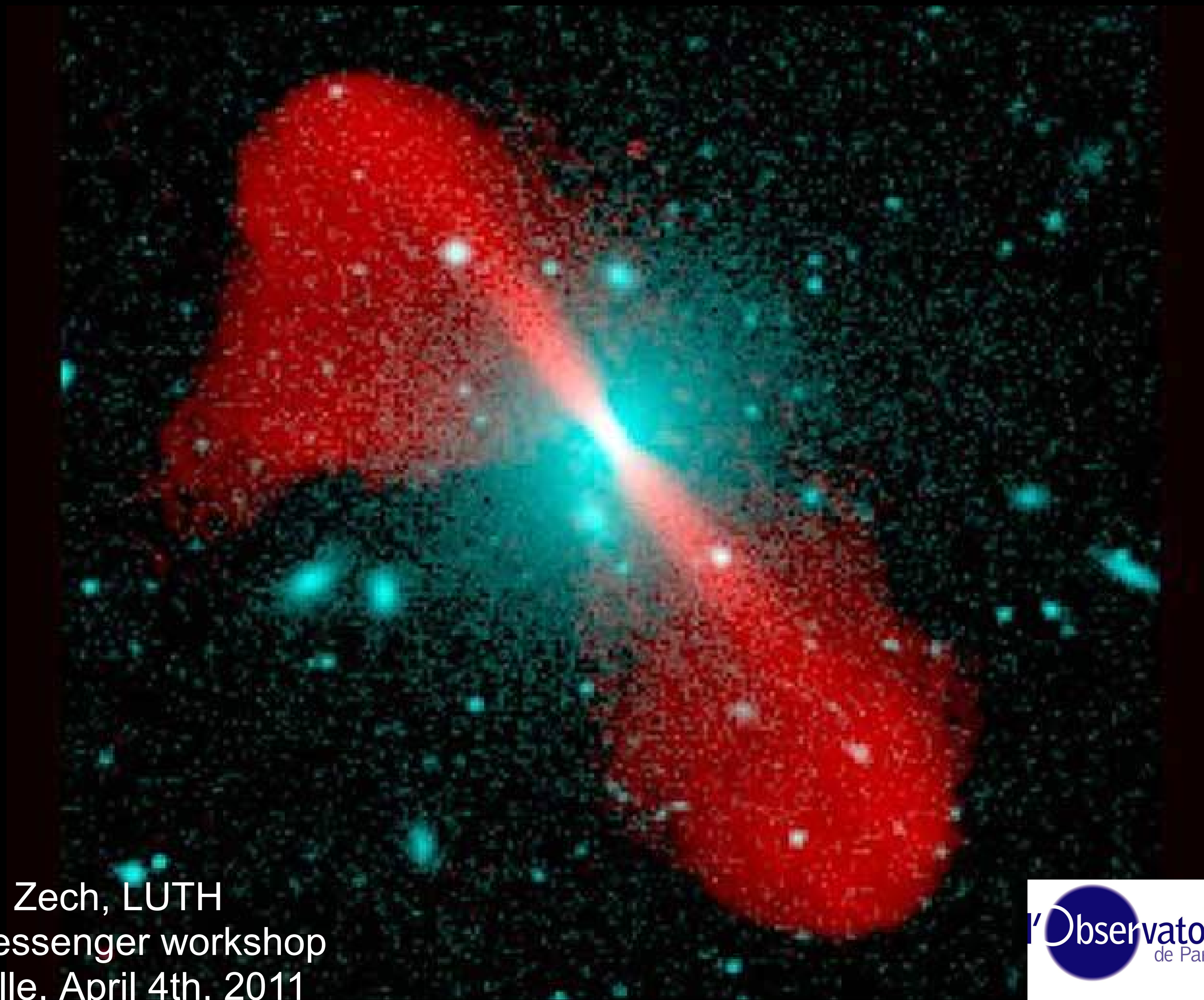
High energy emission from AGN



3C296 in radio and optical, NASA

A. Zech, LUTH
multi-messenger workshop
Marseille, April 4th, 2011

l'Observatoire de Paris | LUTH
Laboratoire de l'Univers et de ses Théories

Outline

- introduction: the AGN zoo & unification
- (V)HE γ-rays from AGN
- hadronic emission models:
  cosmic rays & neutrinos ?

