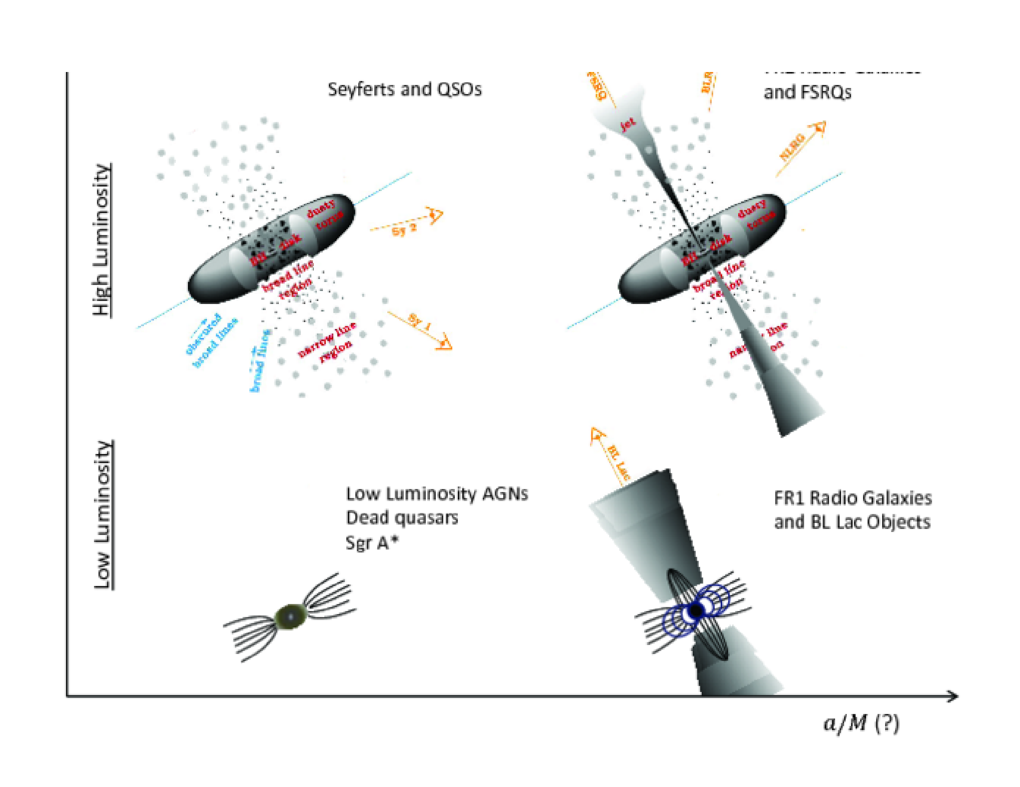
radio



visual

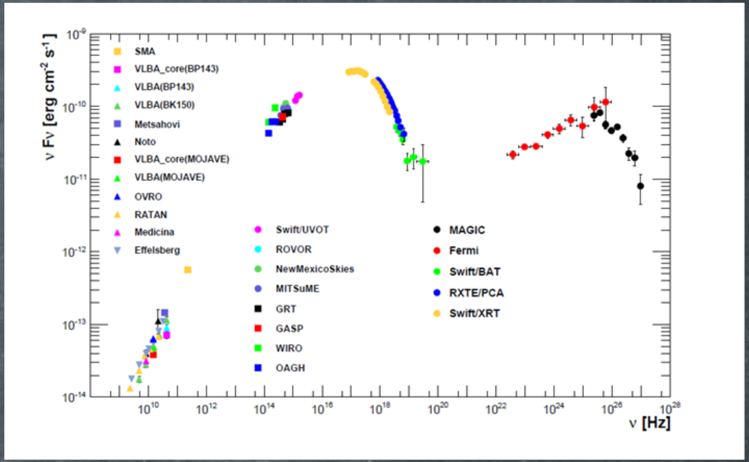
AGN TAXONOMY

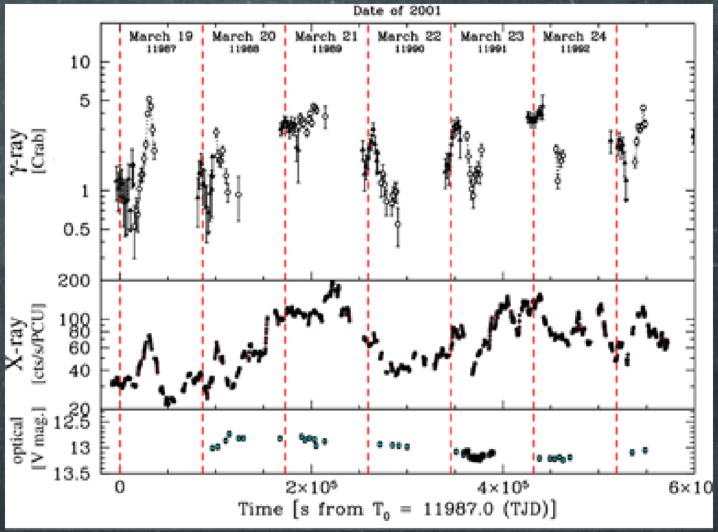




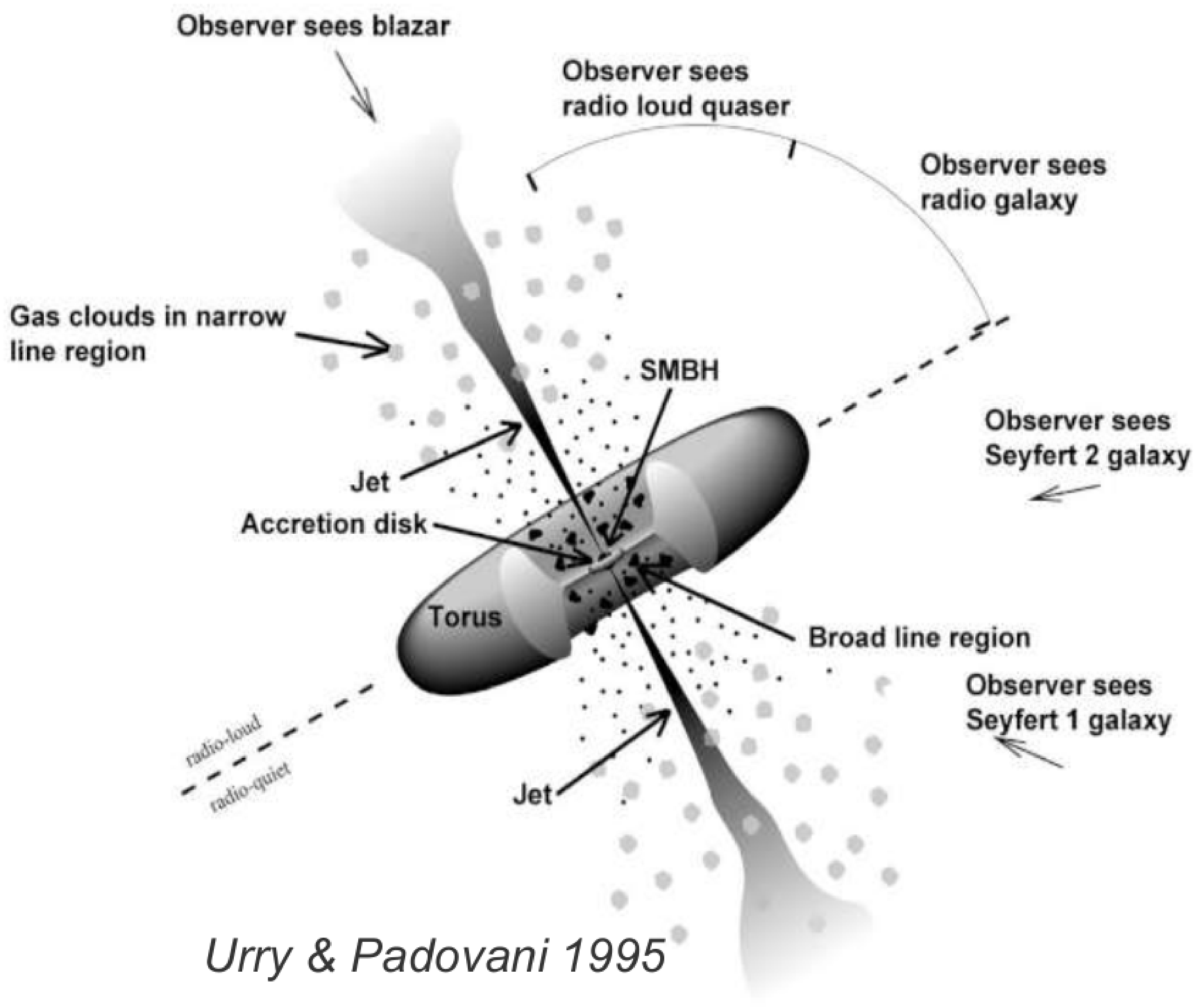
BLAZARS

- Few (~5% of all AGN)
- Compact , flat spectrum radio sources
- Broad (radio-gamma) non-thermal continuum : ‘Double hump’ spectrum
- Variable at all energies: short – large amplitude variability + correlations
- Superluminal motion





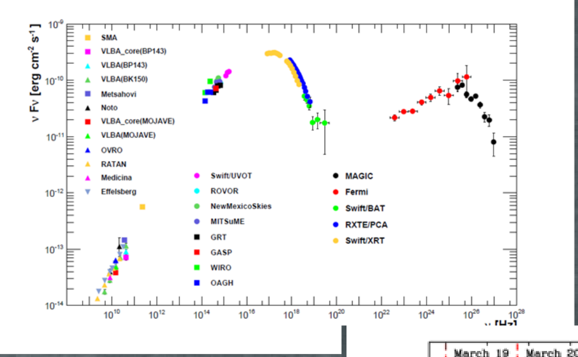
AGN UNIFICATION

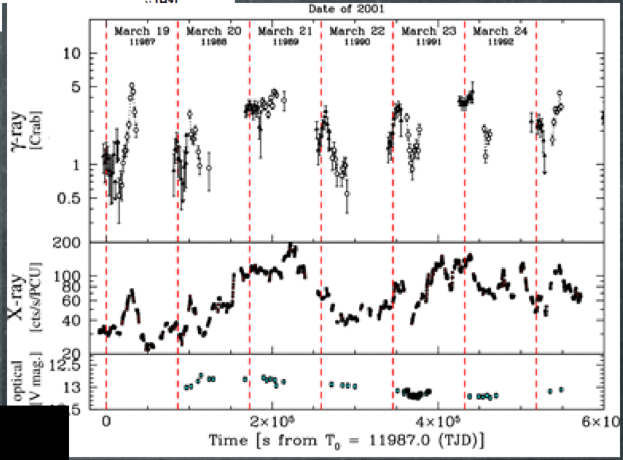


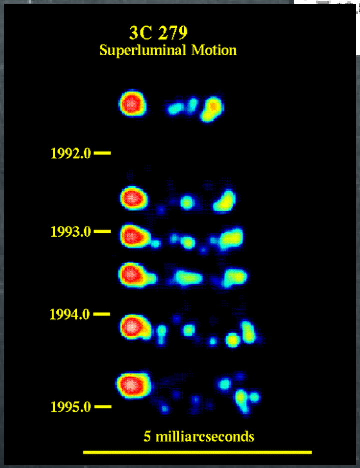
Urry & Padovani 1995

BLAZARS: THE HARD FACTS

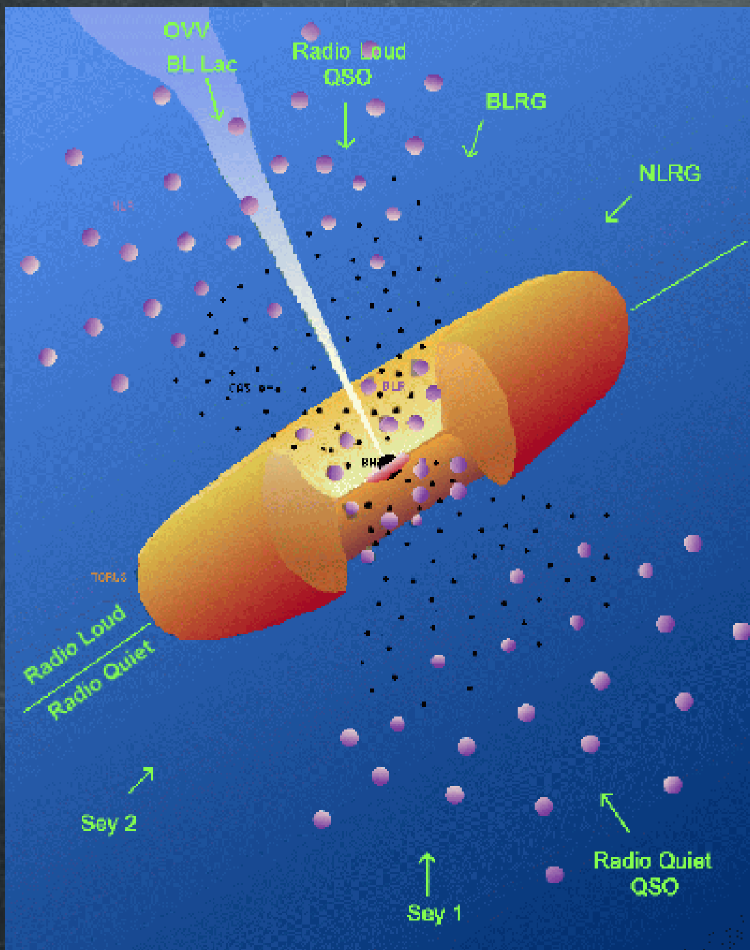
- MW Spectrum → Non-thermal radiation mechanisms
- Gamma-ray emission → High energy particles → Acceleration
- Fast + correlated variability → emission from a localized region
- Superluminal motion → emission from inside the jet → relativistic beaming







BLAZARS: THE OPEN ISSUES



– **Distance of the active region**
  (close or far from BH?)

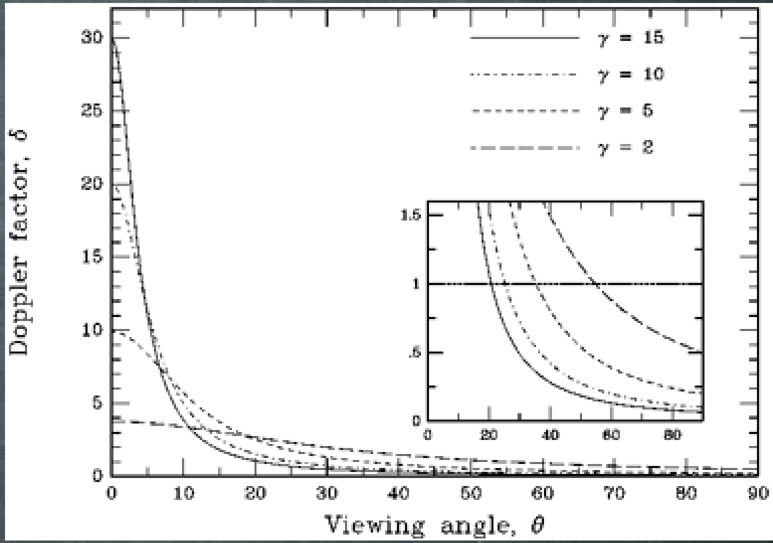
– **Geometry of the active region**
  (blob or jet?)