the AGN zoo & unification

IBL

FSRQ

LLAGN

QSO

blazar

FR I

LBL

HBL

BL Lacs

Seyfert 1

SSRQ

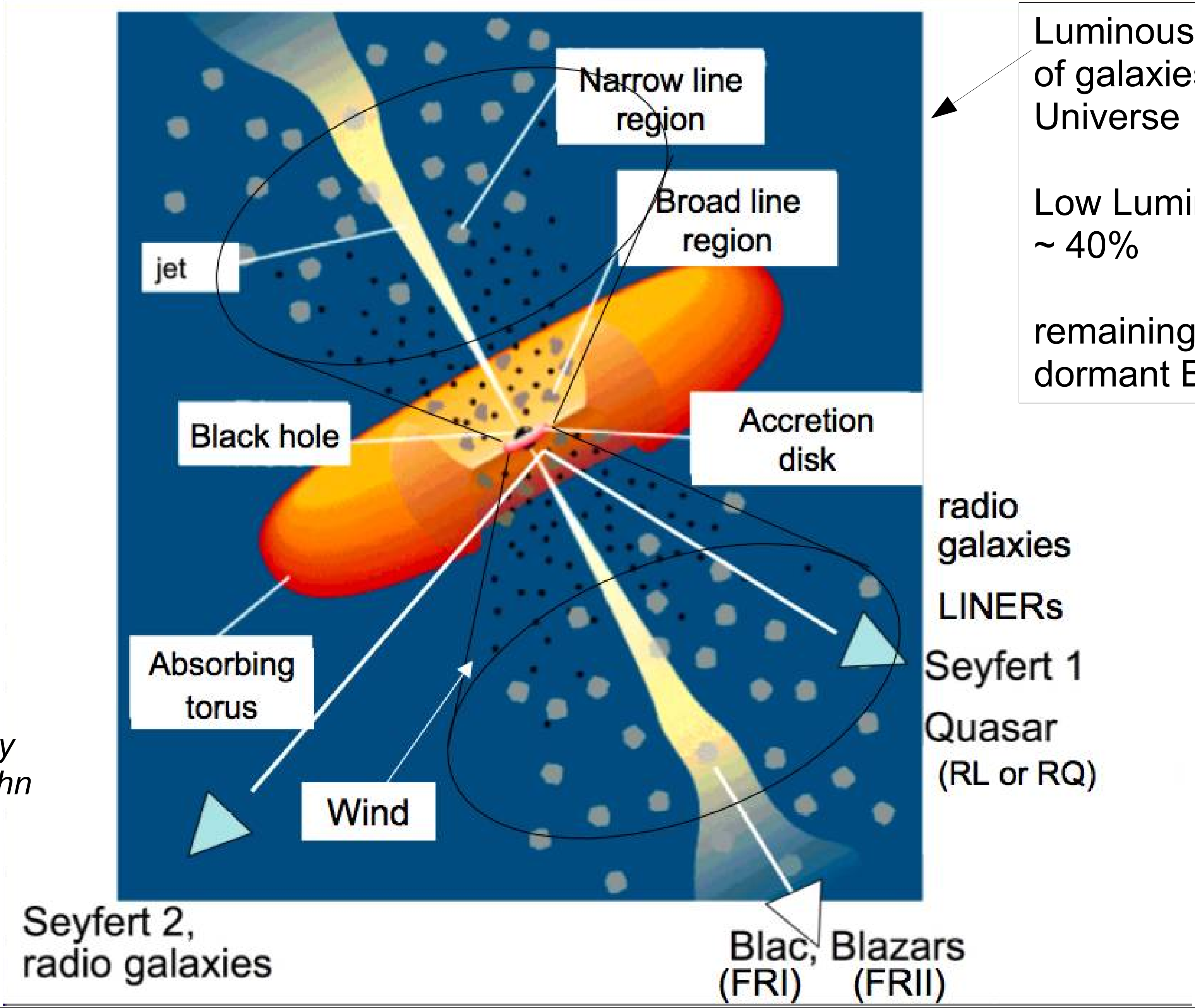
LINER

Seyfert 2

FR II

quasar

Unification by viewing angle



Luminous AGN ~ 1% of galaxies in local Universe

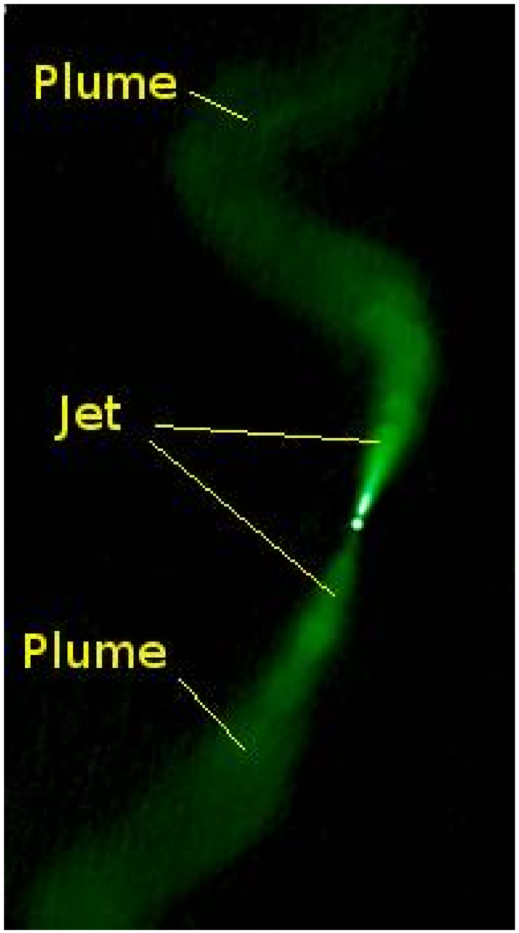
Low Luminosity AGN: ~ 40%

remaining ~60%: dormant BH

annotated by S. Collin-Zahn

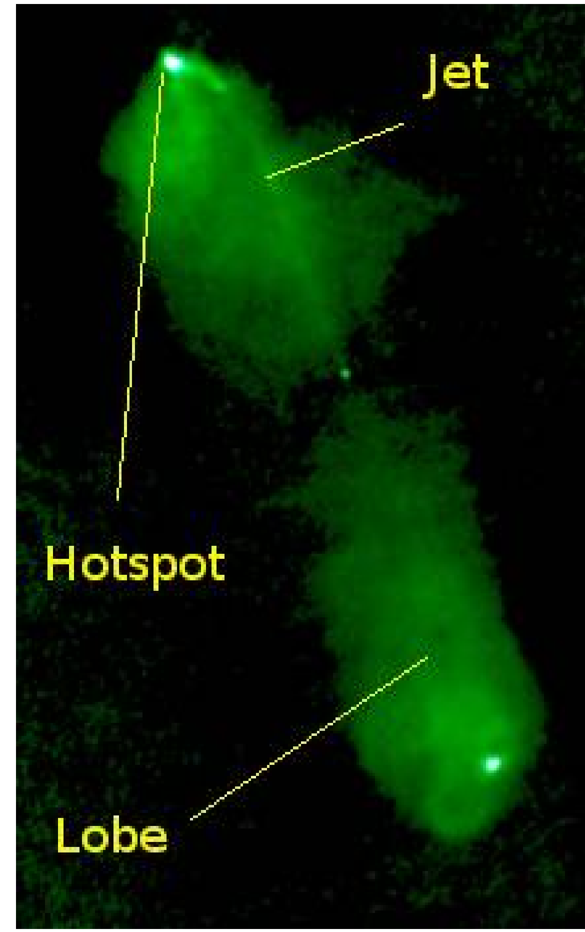
radio-galaxies & blazars

FR-I (and BL Lacs)



3C31, Hardcastle

FR-II (and FSRQ)



3C98, Hardcastle

- low luminosity (Lγ ~ 10^{44}-10^{47} erg s^{-1})
- BL Lacs: very weak emission lines

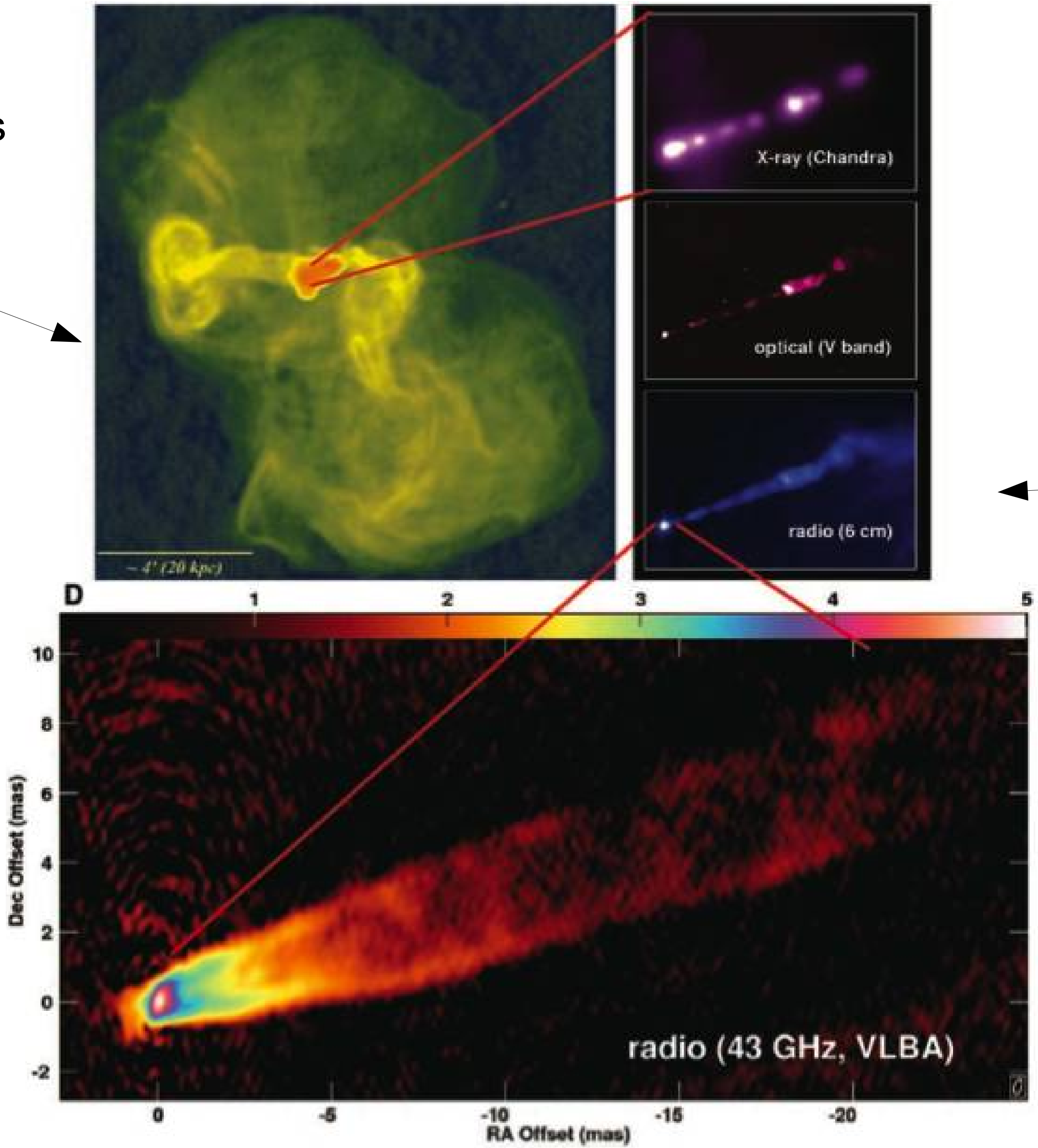
-> difficult to determine redshift !

- high luminosity (Lγ 10^{47}-10^{49} erg s^{-1})
- FSRQ: distinct emission lines from BLR

M87 - a close look at a radio galaxy

VLA radio emission shows **kpc jets and radio lobes**

synchrotron emission from the **plasma jet, its core and bright knots** seen by Chandra, HST, VLA (size ~ 2kpc)



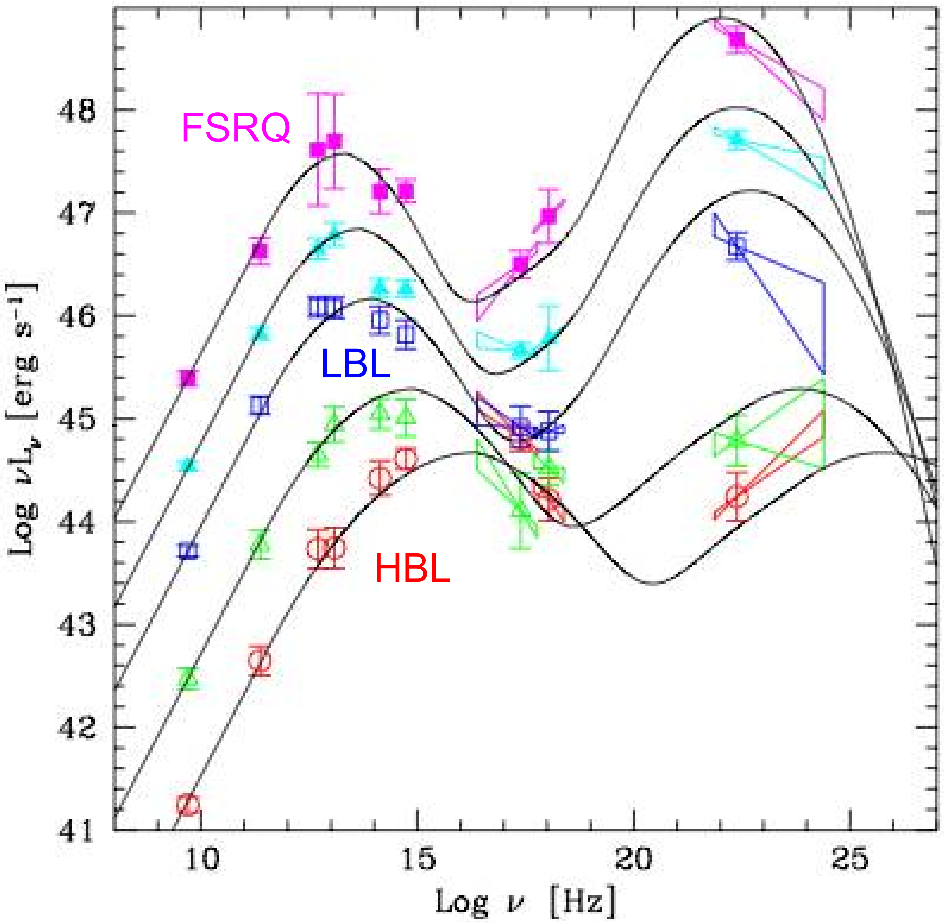
inner jet and core resolved by VLBA

The central black hole is thought to be found at most a few R_s from the radio core.

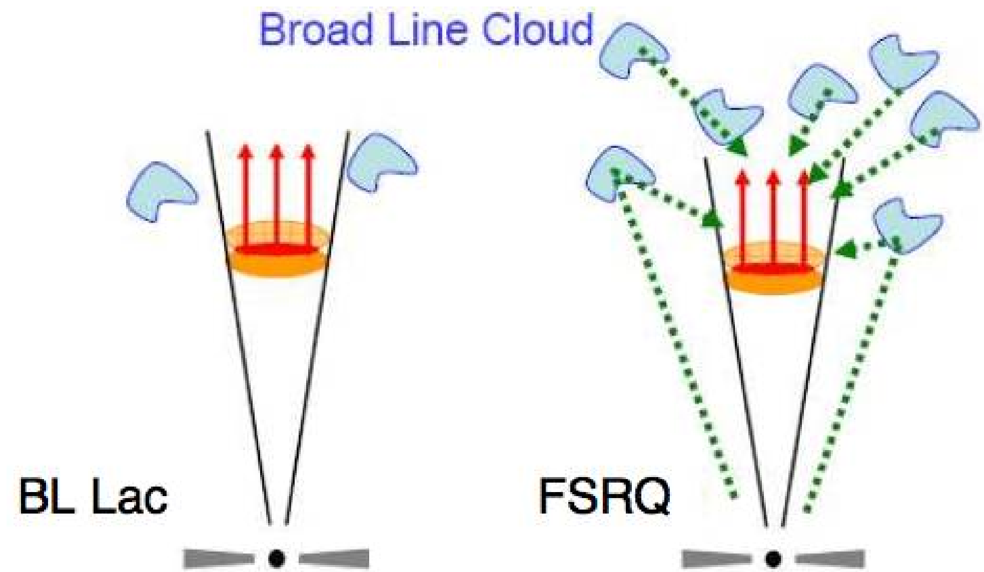
Science, 325, 444 (2009)

γ-rays from AGN

the blazar sequence & γ-ray origin



Donato et al. (2002), based on Fossati et al. (1998)



B. Lott, Cospar 02/10

- observed anti-correlation between peak frequency and luminosity
- disputed due to observational biases & outliers

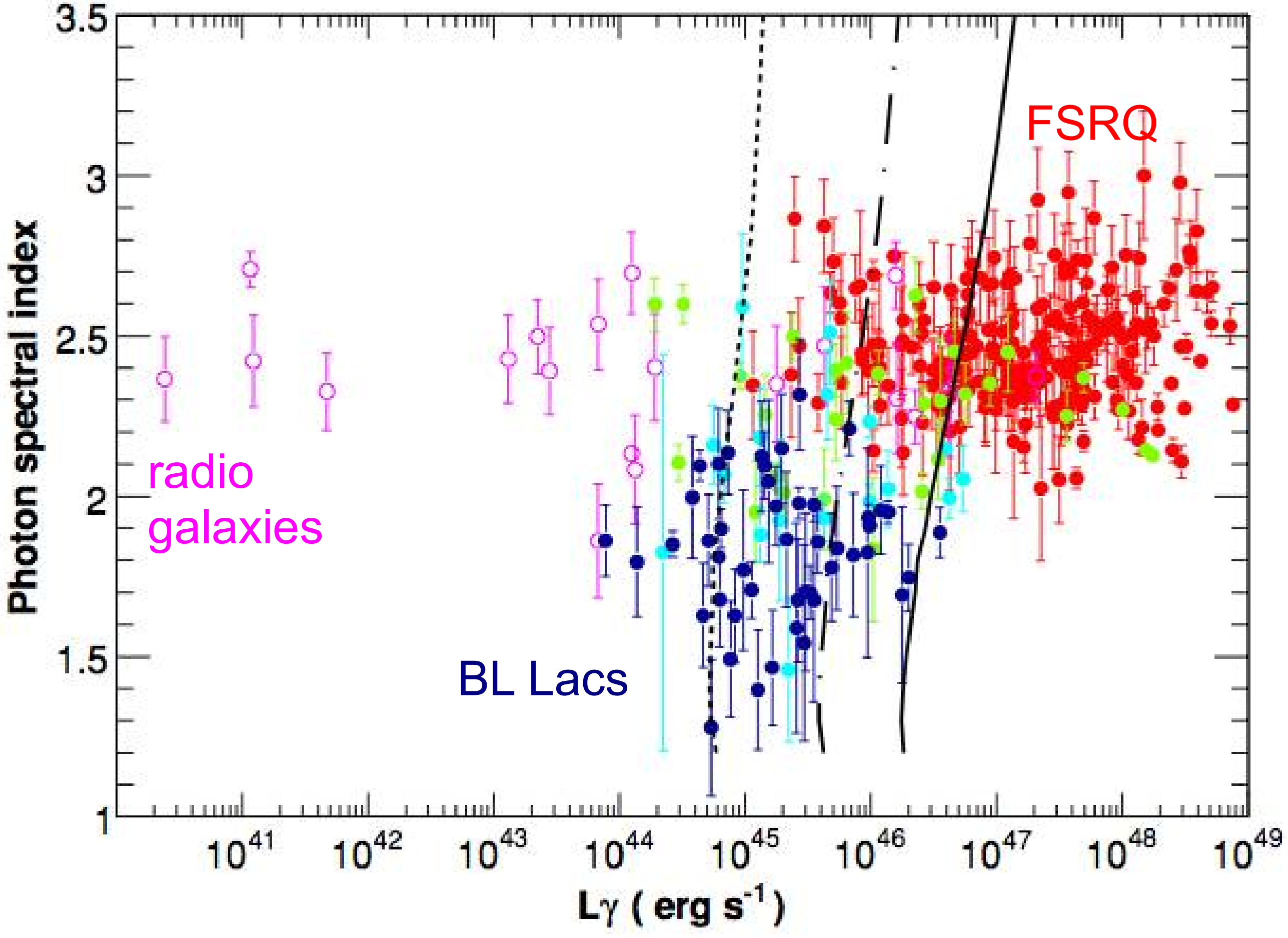
BL Lac:

- Disk and Broad Line Region weak
- γ-rays due to Synchrotron Self Compton

FSRQ:

- Disk and Broad Line Region strong
- γ-rays due to Synchrotron Self Compton & External Inverse Compton

the blazar sequence seen by Fermi



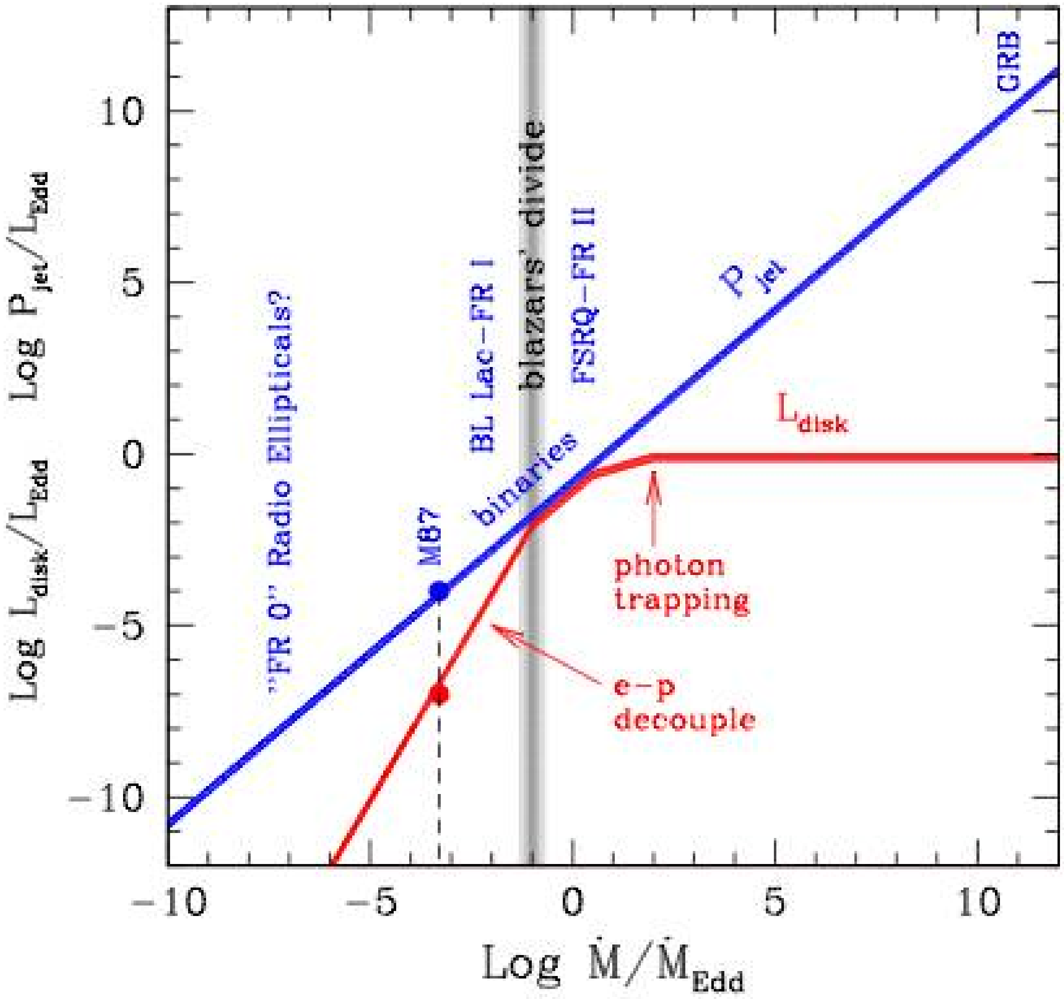
Luminosity is correlated with photon index (and blazar class):

higher luminosity <-> steeper spectrum

- consistent with blazar sequence
- caveat: observational biases

Fermi 1 yr catalog of 671 high latitude AGN
Abdo et al. (Fermi), ApJ, 715, 429 (2010)

Dependence on the accretion rate ?