– **Species of radiating particles**
  (electrons or protons?)

– **Acceleration mechanisms**
  (shock or magnetic reconnection or...?)

RELATIVISTIC BEAMING AND JET ORIENTATION

Relativistic effects are important



Doppler boosting:

$F = \delta^4 F'$ (F observed flux)

$\delta = [\Gamma\,(1-\beta \cos\theta)]^{-1}$ Doppler factor

$\beta = v/c$

$\Gamma = (1-\beta^2)^{-1/2}$ Lorentz factor of the flow

For $\Gamma \gg 1$ and $\theta \ll 1$

(superluminal motion)

$\rightarrow \delta \gg 1$

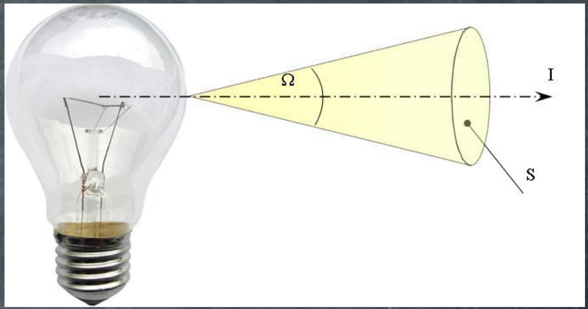
RADIATIVE TRANSFER

Observed flux $$F_\nu = I_\nu . d\Omega$$

Specific intensity

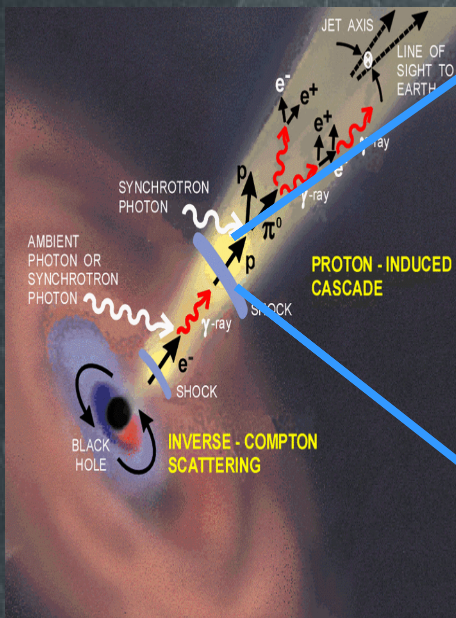
RTE $$\frac{dI_\nu}{ds} = j_\nu - a_\nu . I_\nu$$

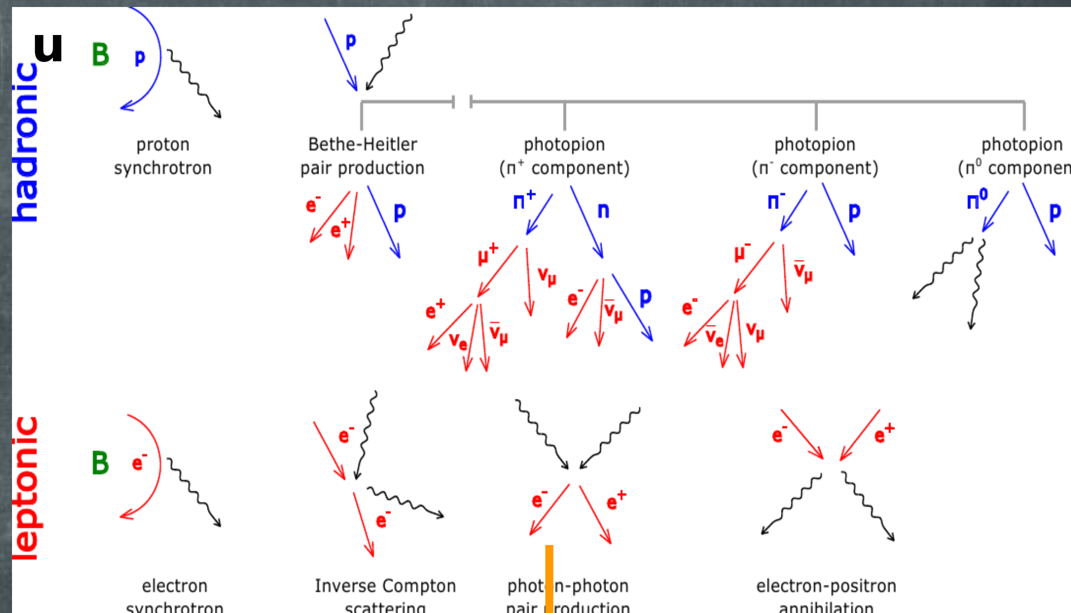
emission absorption

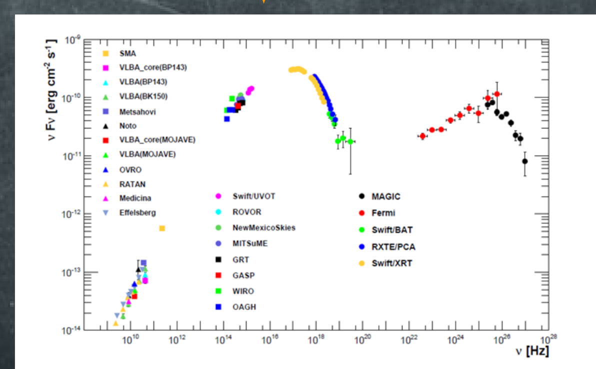


For Blazar jets: Specify j, α and geometry of emitting region →
Solve RTE in the comoving frame → Specific Intensity →
Doppler boosting → Flux

PHYSICAL PROCESSES FOR SPECTRAL FORMATION

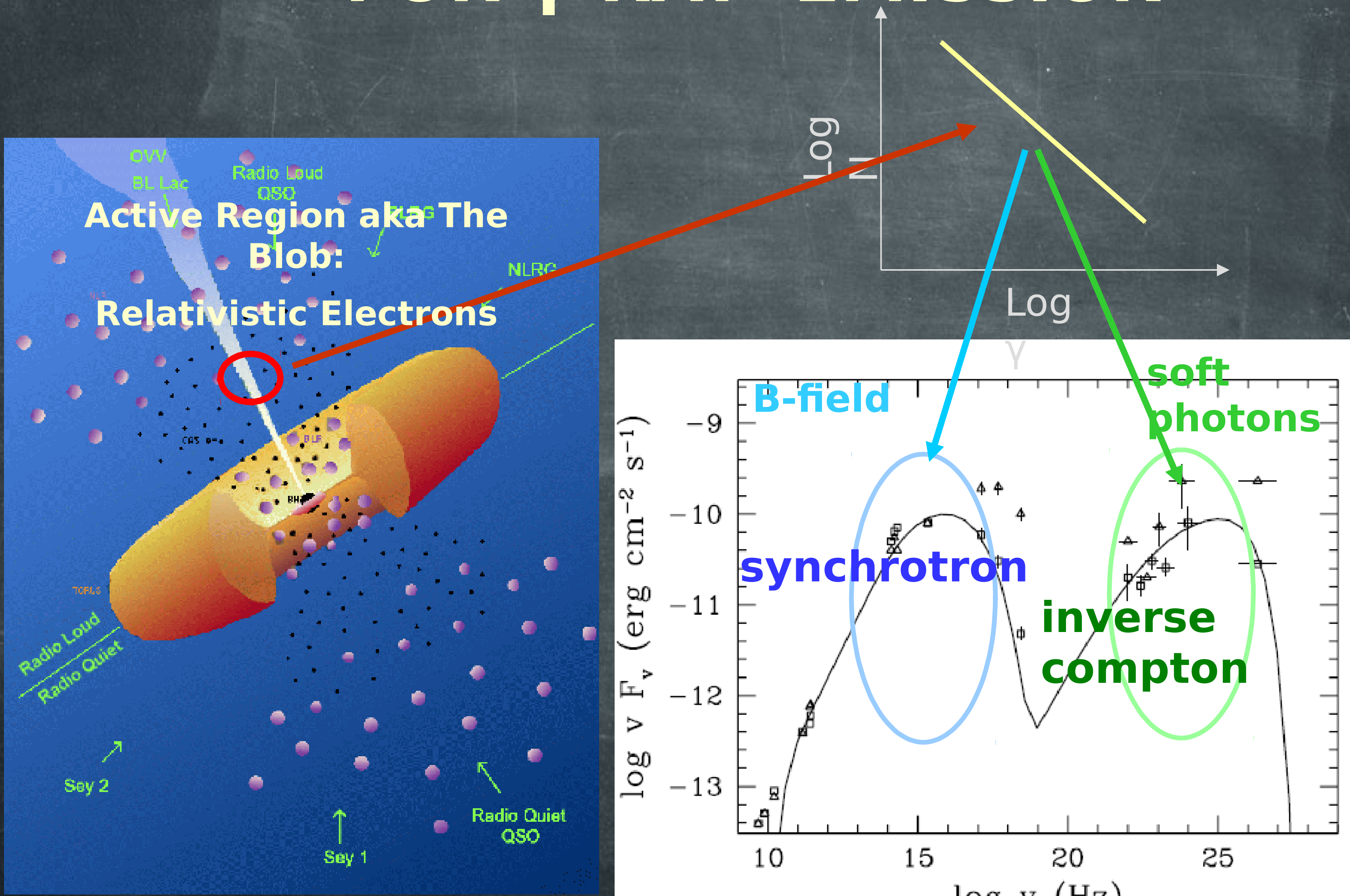




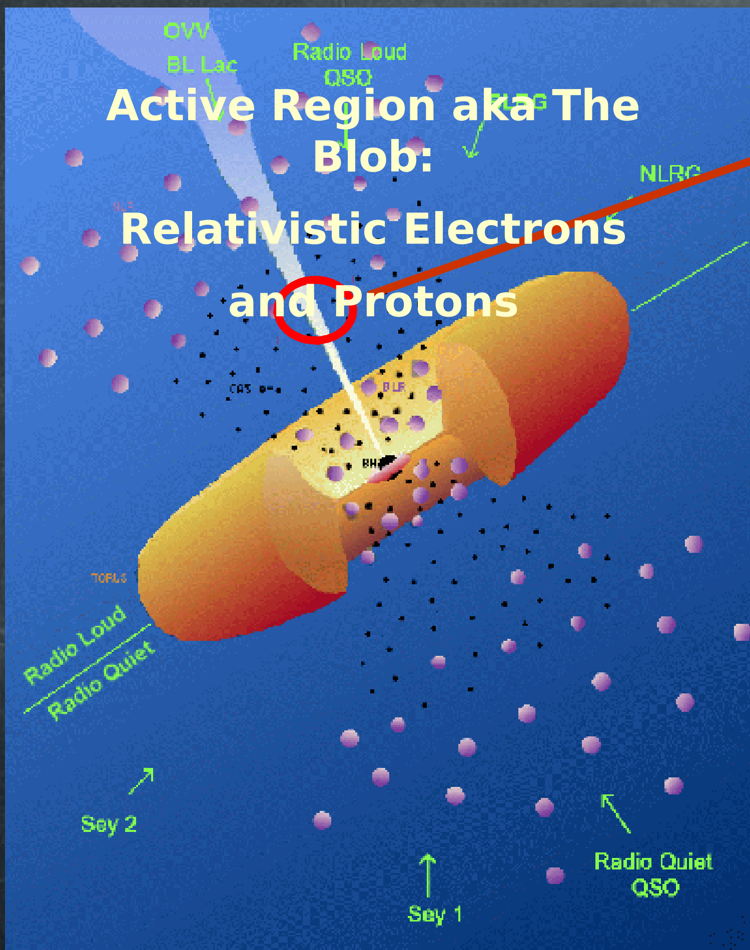


Emissivities jν, absorption coefficients αν from hadronic and leptonic high energy processes.

THE ONE-ZONE LEPTONIC MODEL FOR γ-RAY EMISSION

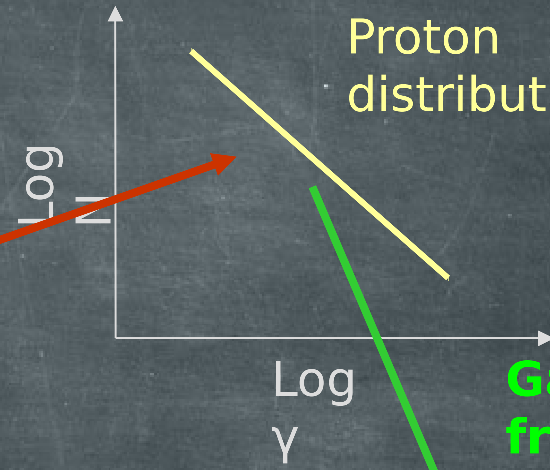


THE (LEPTO)HADRONIC MODEL



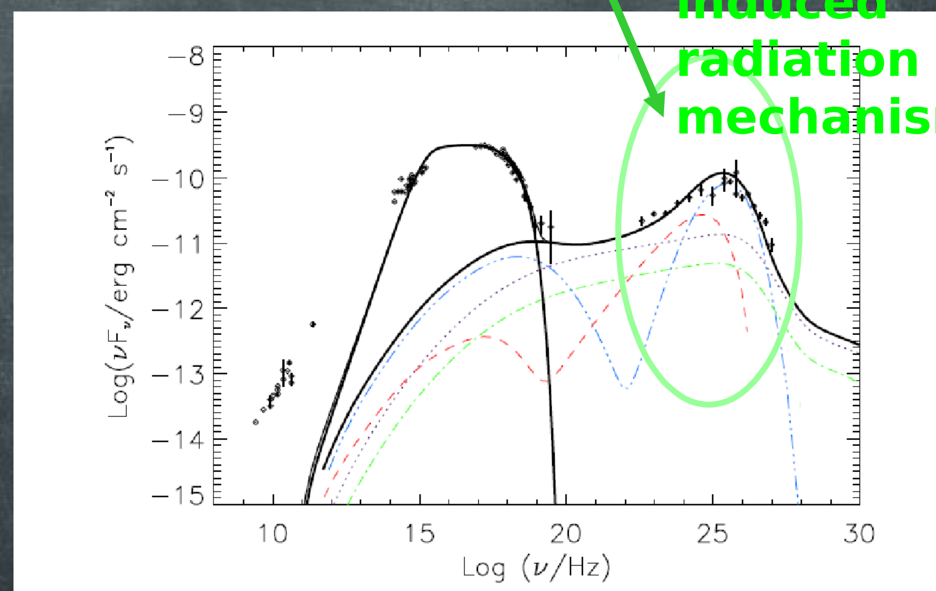
Active Region aka The Blob:

Relativistic Electrons and Protons

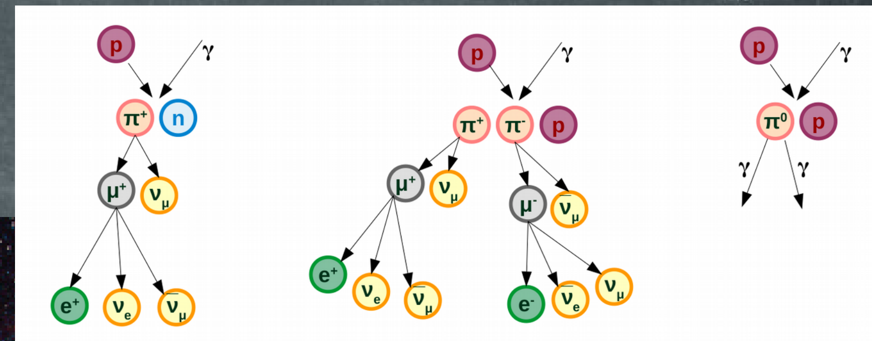


Proton distribution

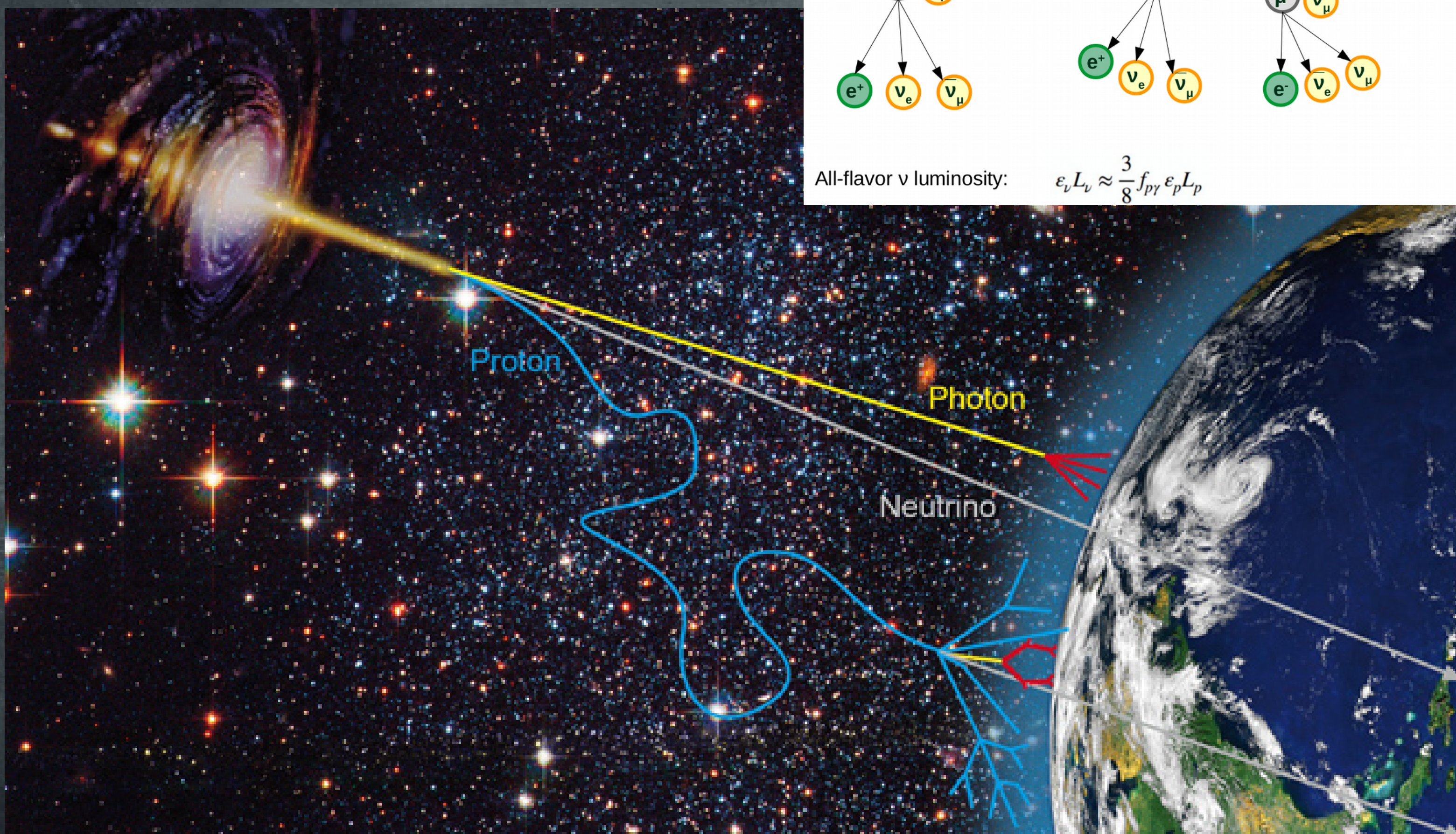
Gamma-rays from proton induced radiation mechanisms



IMPLICATIONS FOR COSMIC RAY AND NEUTRINO ASTRONOMY

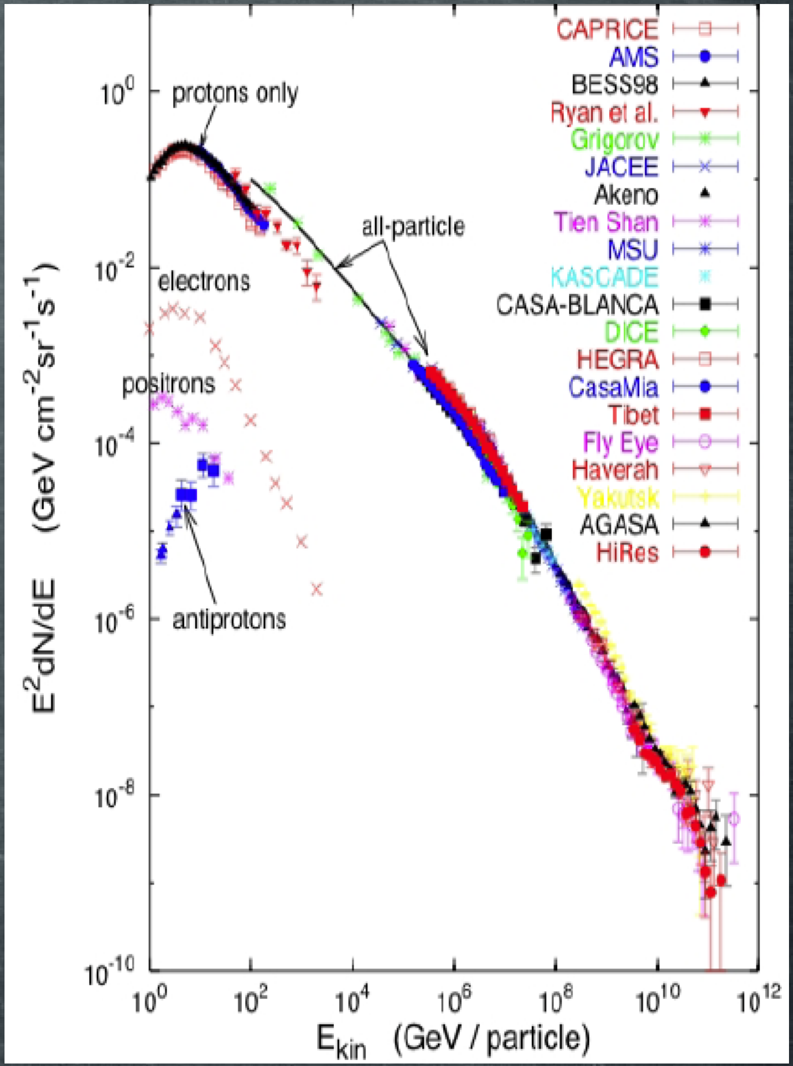


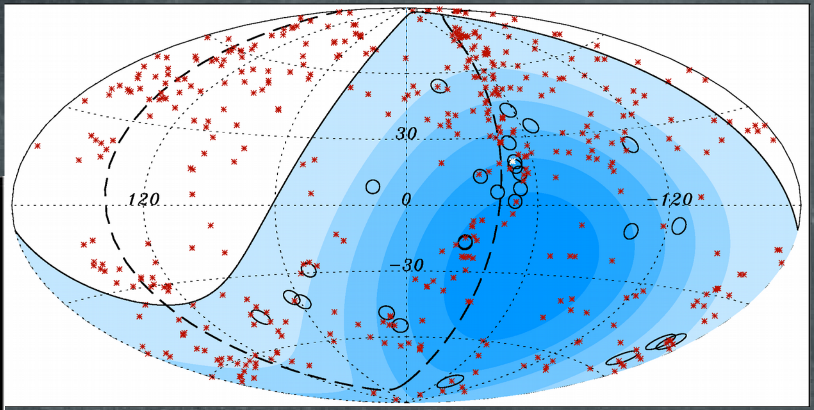
All-flavor ν luminosity: $\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$

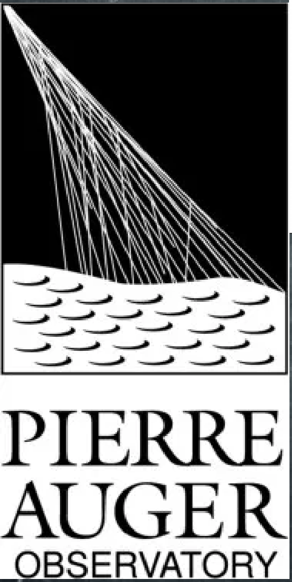


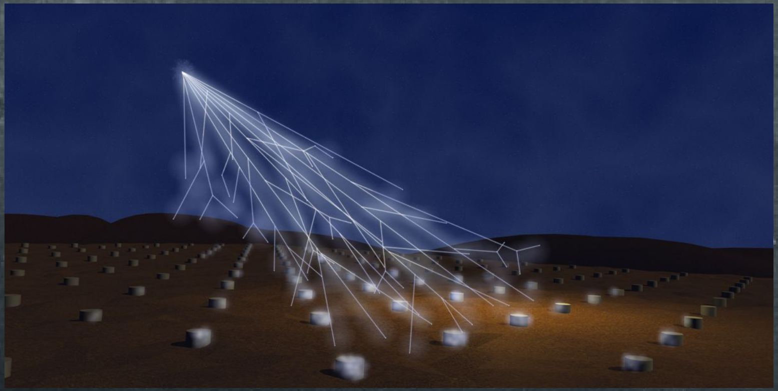
COSMIC RAYS

- Cosmic Rays: Protons + heavy nuclei up to energies of 300 EeV
- Highest energies extragalactic
- So far, no significant correlation with any known population
- Origin uncertain due to IGMF deflection
- Propagation effects important