Ghisellini (2010)

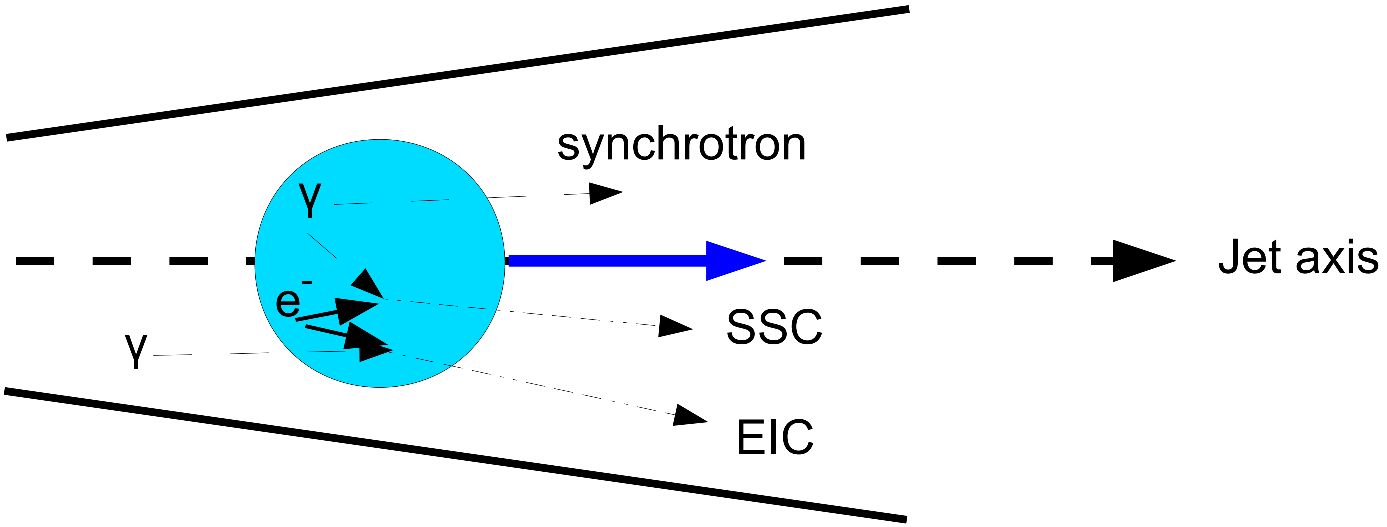
- **Jet power** P_{jet} / L_{Edd} depends directly on the **accretion rate** (dM/dt) / (dM_{Edd} /dt) (and on the black hole mass)
- Blazar's divide occurs for $L_{disk} \sim 10^{-2}$ L_{Edd}.

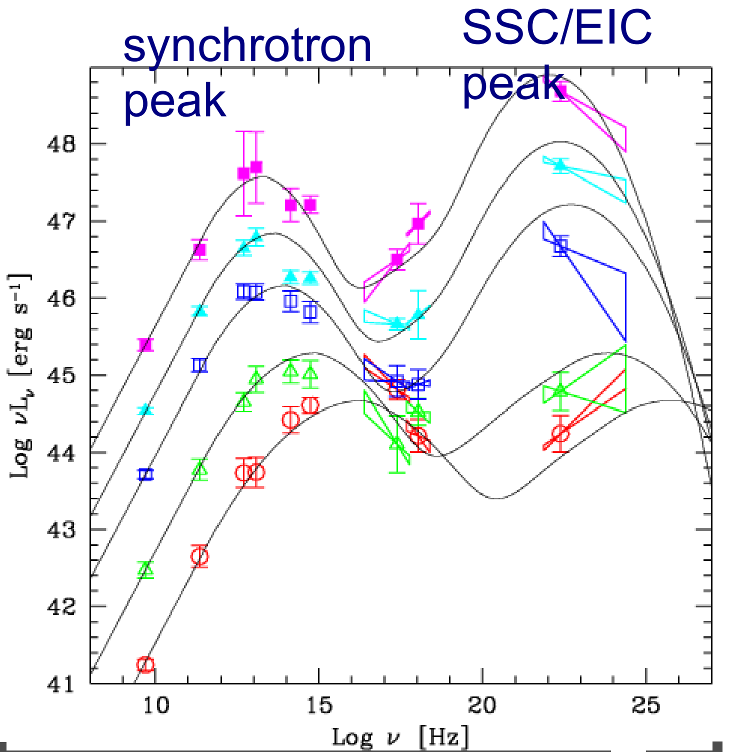
below**:** disk radiatively inefficient

above**:** disk radiation ionizing BLR

-> **evolution of FSRQs into BL Lacs due to evolution in accretion rate ?**
(*Ghisellini, Tavecchio, MNRAS 387, 1669, 2008)*

SSC / EIC - "standard models" for blazars

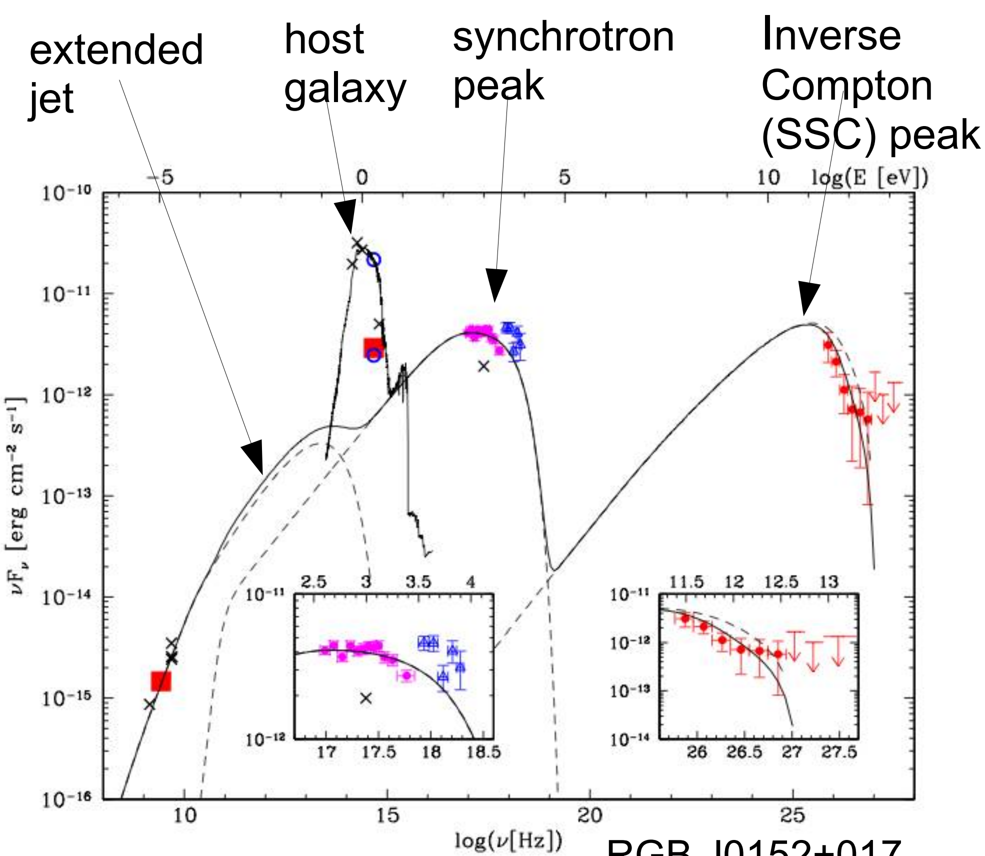




- plasma blob inside jet with turbulent magnetic field and high energy electrons
- γ-rays from **S**ynchrotron **S**elf-**C**ompton or **E**xternal **I**nverse **C**ompton diffusion (on BLR or torus photons)
- other leptonic models exist (e.g. stratified jet, decelerating jet,...), but basic emission processes are the same.

modelling of blazar spectra

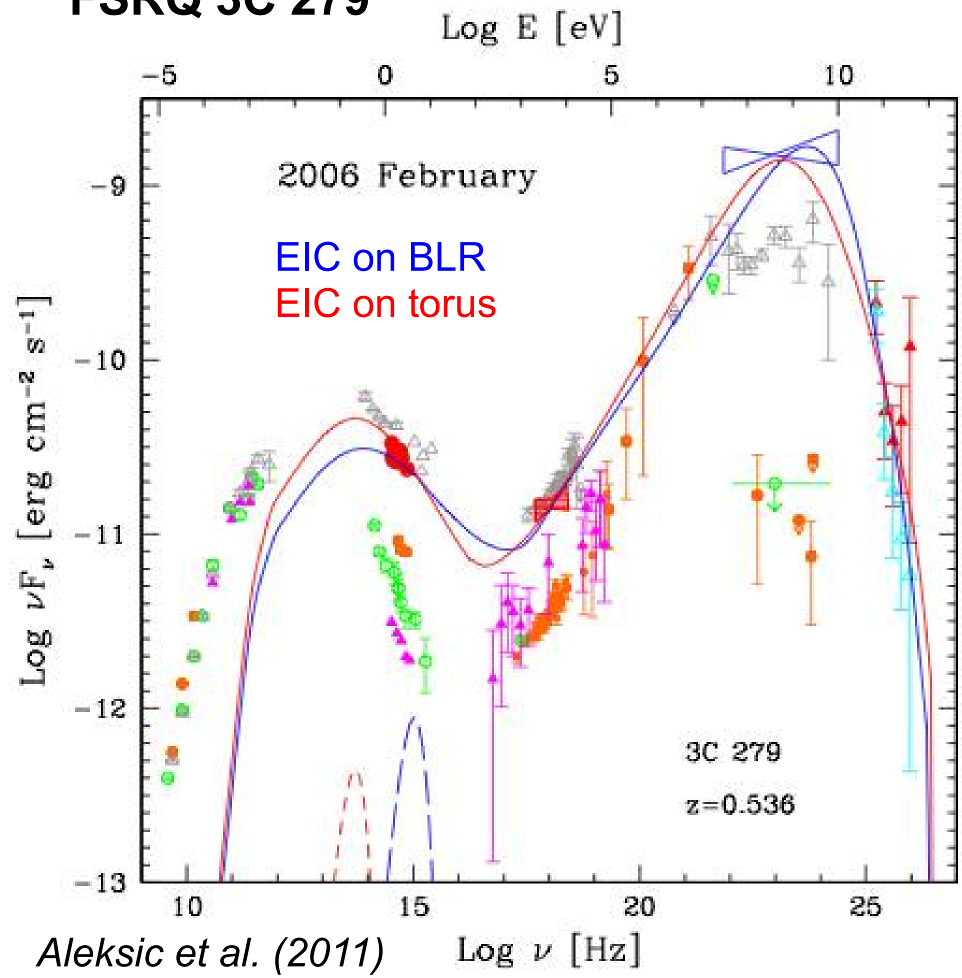
BLLac object RGB J0152+017



Aharonian et al. (2008)

parameters:
B ~ 0.10 G
δ ~ 25
R ~ 1.5 x 10^{15} cm

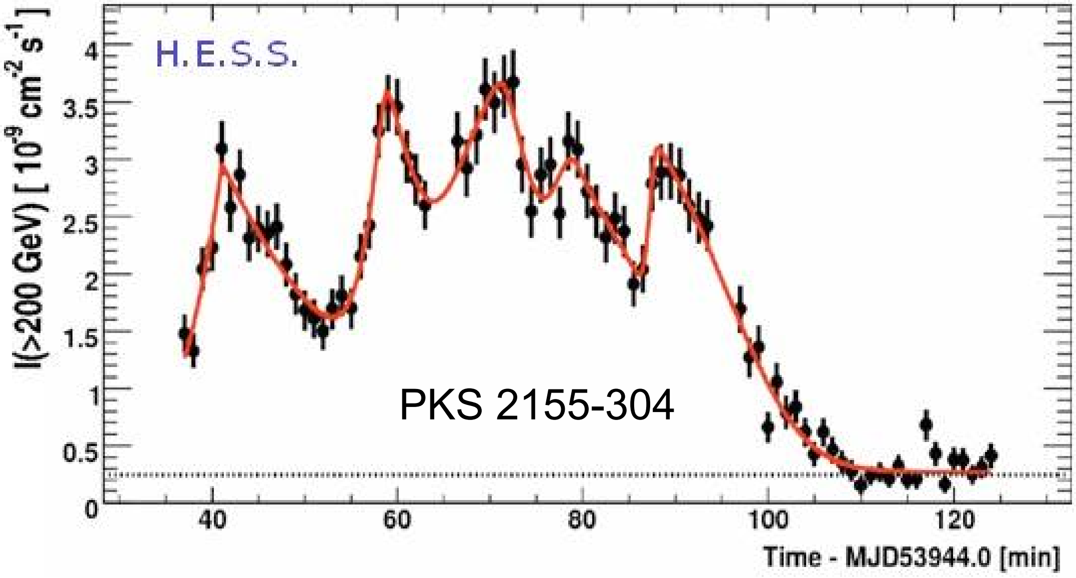
FSRQ 3C 279



Aleksic et al. (2011)

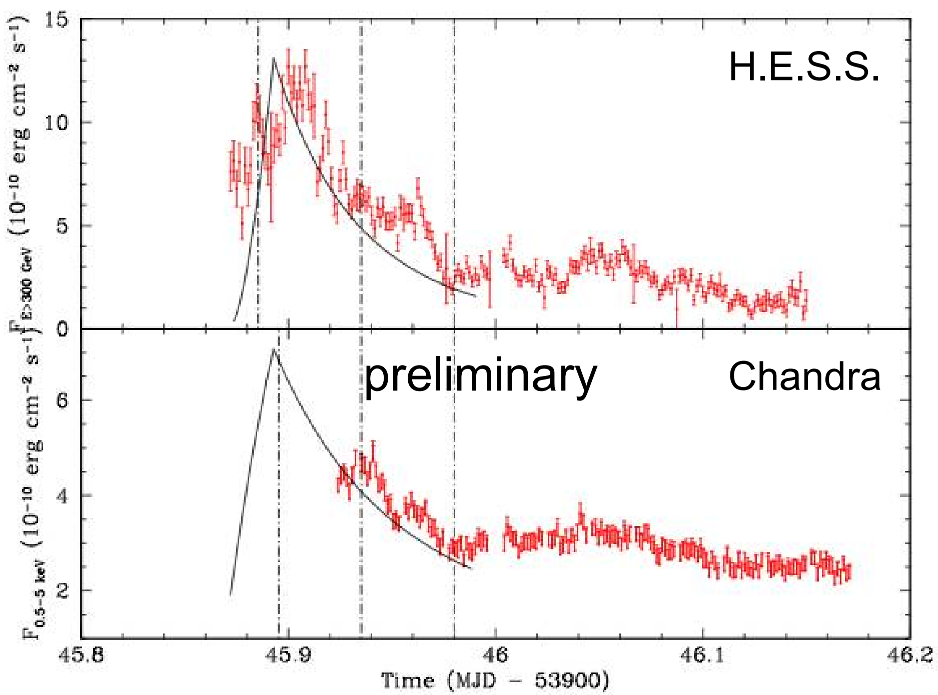
parameters for BLR case:
B ~ 0.15 G
δ ~ 20
R ~ 5 x 10^{16} cm

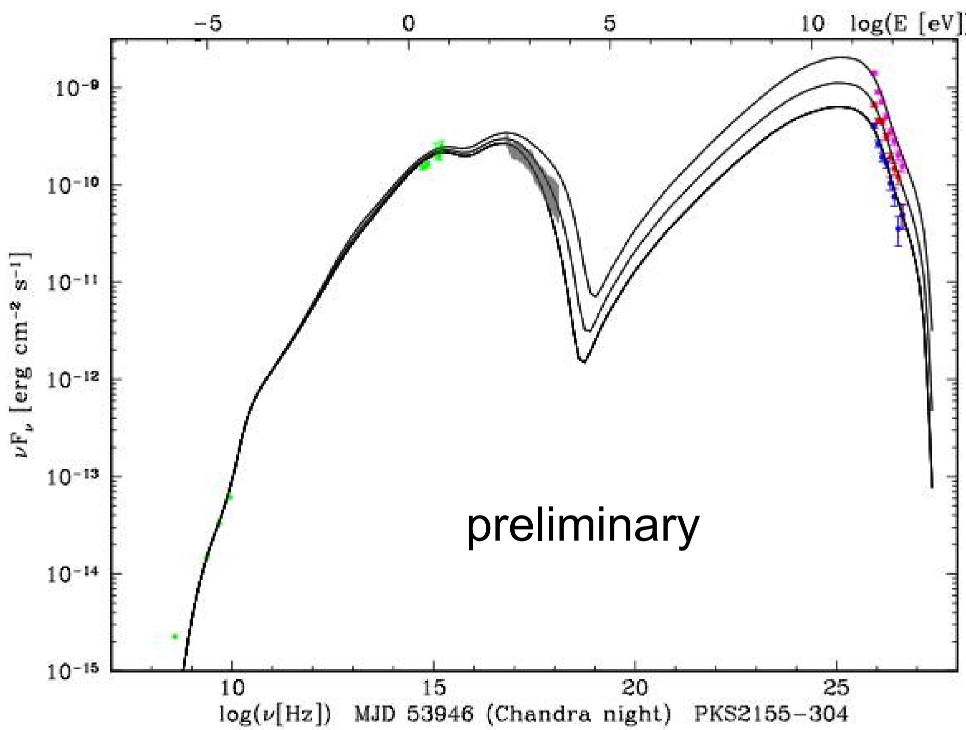
limits of the "standard model"



- **multiple emission zones** required to explain X-ray and γ-ray emission for several blazars

- **very rapid variability** (minute time scale for PKS 2155-304) requires very large Doppler factors (> 100) and remains difficult to explain





hadronic emission models: cosmic rays and neutrinos ?

hadronic emission processes

- **proton synchrotron** (need high B field ~ order 100 G)

$$p^+ + \vec{B} \rightarrow p^+ + \gamma$$

- **photo-meson** (need dense photon field)

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

$$\rightarrow n^0 + \pi^+ \longrightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

$$\rightarrow p^+ + \pi^+ + \pi^- \quad (...)$$

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

synchrotron,
synch. pair cascades

- **proton-proton** (need high proton density)

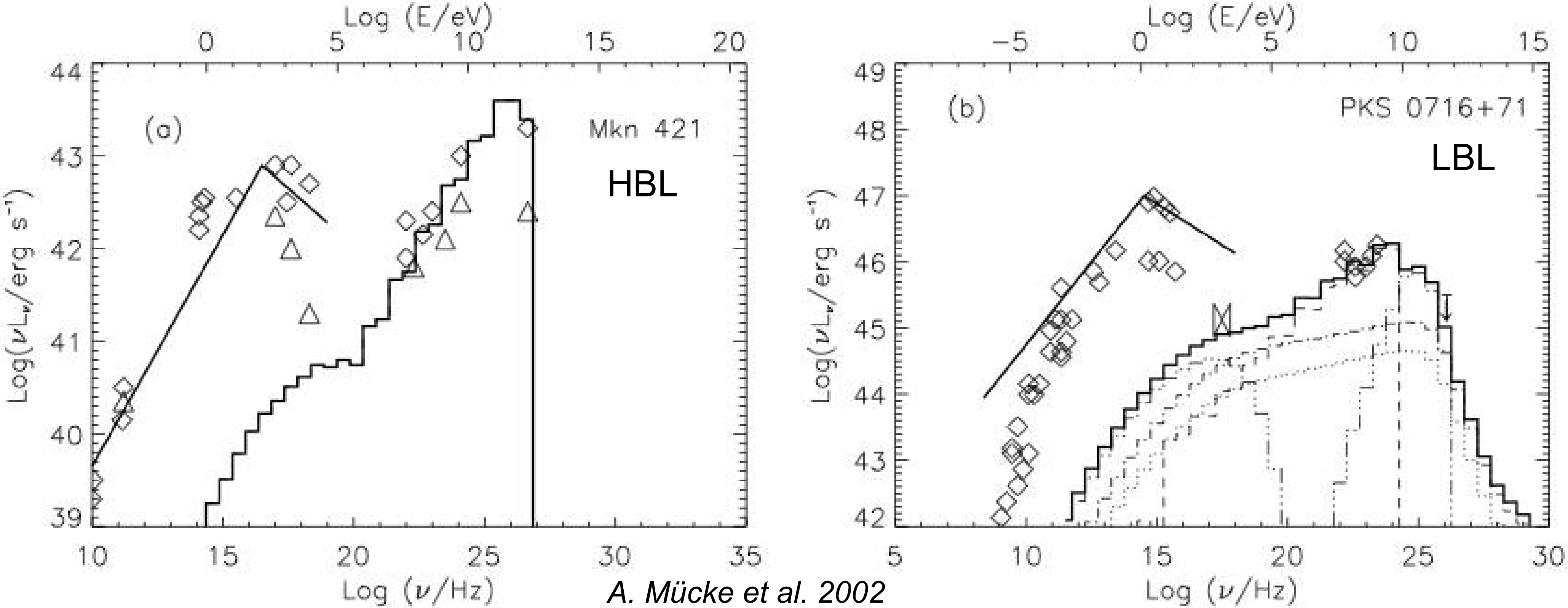
$$p^+ + p^+ \rightarrow p^+ + p^+ + \pi^0 \quad (...)$$