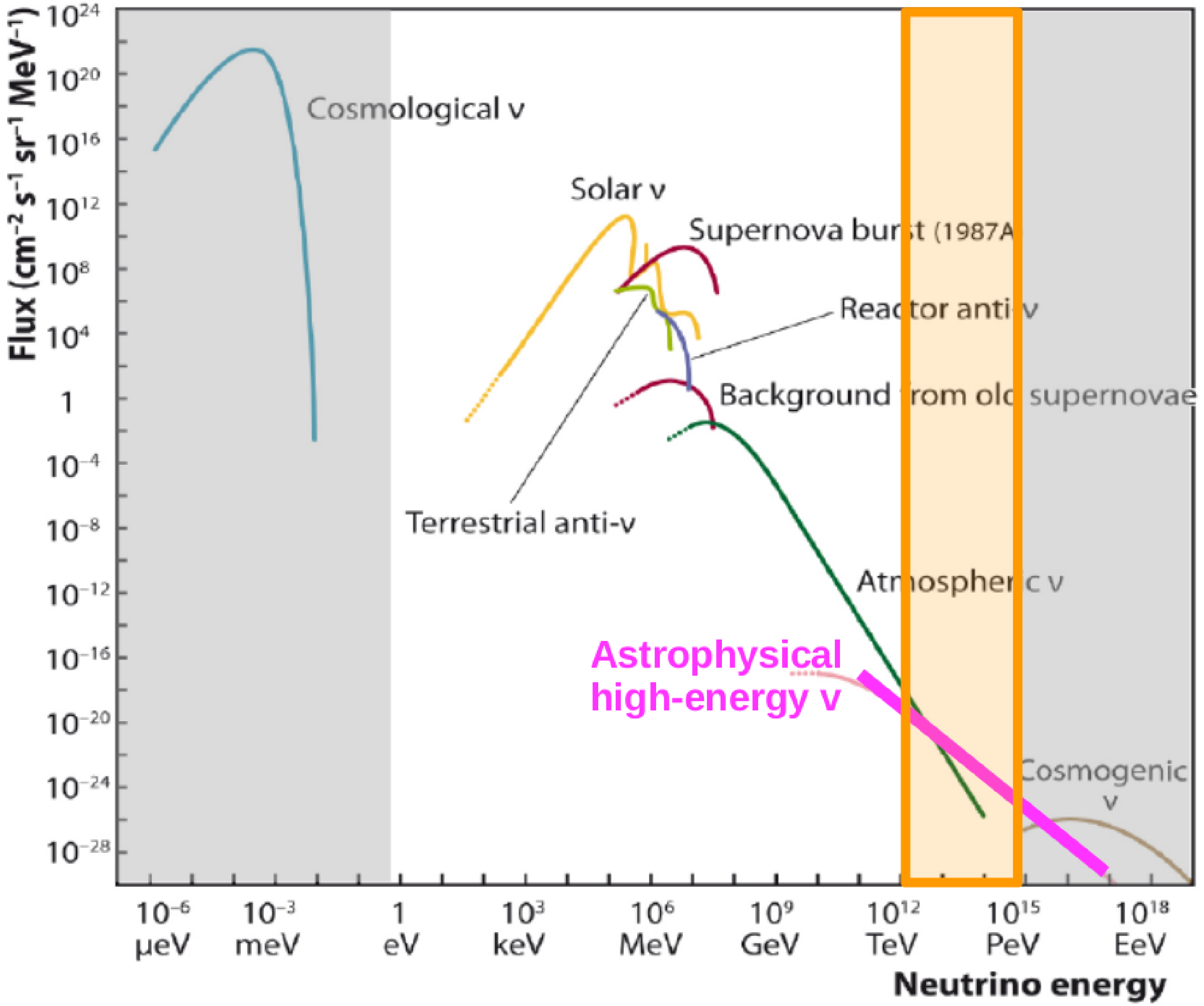




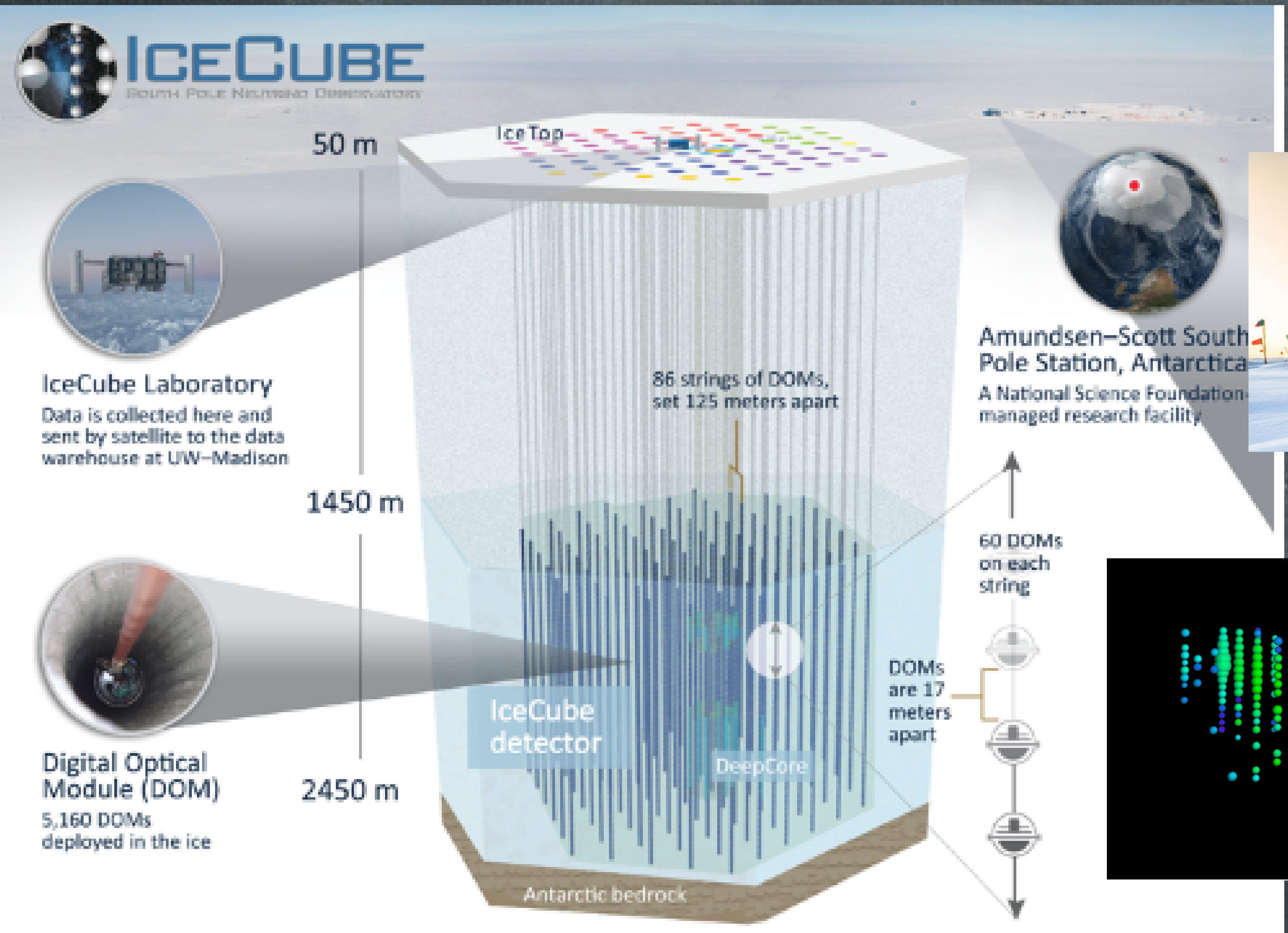




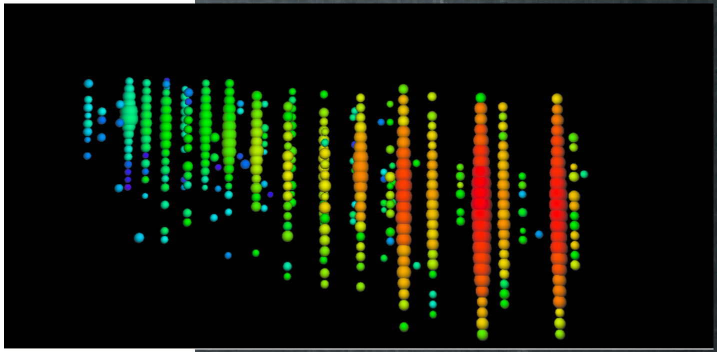
COSMIC NEUTRINOS



ICECUBE

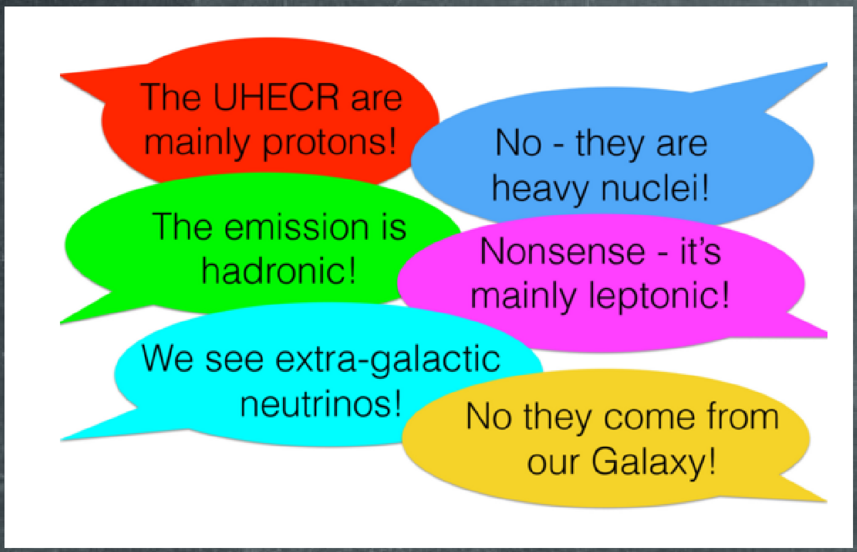


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock



CONTESTED ASTROPHYSICS

Dublin, 12-14 April, 2016



When Experts Disagree
WEXD

Organised by DIAS, the workshop will examine areas of current disagreement in high-energy astrophysics and will be attended by scientists as well as some philosophers of science and experimental philosophers. It forms part of an interdisciplinary project between philosophy and science on expert disagreement funded by the Irish Research Council. There will be no written proceedings and we hope to emulate something of the open discussion of the Aspen workshops with frank discussions of disputed areas, if desired under the Chatham House rule (you can say what was said, but not who said it).

SPECTRAL FORMATION: THREE DIFFERENT APPROACHES

Use a ‘tailor-made’ particle distribution function + textbook emissivities

- Very good fits

- Some ad-hoc assumptions (e.g. multiple breaks in power-law distribution)Use a ‘tailor-made’ particle distribution function + textbook emissivities

2. Create particle distribution functions from injection rates → kinetic equations (→ RTE analogy)

   - Self-consistency (energy conserved)

   - Temporal studies (flaring)

   - Injection rates? (e.g. functional form)

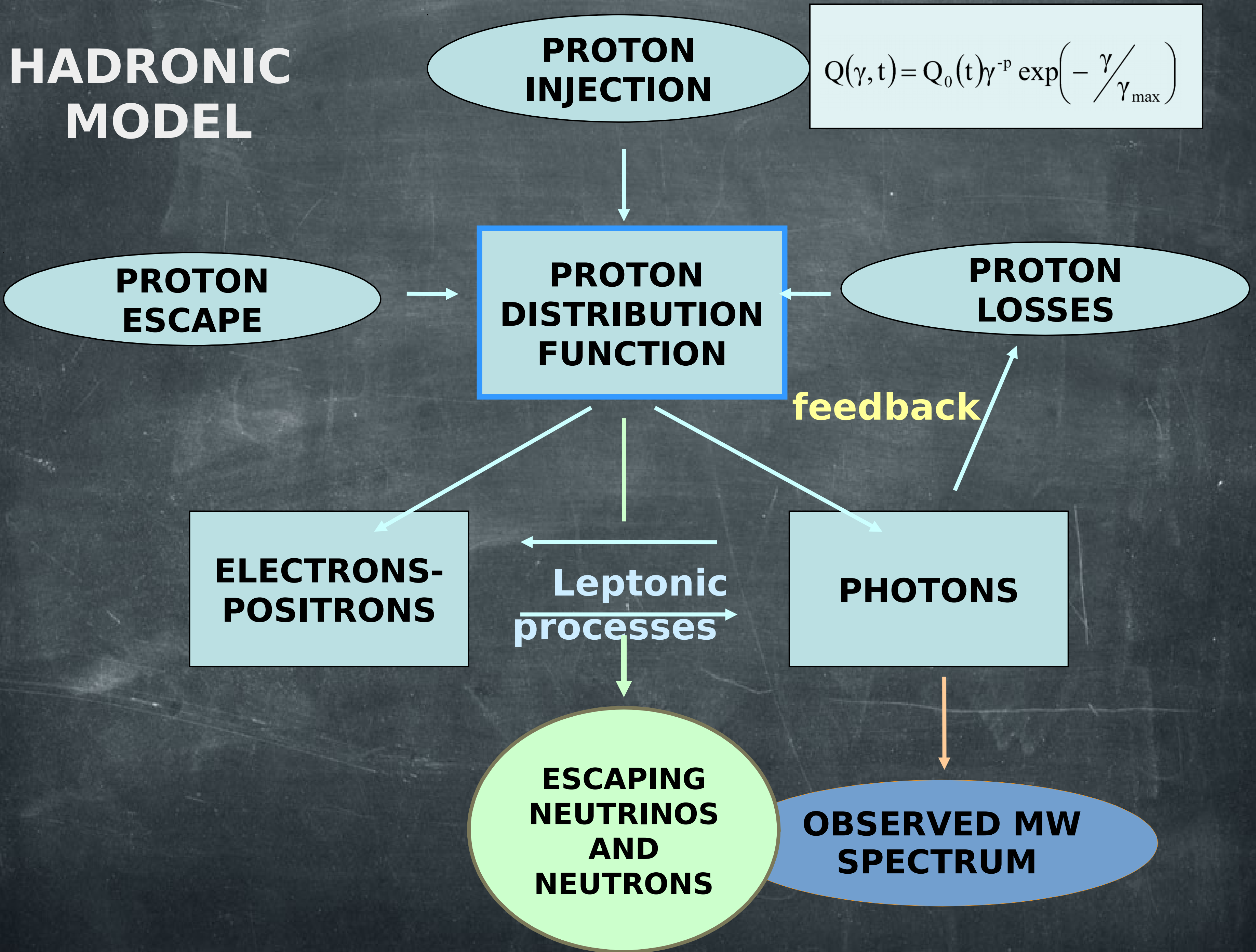
3. Use acceleration scheme → injection rates

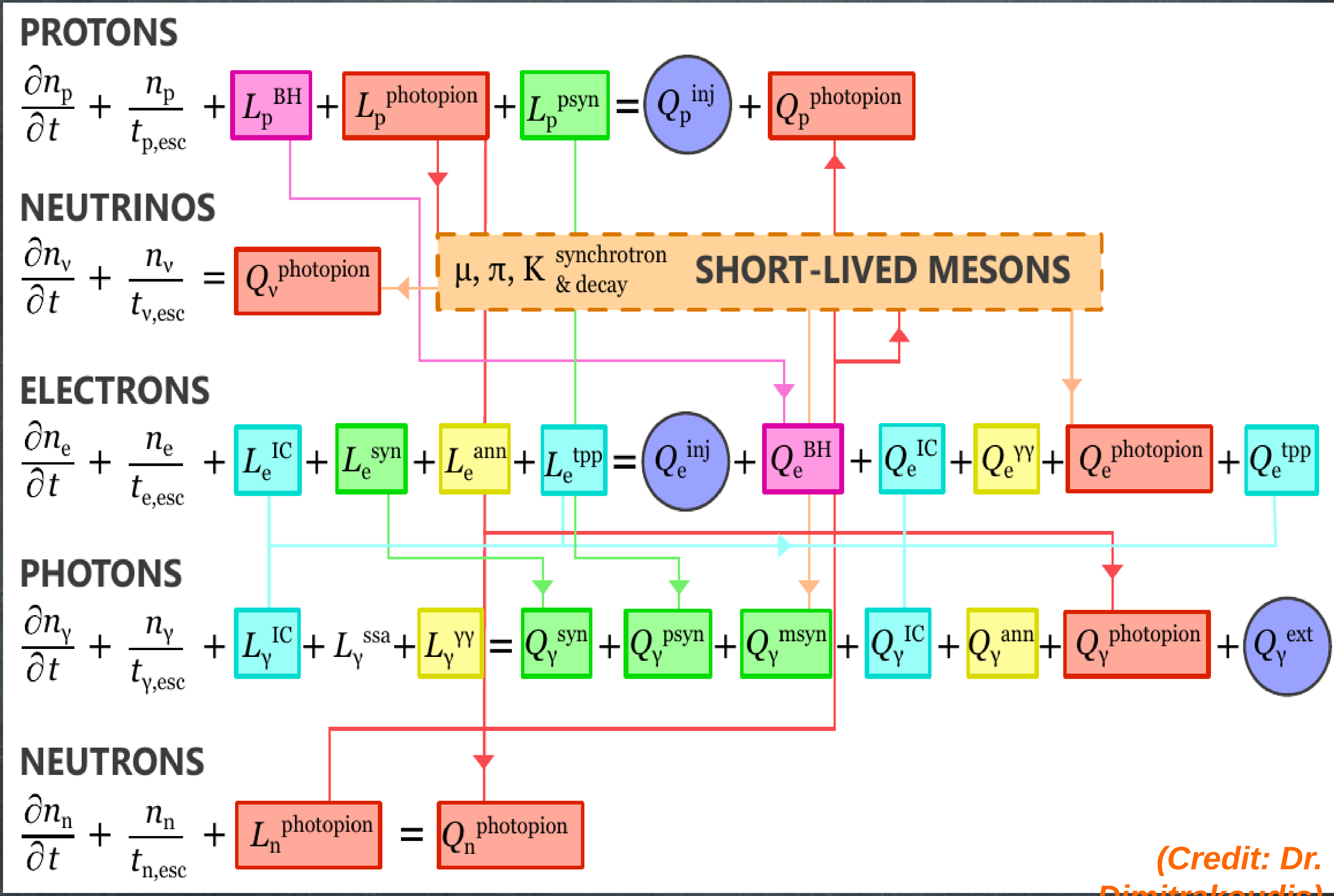
   - More consistency (functional form of injection: power-laws, cutoffs)