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

(...)

synchrotron,
synch. pair cascades

proton-synchrotron & photo-meson



A. Mücke et al. 2002

High-frequency peaked BLLacs:
- low synchrotron photon field
- γ-ray emission dominated by p-synchrotron

parameters:

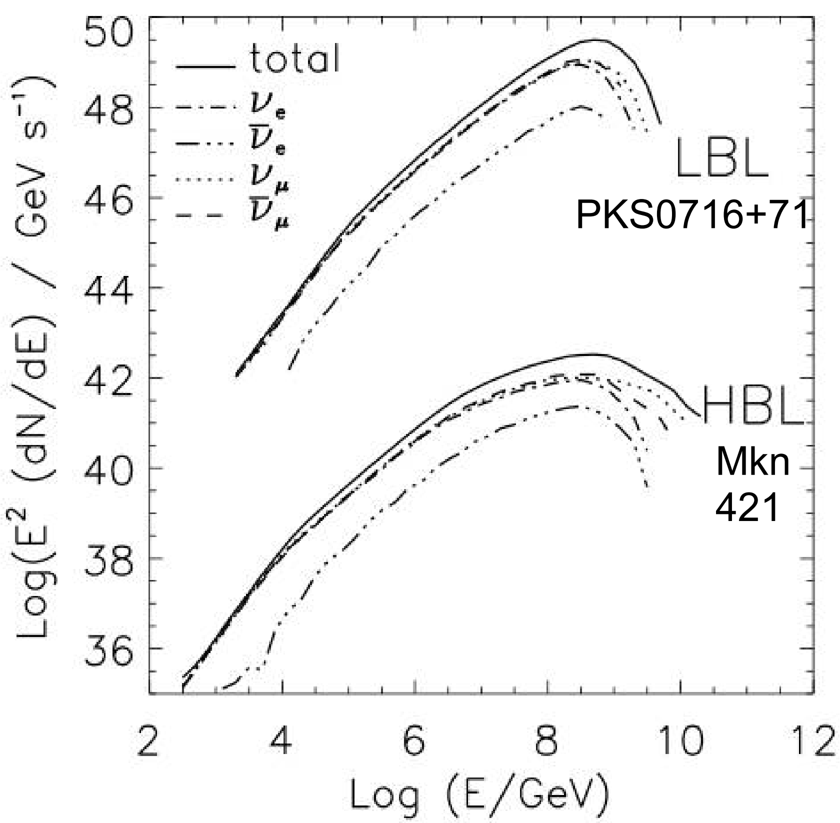
HBL: B=30 G, δ=10, R=3x10^{15}cm, $E_{p,max}$~4x10^{19}eV

LBL: B=30 G, δ=7, R=10^{17}cm, $E_{p,max}$~3x10^{18} eV

Low-frequency peaked BLLacs:
- high synchrotron photon field
- γ-ray emission is a combination of p-synchrotron, μ-synchrotron (resulting from p-γ interactions) and cascades

FSRQ:
- added external radiation fields (accretion disk & BLR) increase p-γ interactions

neutrinos from p-synch & p-γ



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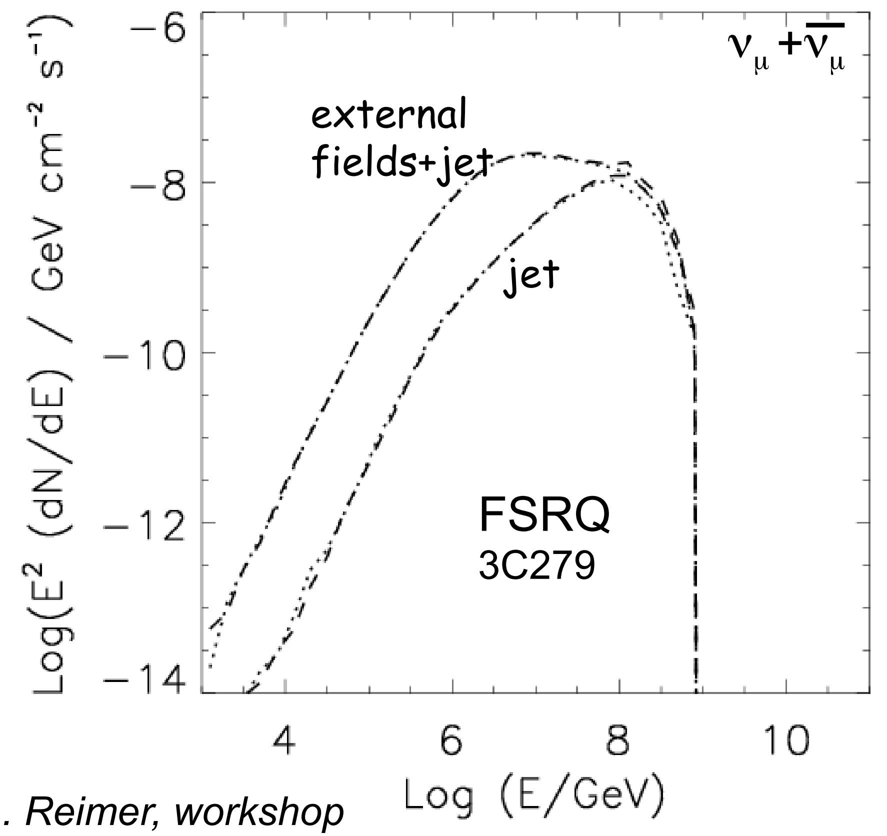
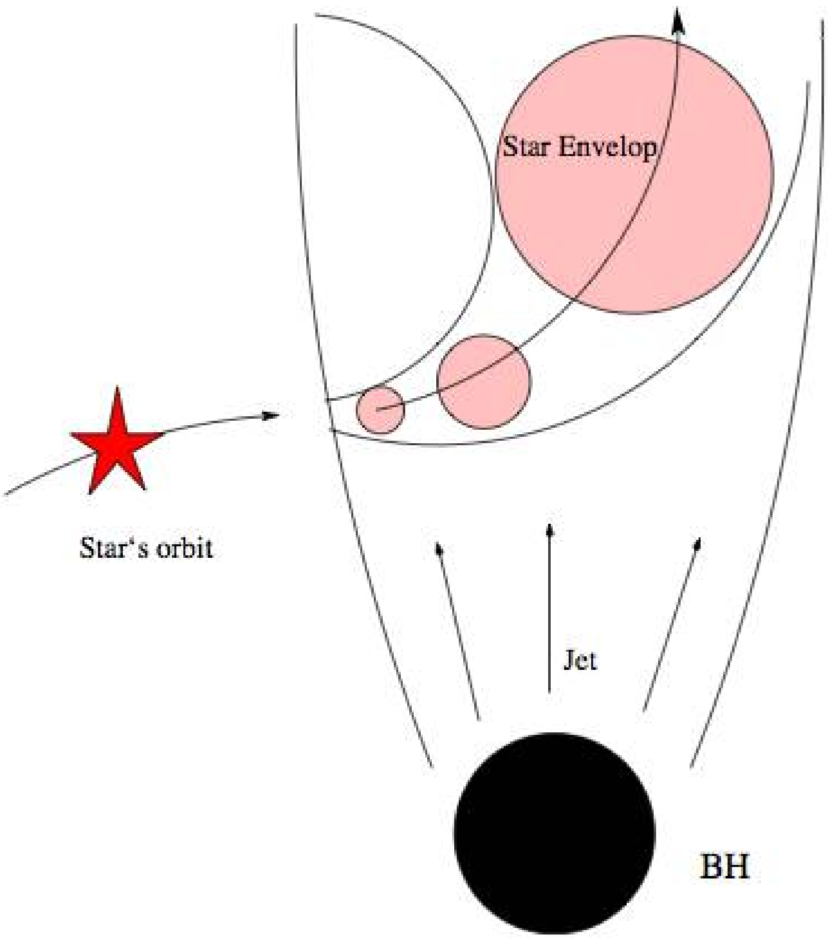


A. Reimer, workshop Heidelberg 2010

- LBL have higher intrinsic photon fields -> much better conditions for pion-production than HBL

- for FSRQ, additional component from pion-production in BLR radiation field
- "*more than an order of magnitude below typical flux upper limits of neutrino source candidates at PeV*"

rapid variability in hadronic models



M.V.Barkov et al. (2010)

- Red giant stars crossing the blazar jet

- Fragmentation of star envelope and formation of dense blobs in the jet.