   - Simplified acceleration schemes

complexity

HADRONIC MODEL



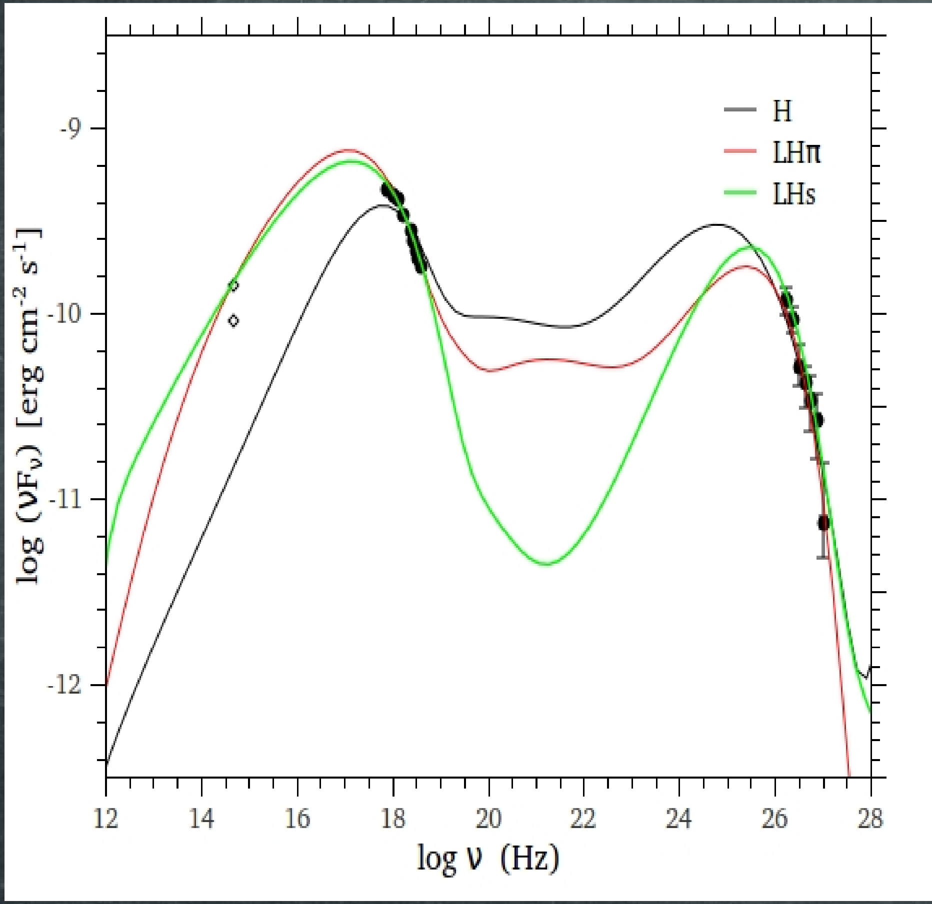


(Credit: Dr. Dimitrakoudis)

AM & Kirk 1995

Dimitrakoudis et al. 2012

SED OF Mrk 421: LEPTO-HADRONIC MODELING



	V-X-rays	γ-rays
LH-π model	e-syn	photopion
LH-s model	e-syn	p-syn

	LH-π	LH-s
Dominant energy density	Protons	B-field
Maximum proton energy	~PeV	~EeV

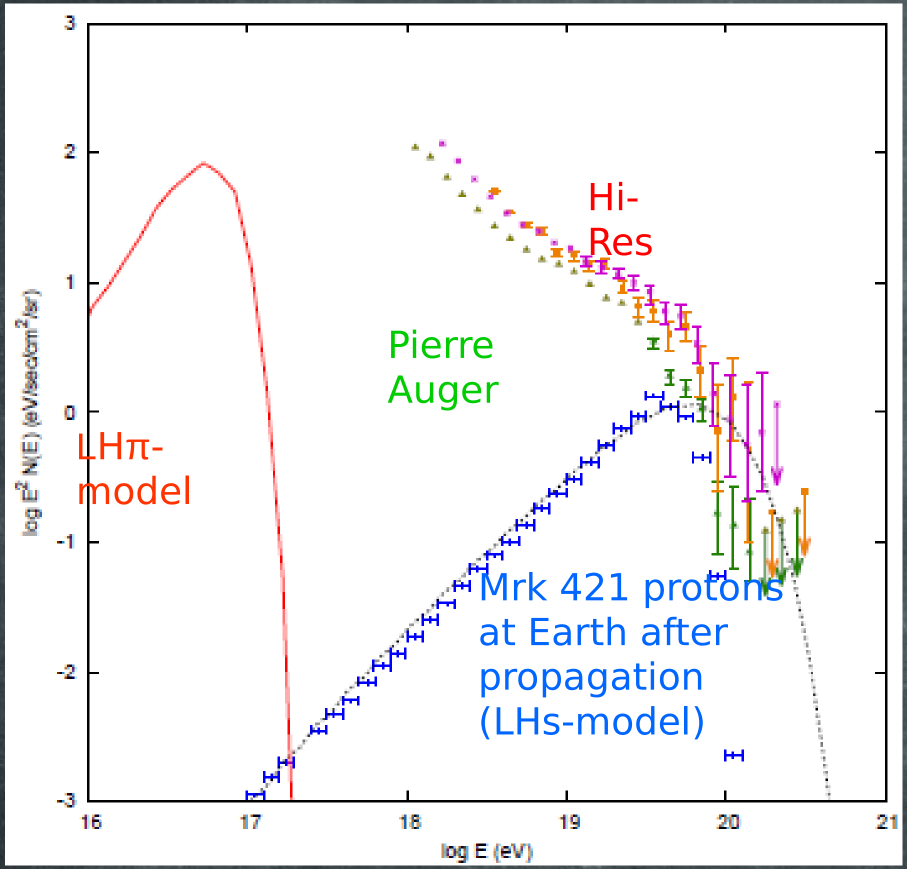
AM, M. Petropoulou, S. Dimitrakoudis 2013

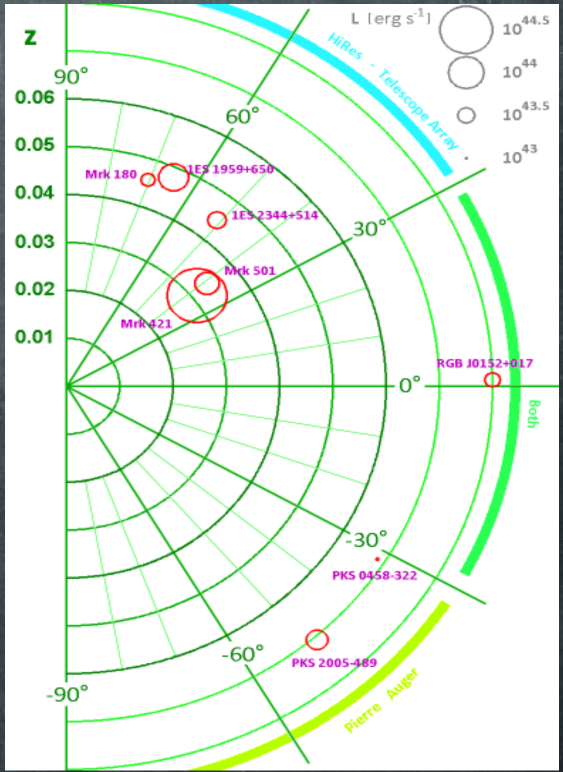
MODEL SIGNATURES: COSMIC RAYS

CR protons from escaping the source n → p (Kirk & AM 1989)

Small UHECR contribution from nearby BL Lac objects if similar to Mrk 421

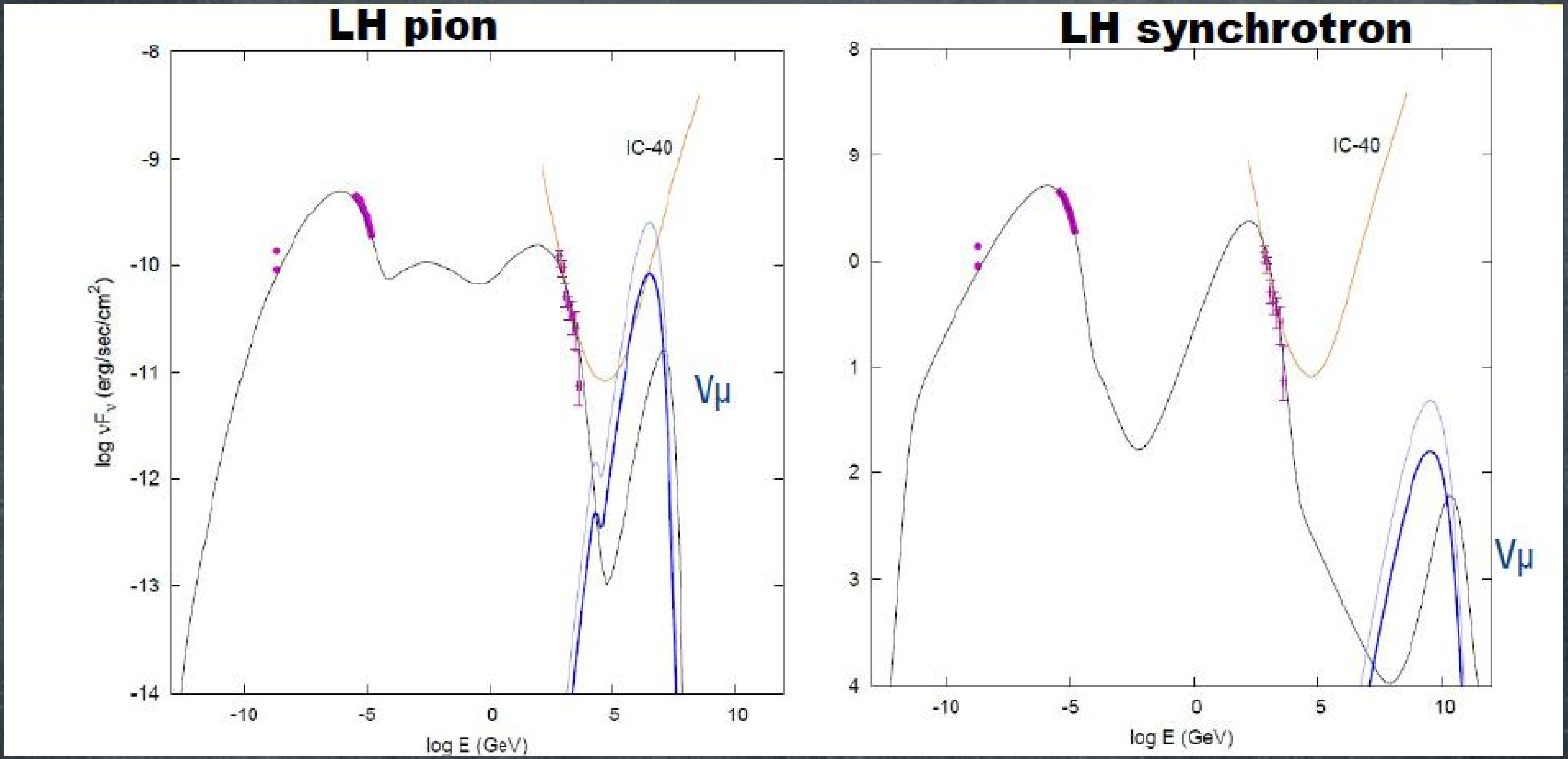
- ➢ Lower luminosities
- ➢ Larger distances





LHs model: Mrk 421 CR peak at ~30 EeV

MODEL SIGNATURES: SELF-CONSISTENT NEUTRINO EMISSION



Due to differences in fitting parameters

- LHπ model: PeV neutrinos with high flux → **IceCube**
- LHs model: EeV neutrinos with low flux

S. Dimitrakoudis et al. 2014

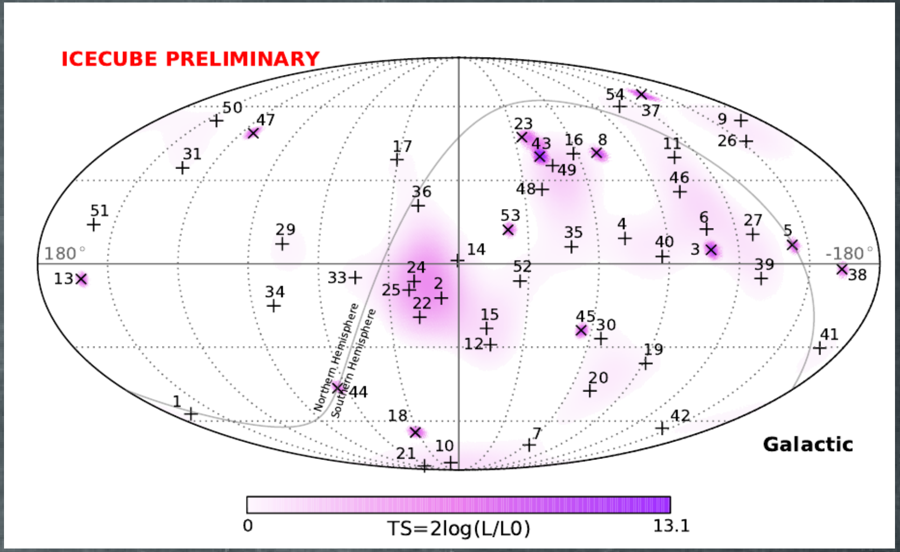
BL Lac – IceCube EVENTS ASSOCIATION?

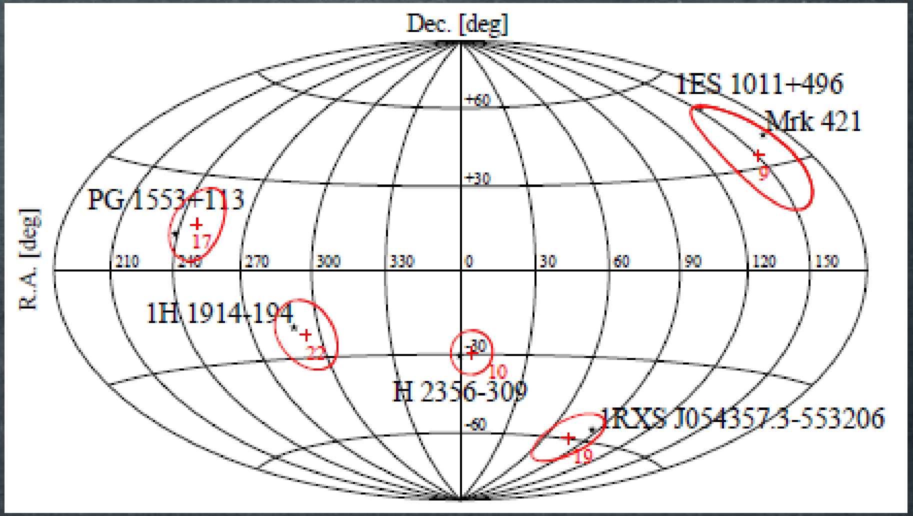
The facts

- IceCube: 54 events 0.03 – 2 PeV *(Aartsen et al 2013,2014)*
- Background or point sources?
- 8 possible associations between BL Lac – IceCube events *(Padovani & Resconi 2014)*
- 6 (out of 8) BLLacs with good quality observations

The challenges

1. Can hadronic models (LHπ) fit the SED of these blazars? *(sources not a-priori selected!)*
2. Is the associated neutrino flux compatible with IceCube detections? *(SED fit → source parameters → neutrino flux)*



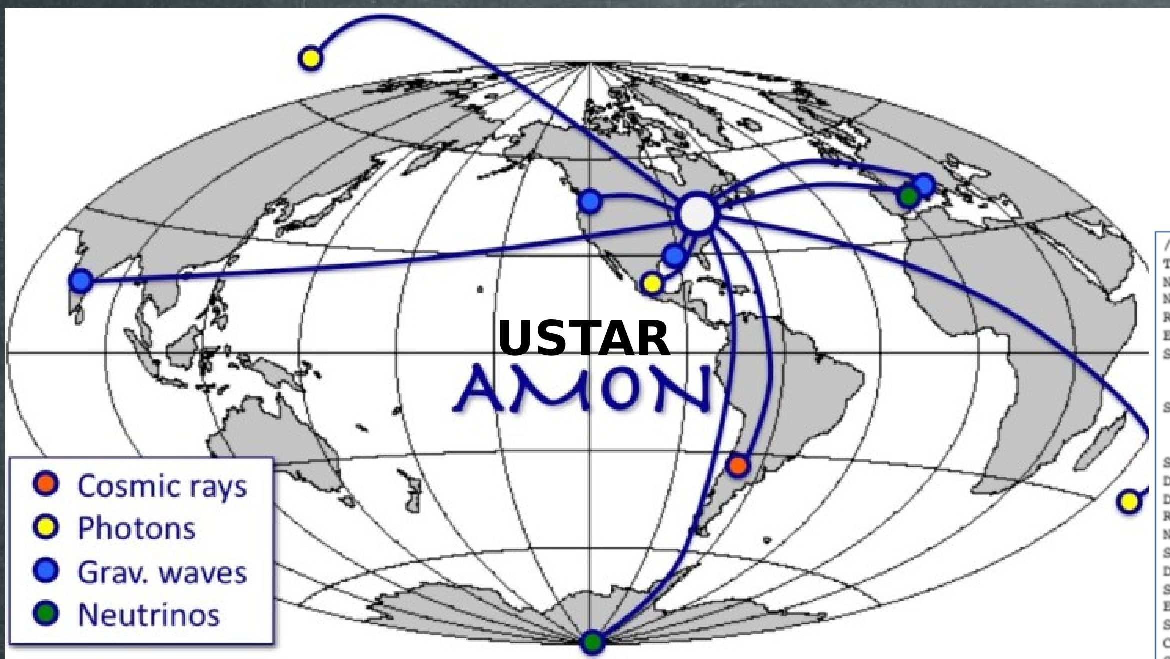


Padovani & Resconi 2014

AMON, IC170922A and TXS 0506+056

IC170922A is a track with Ev~300 TeV (ang.res < 1 deg)

AMON circulated GCN ~43 s after its detection

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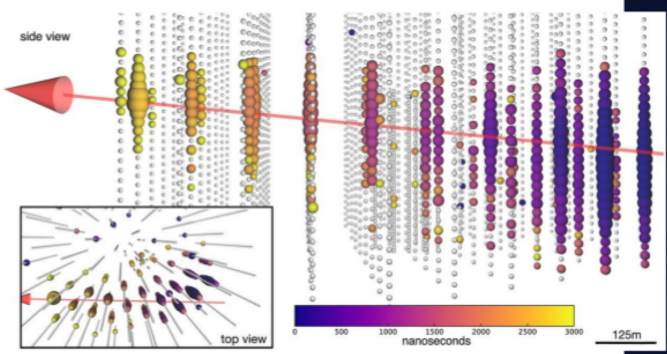
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

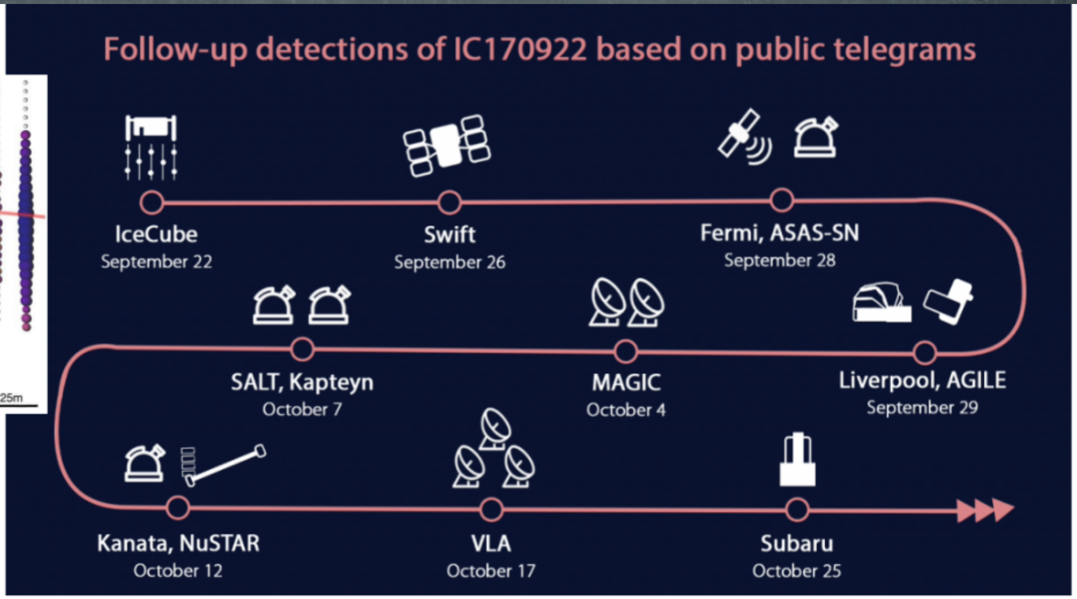
– *Swift* observations (Keivani+): GCN #21930, Atel #10942 (26/9/17)
– NuSTAR observations (Fox+): Atel#10861 (12/10/17)
– *Swift* detected the blazar TXS 0506+56
– *Fermi* reported that TXS 0506+056 was in a flaring state: Atel #10781

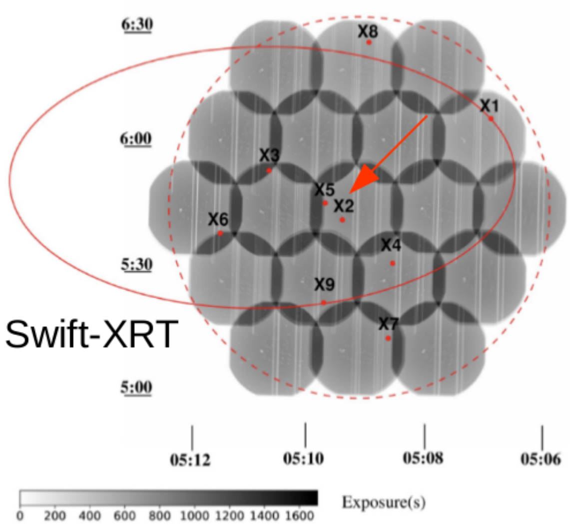
THE MULTI-MESSENGER FLARE OF BLAZAR TXS 0506+056 IN 2017

IC-170922A: a 290 TeV neutrino

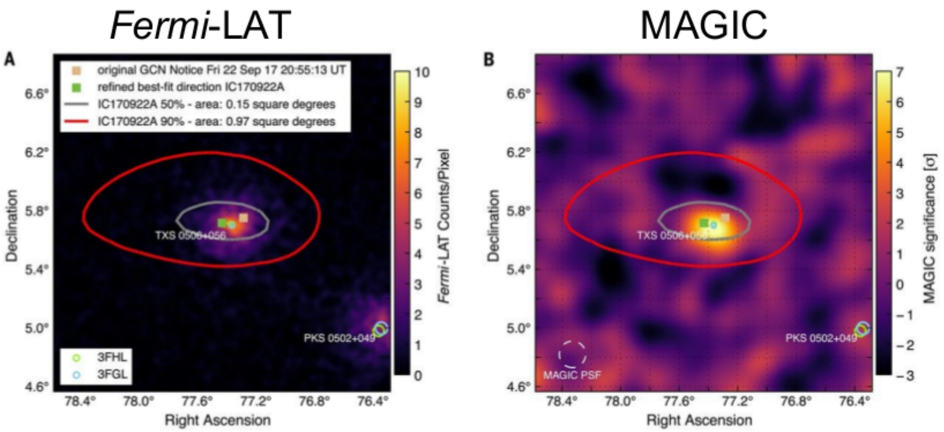


IceCube Colloboration et al. 2018a





Keivani, Murase, MP, Fox et al. 2018



IceCube Colloboration et al. 2018a

PHYS ORG Nanotechnology Physics Earth Astronomy & Space Technology Chemistry Biology Other Sciences

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More than century-old riddle resolved—a blazar is a source of high-energy neutrinos

July 12, 2018, University of Wisconsin-Madison

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In this artistic rendering, based on a real image of the IceCube Lab at the South Pole, a distant source ... below the ice by IceCube sensors, called DOMs. Credit: Icecube/NSF

An international team of scientists has found the first evidence of a source ... ghostly subatomic particles that can travel unhindered for billions of light ... environments in the universe to Earth

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The New York Times

It Came From a Black Hole, and Landed in Antarctica

For the first time, astronomers followed cosmic neutrinos into the fire-spitting heart of a supermassive blazar.

By Dennis Overbye

July 12, 2018

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Why a 4-Billion-Year-Old Particle That Hit Antarctica Is Such a Big Deal

By Rafi Letzter, Staff Writer | July 12, 2018 11:25am ET

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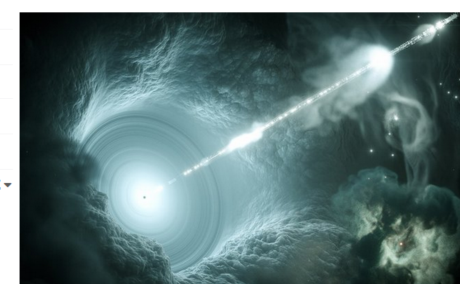


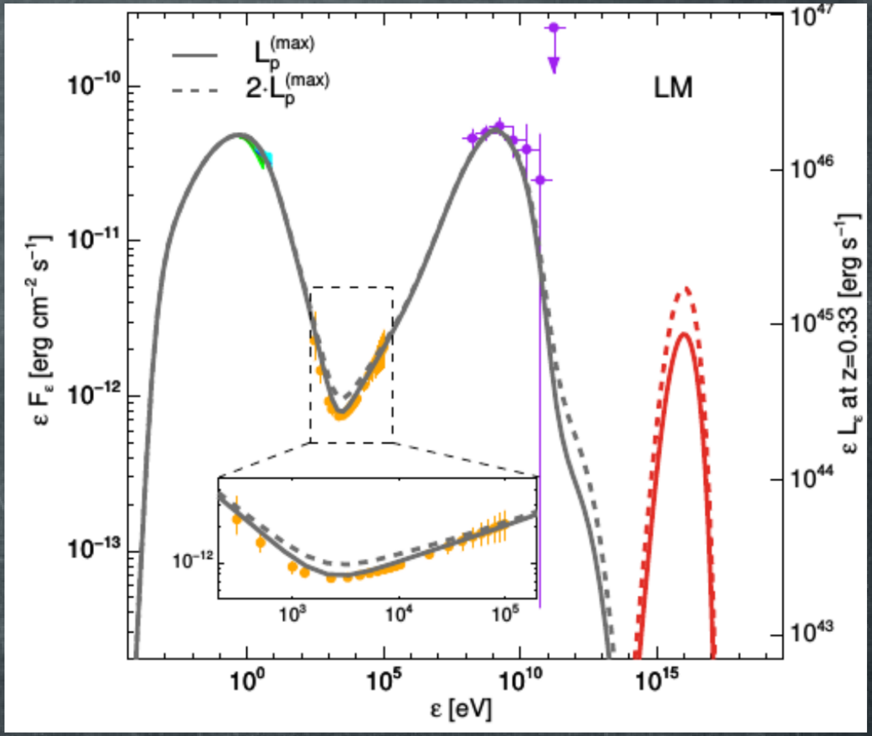
MODELING OF THE TXS 0506+056 FLARE

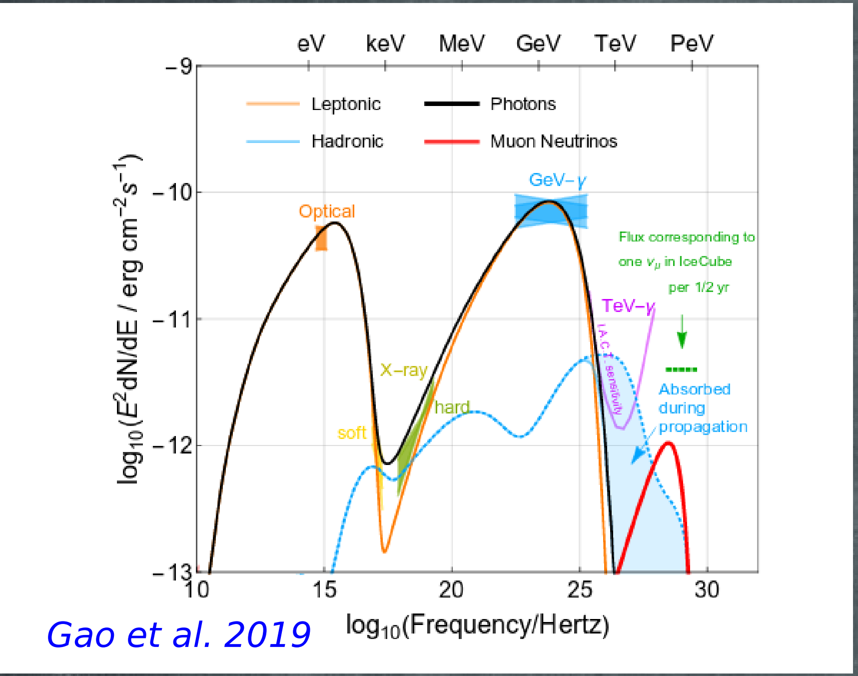
Keivani et al 2018

Analysis of Swift/UVOT, X-SHOOTER, Swift/XRT, NuSTAR, Fermi-LAT data.