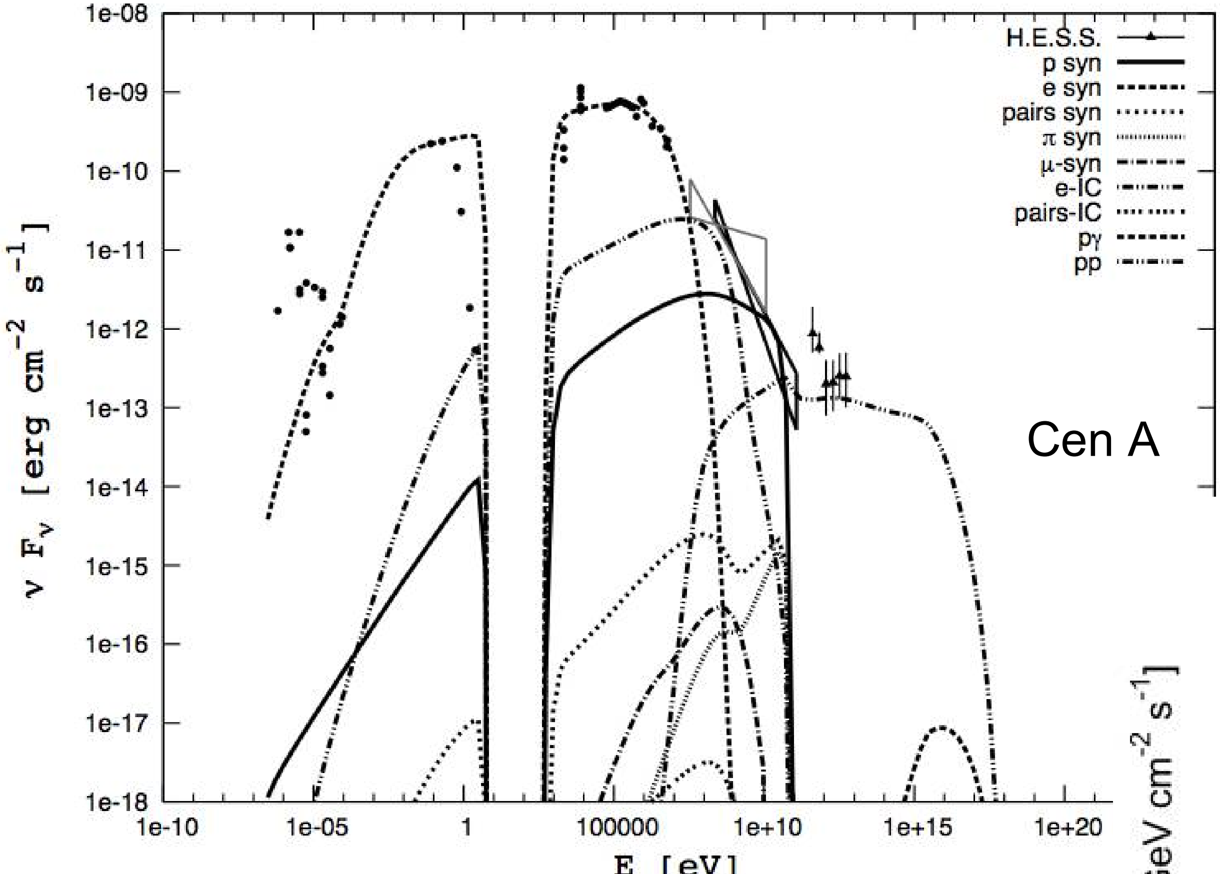
- Blobs are accelerated in jet and **emit γ-rays mainly by p-synchrotron.**

Proton-proton and proton-gamma cooling times too long for rapid variability (proton / photon density not high enough).

- could account for **minute-scale variability**

- potential problem: **sufficiently large population of red giant stars in BH vicinity ?**

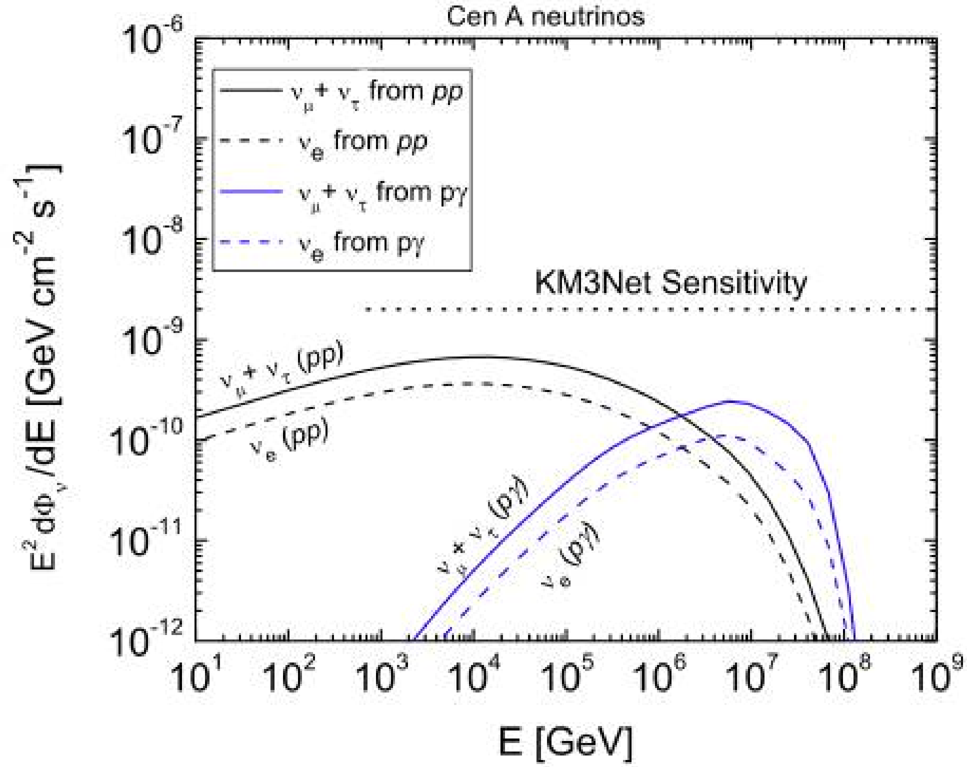
p-p interactions: heavy jets



M. Reynoso et al., astro-ph/1005.3025

Assuming very heavy jets, proton-proton interactions inside the jet could contribute significantly to the TeV γ-ray flux and to neutrino production.

Max. proton energy 6×10^{17} eV.



the problem: **very high proton density required**

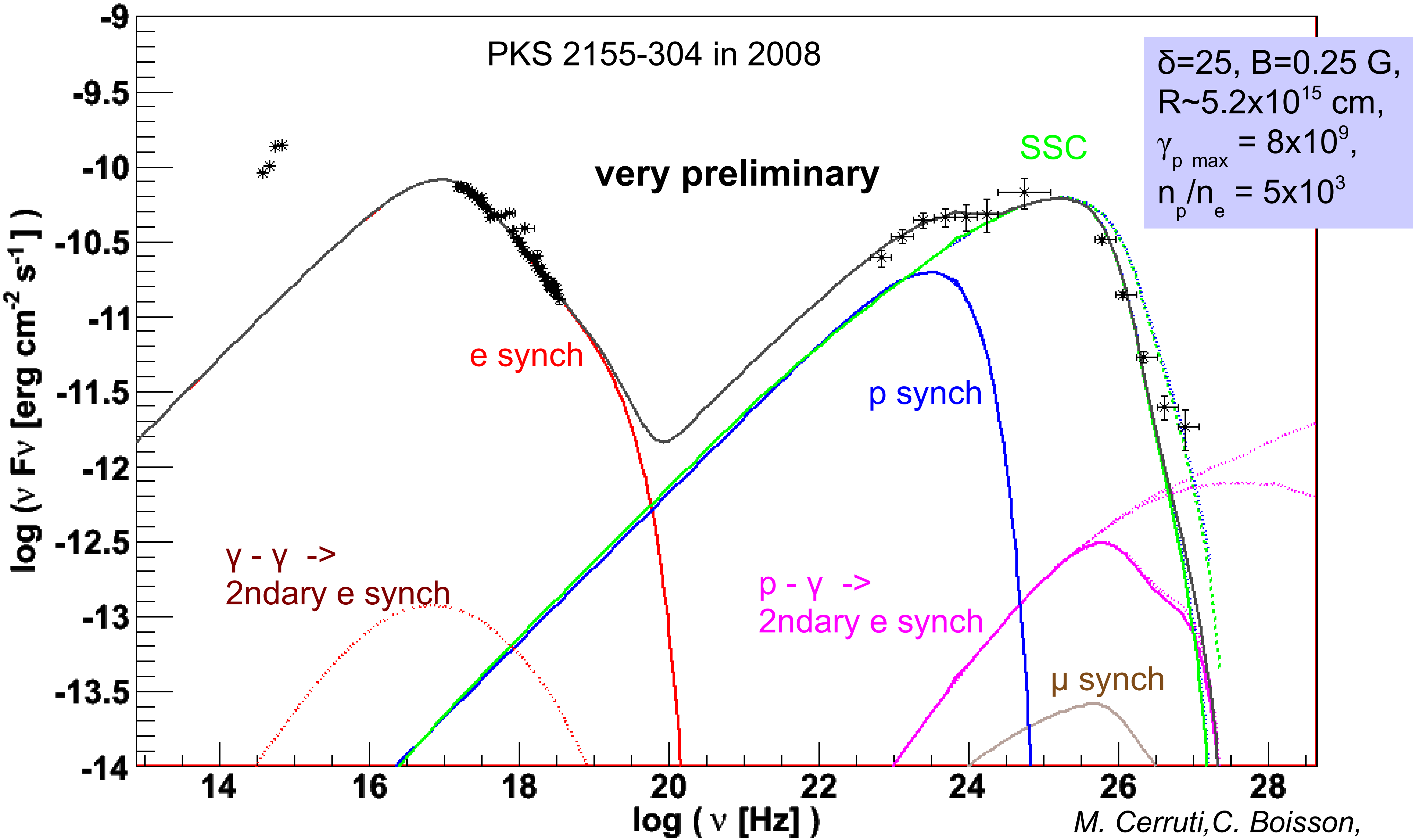
the general problem: energetics

- radiation by p-synchrotron in BL Lacs and p-gamma in FSRQ **does not seem to be efficient enough** to explain the observed high energy luminosities

- "For **realistic jet powers** ($L_{jet} \leq L_{Edd}$ in luminous blazars and $L_{jet} \leq 10^{-3} L_{Edd}$ in low luminosity BL Lac objects), **limited magnetization** ($\sigma \sim L_B/L_{jet} \leq 0.1$ is required to allow formation of strong shocks), and **moderately steep proton injection function** ($q_p \geq 2$ is suggested by IR-optical spectra and by theoretical acceleration models), the **hadronic models fail to**:
  - reproduce γ-ray luminosities of blazars
  - explain formation of very hard X-ray spectra in luminous blazars;
  - provide the spectral extension up to TeV energies in low luminosity blazars. "

M. Sikora, Proc. IAU Symp. 2010

lepto-hadronic models (work in progress)



M. Cerruti, C. Boisson, AZ + S. Inoue

Conclusions

- The simplest leptonic emission models for radio-loud AGN are challenged by recent (V)HE observations.

  However, leptonic models in general describe very well the observed blazar emission.

- Hadronic emission models might not be able to explain all of the (V)HE emission in blazars, due to the high requirements on jet power.