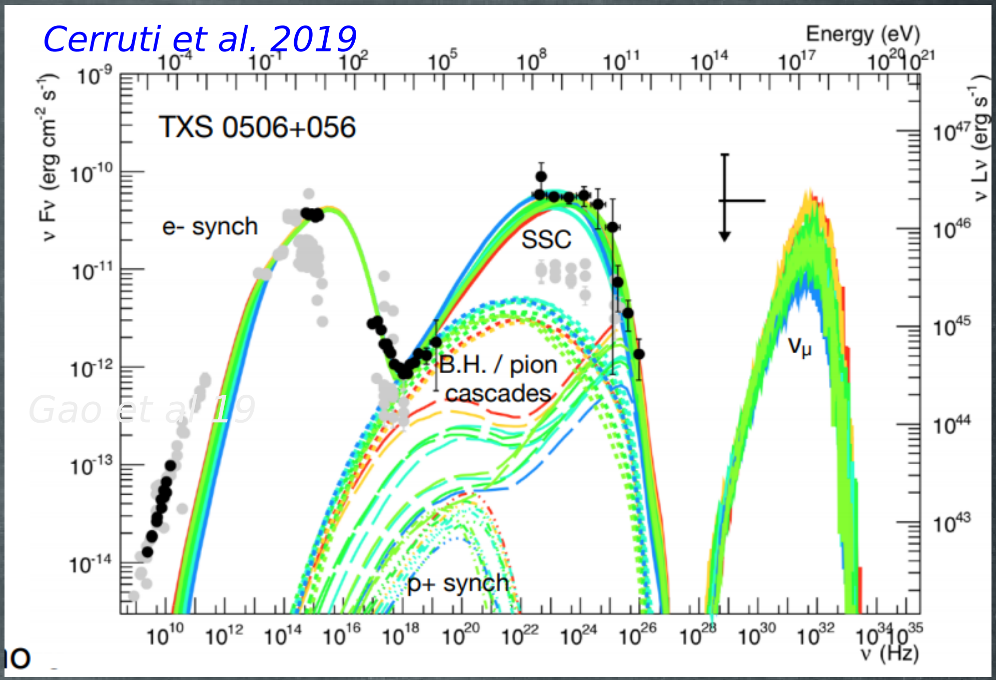
Dominant leptonic component:
– External Compton explains γ-rays
– SSC X-rays (NuSTAR)

Subdominant hadronic component:
→ upper limit on ν and baryon loading (hadronic cascade should not exceed X-ray data)

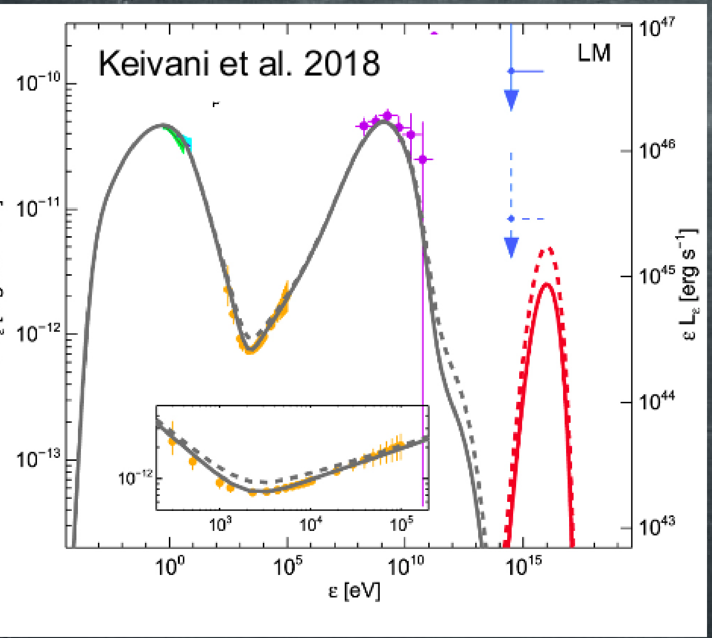




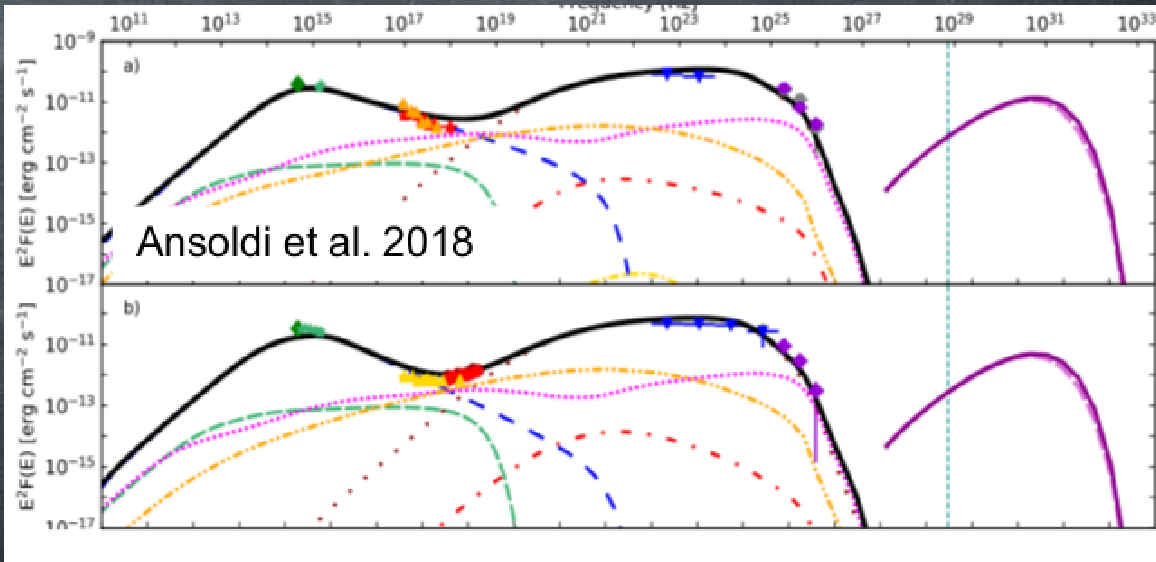
Gao et al. 2019
Leptonic
Hadronic
Photons
Muon Neutrinos
Optical
GeV−γ
TeV−γ
X−ray
soft
hard
Flux corresponding to one ν_μ in IceCube per 1/2 yr
Absorbed during propagation
eV keV MeV GeV TeV PeV
$\log_{10}(E^2dN/dE$ / erg cm^{-2}s^{-1})
$\log_{10}$(Frequency/Hertz)



Cerruti et al. 2019
TXS 0506+056
Energy (eV)
e- synch
SSC
B.H. / pion cascades
p+ synch
ν_μ
ν Fν (erg cm^{-2} s^{-1})
ν Lν (erg s^{-1})
ν (Hz)

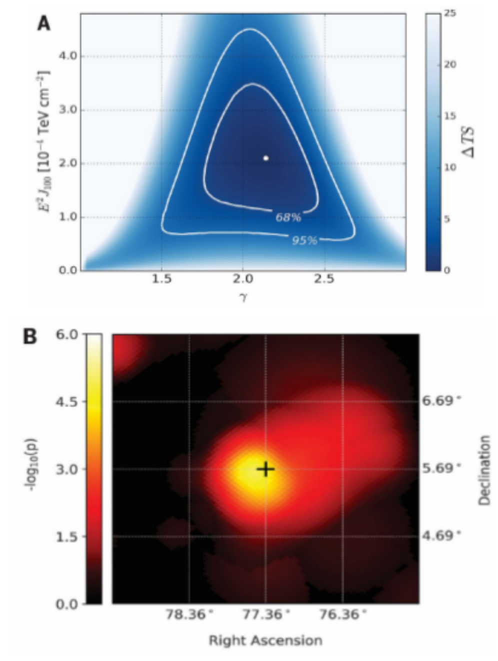


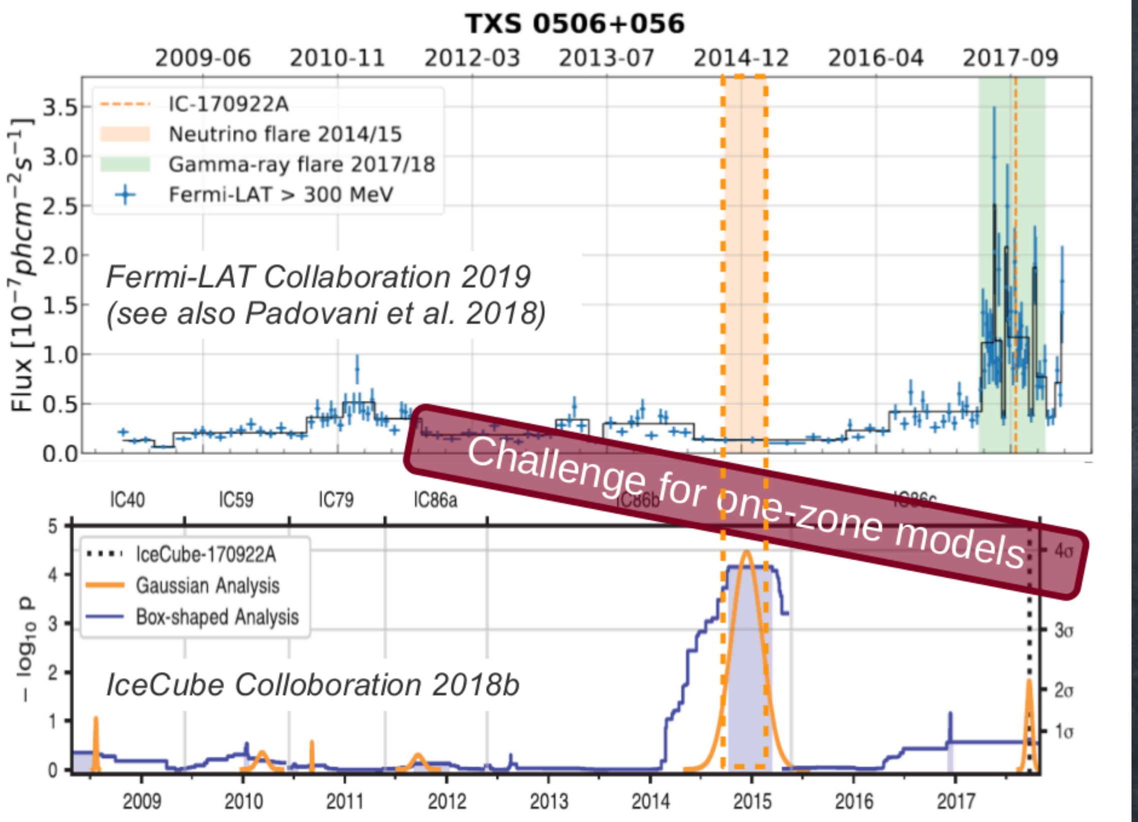
Keivani et al. 2018
LM
ε [eV]
ε L_ε [erg s^{-1}]



Ansoldi et al. 2018
a)
b)
$E^2F(E)$ [erg cm^{-2} s^{-1}]

MORE NEUTRINOS FROM TXS 0506+056





13+/-5 neutrinos over the atmospheric background over 6 months (2014-15, 3.5σ)
L_neutrino ~ 4*L_γ !   (Theory L_neutrino ~(3/8)*L_γ)

CONCLUSIONS

- 25 years after the Blazar gamma-ray discovery hadronic models continue being successful in producing very good fits to their MW data – just like leptonic.
- They are more complicated (more physical processes + non-trivial radiative transfer) and more ‘expensive’ (energy budget) than the leptonic ones but predict UHE cosmic ray and neutrino production
- In 2017: Blazar TXS 0506+056 is the first source to be associated (at 3σ) with a neutrino event → Multi-messenger!
- Searches unearthed more neutrinos from the same direction.
- However:
  1. Hadonic component subdominant. Gamma rays should be leptonic.
  2. Required proton energy ~PeV → TXS cannot be a source of UHECR (~100 EeV)

Φτάσαμε στην πηγή,
αλλά νερό δεν ήπιαμε

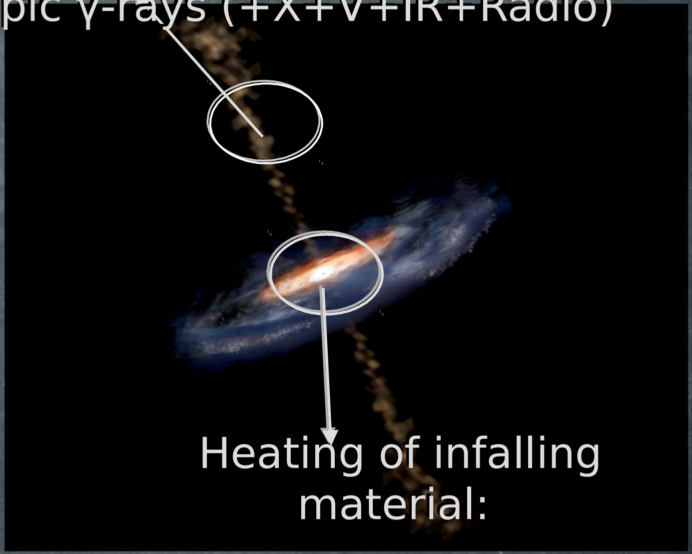
HIGH ENERGY EMISSION FROM AGN

- **Radio Quiet AGN:**
  X-rays: Mostly thermal emission from accretion disk-corona

- **Radio Loud AGN:**
  γ-rays: Non-thermal emission from ultrarelativistic electrons and/or protons
  → particle acceleration

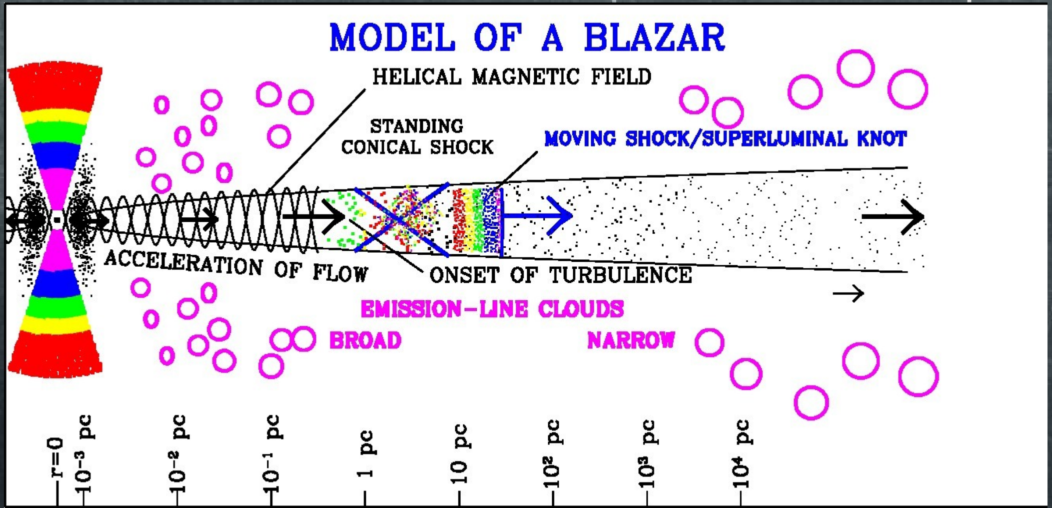
Acceleration of outgoing material:

anisotropic γ-rays (+X+V+IR+Radio)



Heating of infalling material:

quasi-isotropic X-rays

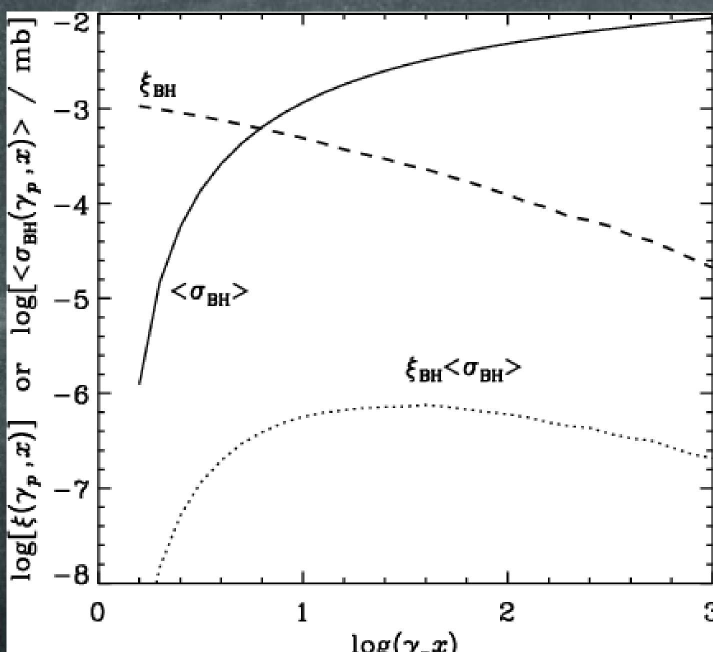


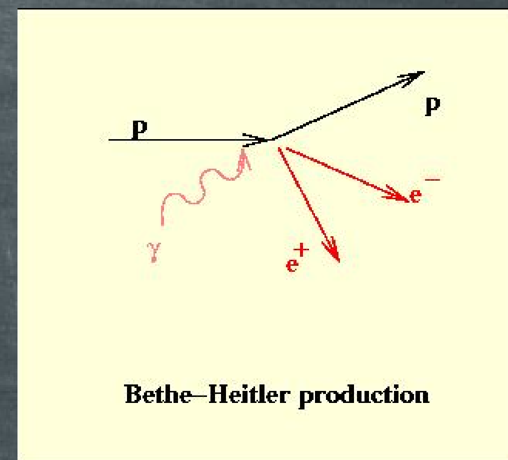
A. Marscher

INTERACTIONS OF PROTONS WITH PHOTON FIELDS – PHOTOPAIR

$$N + \gamma_{\mathrm{target}} \longrightarrow N + e^{+} + e^{-}$$

$$s^{1/2}_{\mathrm{threshold}} = m_p + 2m_e$$

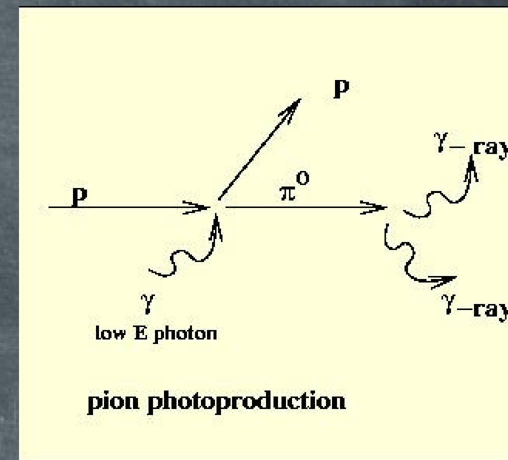


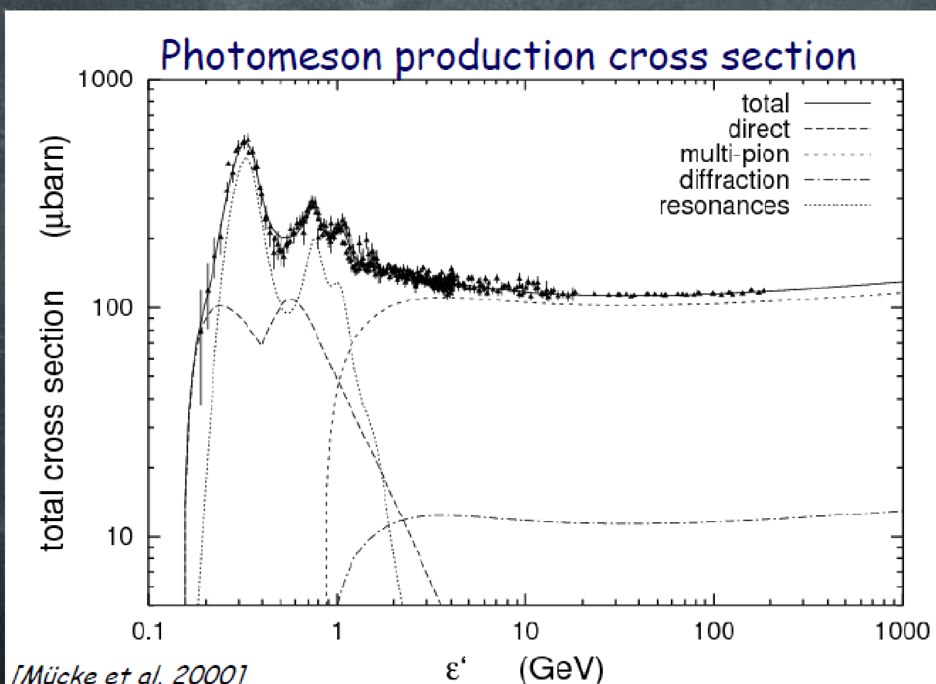


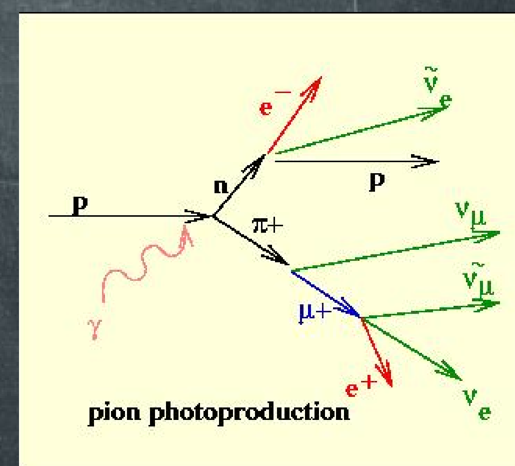
INTERACTIONS OF PROTONS WITH PHOTON FIELDS – PHOTOPION

$$N + \gamma_{target} \longrightarrow N + \pi s + \ldots$$

$$s^{1/2}{}_{threshold} = m_p + m_{\pi 0}$$







PRESENT-DAY STATUS

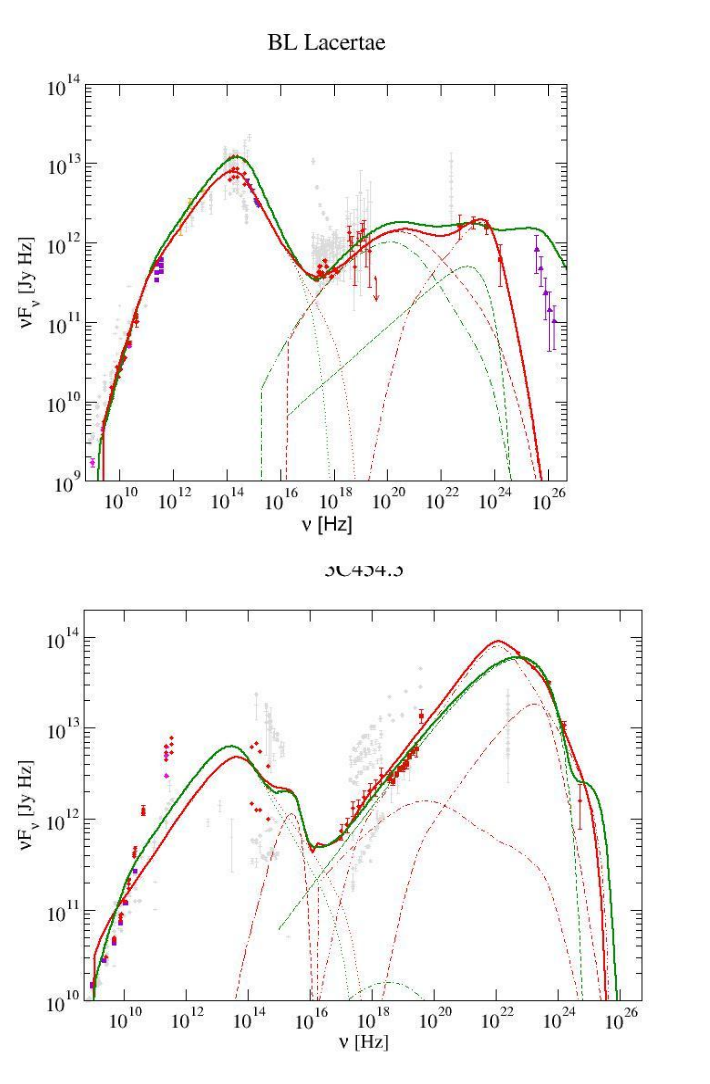
– Both classes produce equally good fits

– Leptonic models mostly in particle - B-field Equipartition

– Hadronic models require

1. High power (L~ 10^48 erg/s)
   – hadronic processes are inefficient
2. High E_max
   For TeV emission
   – Photo-hadronic ~ PeV (threshold V-phot)
   – Proton synchrotron ~ EeV
3. High B (>10 G) – gyroradii < source size
   (+ supress the SSC component)

– How to discriminate?
   – Variability?



Boettcher et al 2013

INJECTION OF SECONDARY ELECTRONS - RESULTING PHOTON SPECTRA

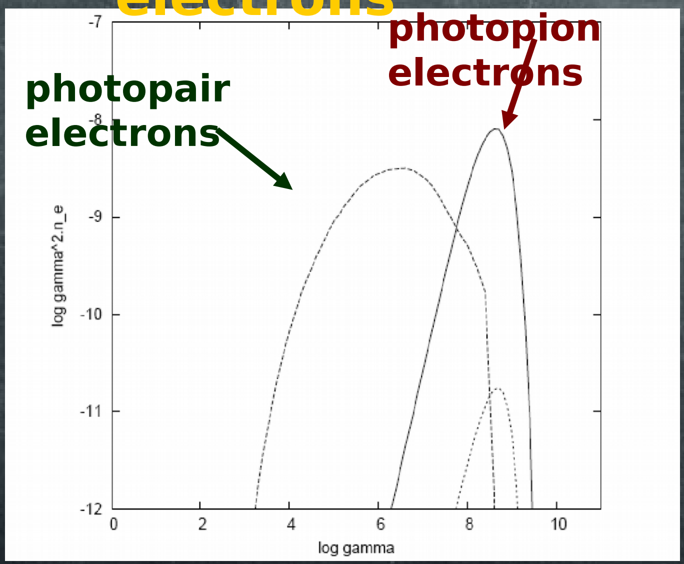
- Energy lost from protons = Energy injected in secondaries

  = Energy radiated in photons
- Photopair injection spectrum different from photopion

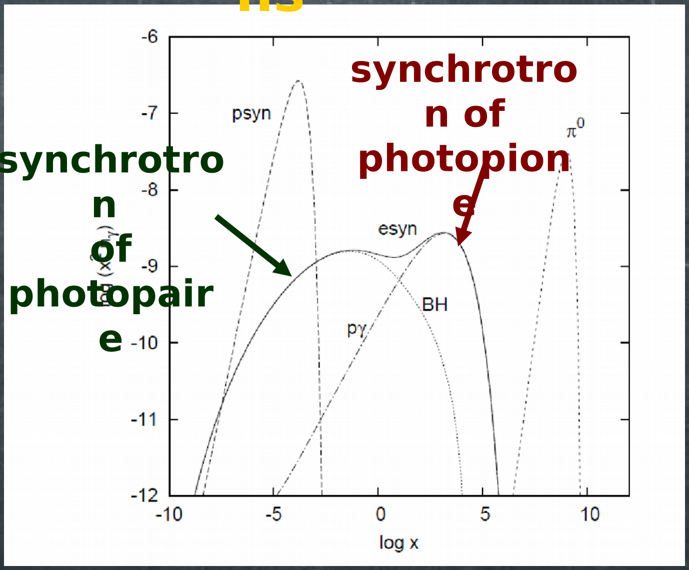
  → the two processes have inherently different radiative signatures

A SIMPLE CASE

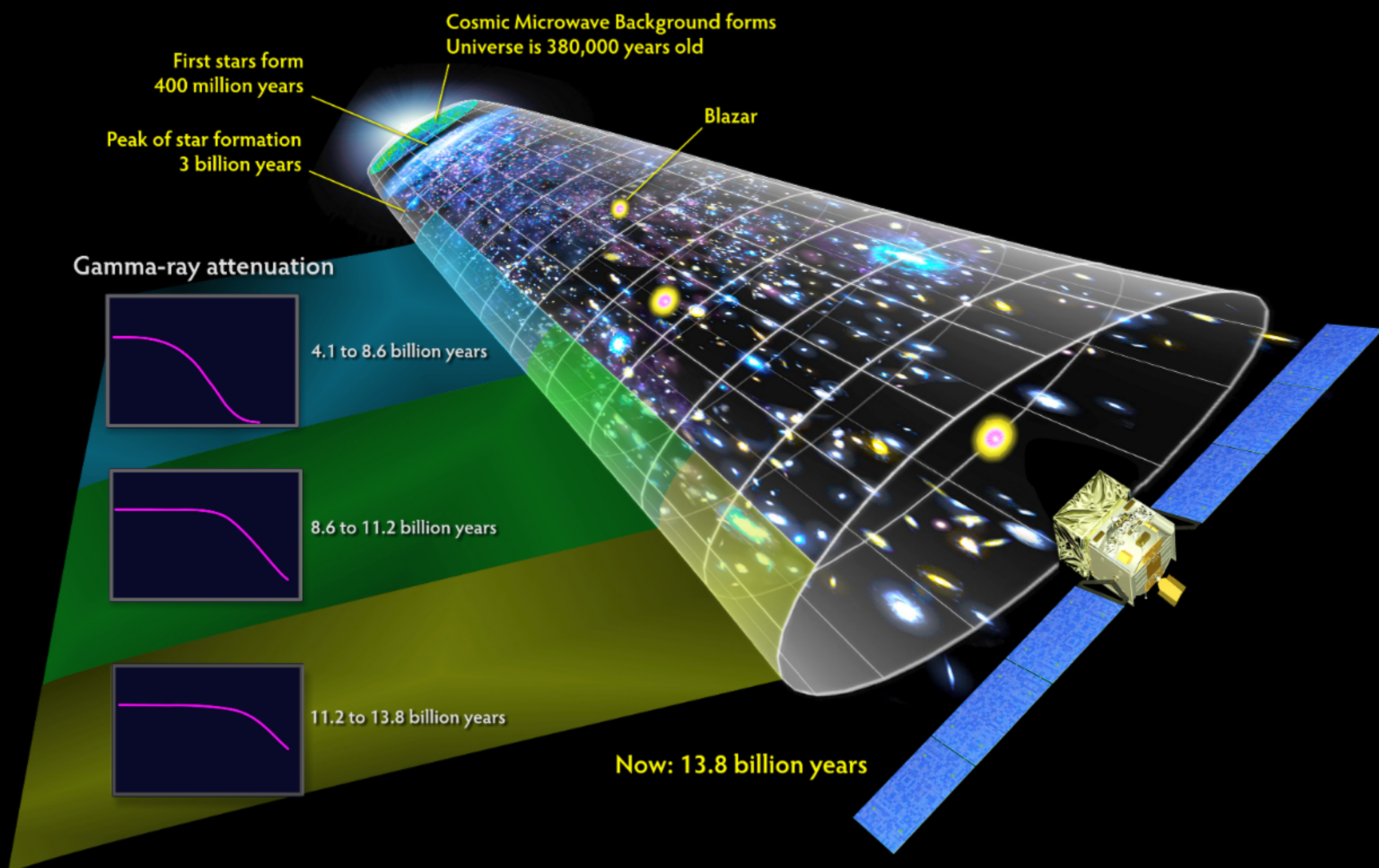
injected electrons



photons



S. Dimitrakoudis et al.



Cosmic Microwave Background forms
Universe is 380,000 years old
First stars form
400 million years
Blazar
Peak of star formation
3 billion years
Gamma-ray attenuation
4.1 to 8.6 billion years
8.6 to 11.2 billion years
11.2 to 13.8 billion years
Now: 13.8 billion years