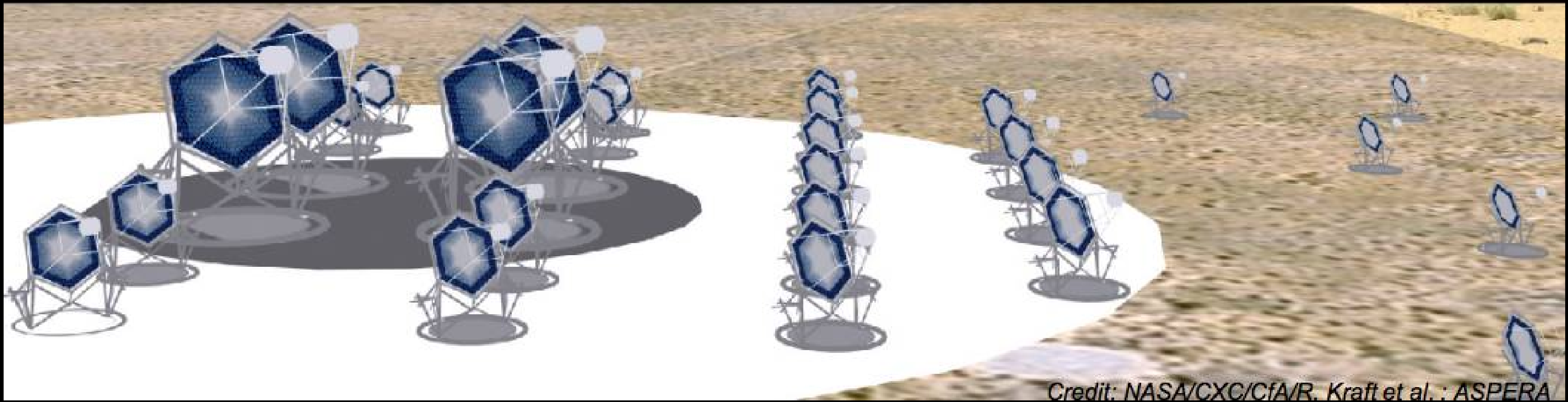
  Protons are however present in jets and hadronic processes might well contribute to the emitted spectrum.

- High luminosity blazars (FSRQ and LBL) and GPS/CSS seem the most promising AGN if one is looking for neutrinos.

AGN PHYSICS IN THE CTA ERA

Open workshop on 16 - 17 May 2011, Toulouse, France

http://cta.irap.omp.eu/toulouse2011 -> "AGN workshop"



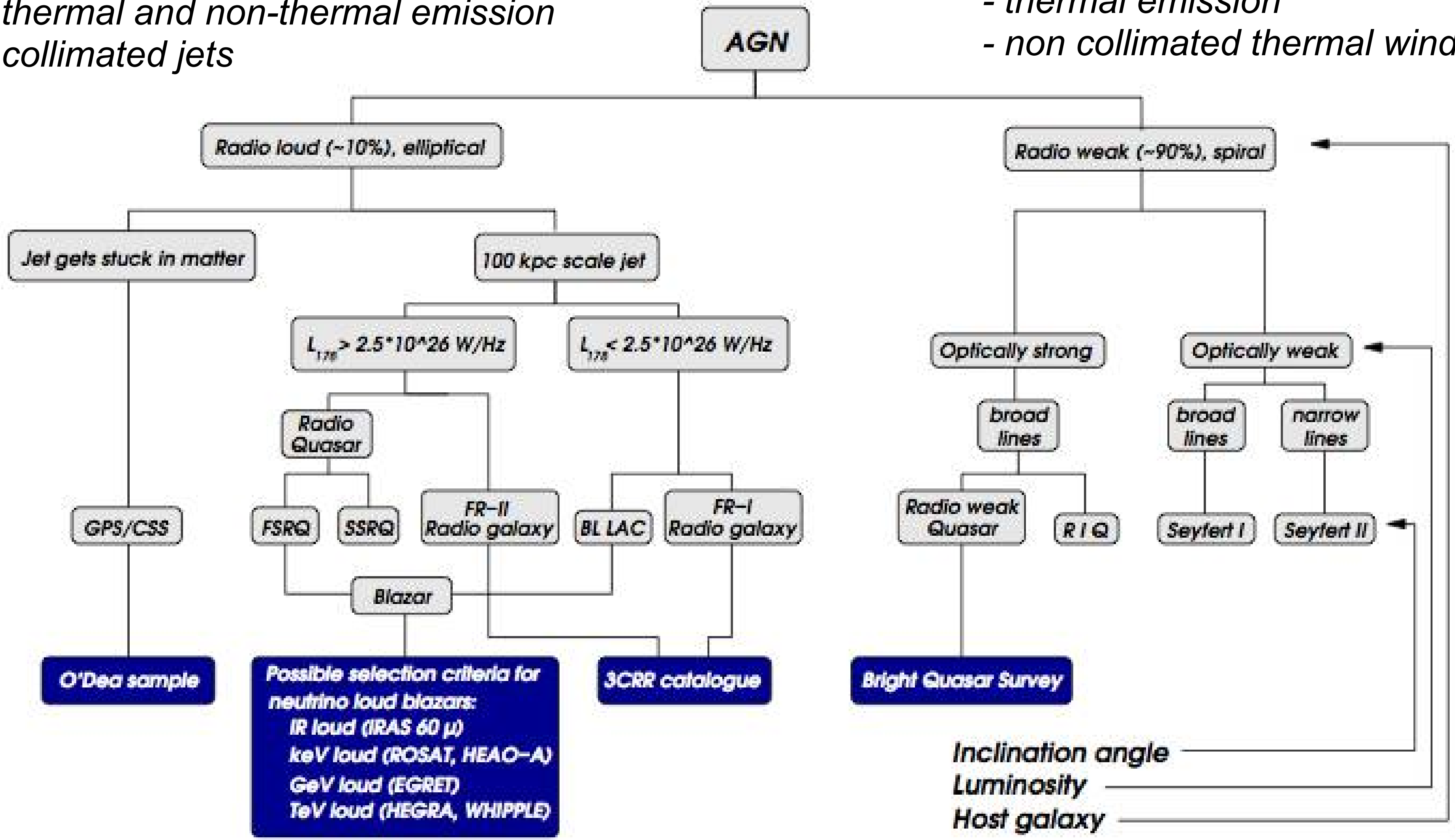
Credit: NASA/CXC/CfA/R. Kraft et al. : ASPERA

BACKUPS

AGN classification

- *thermal and non-thermal emission*
- *collimated jets*

- *thermal emission*
- *non collimated thermal winds*



influence of: BH spin ?
BH mass ? accretion ?

A. Achterberg et al., Astropart.Phys.26:282-300,2006

AGN classification

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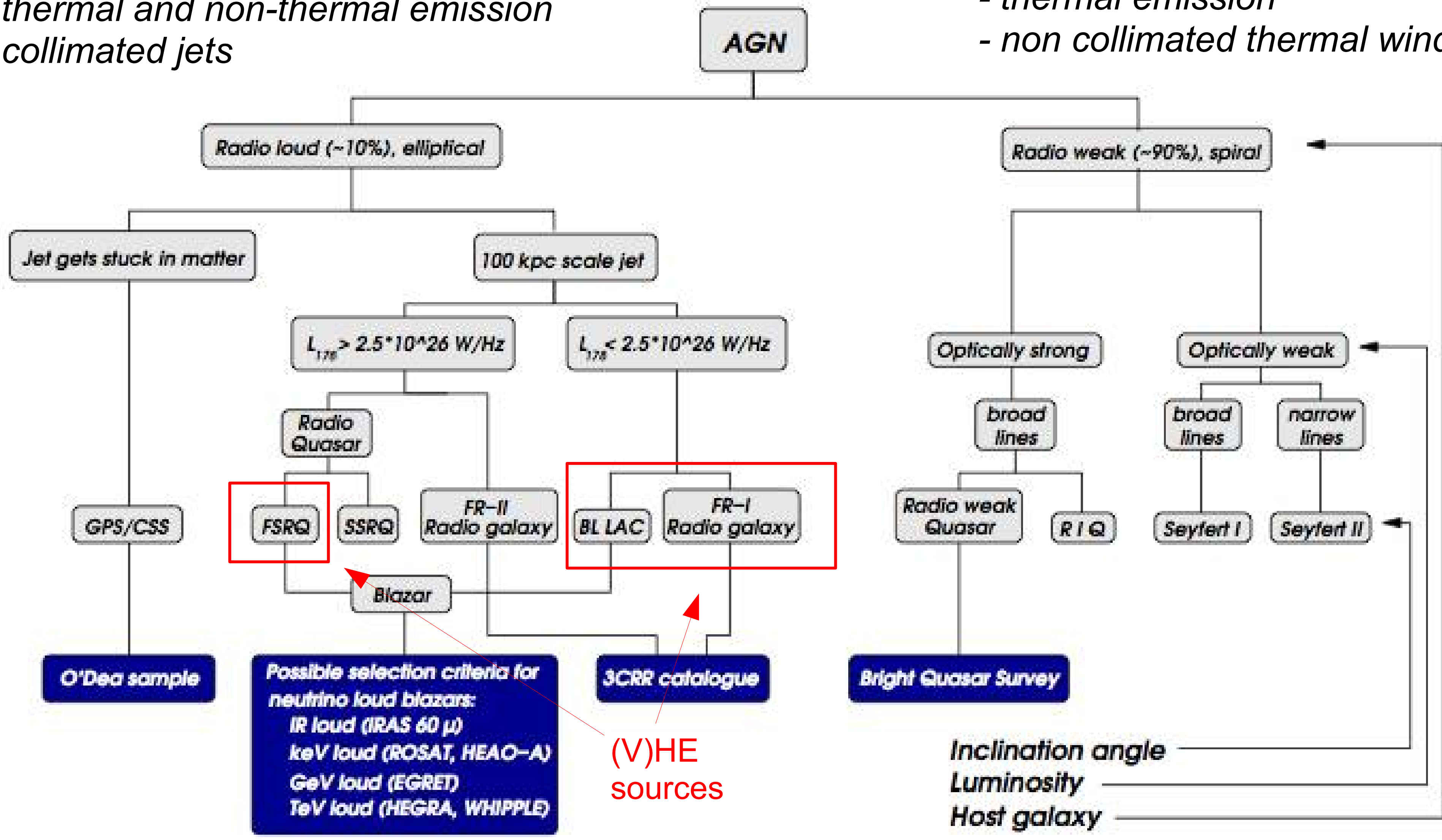

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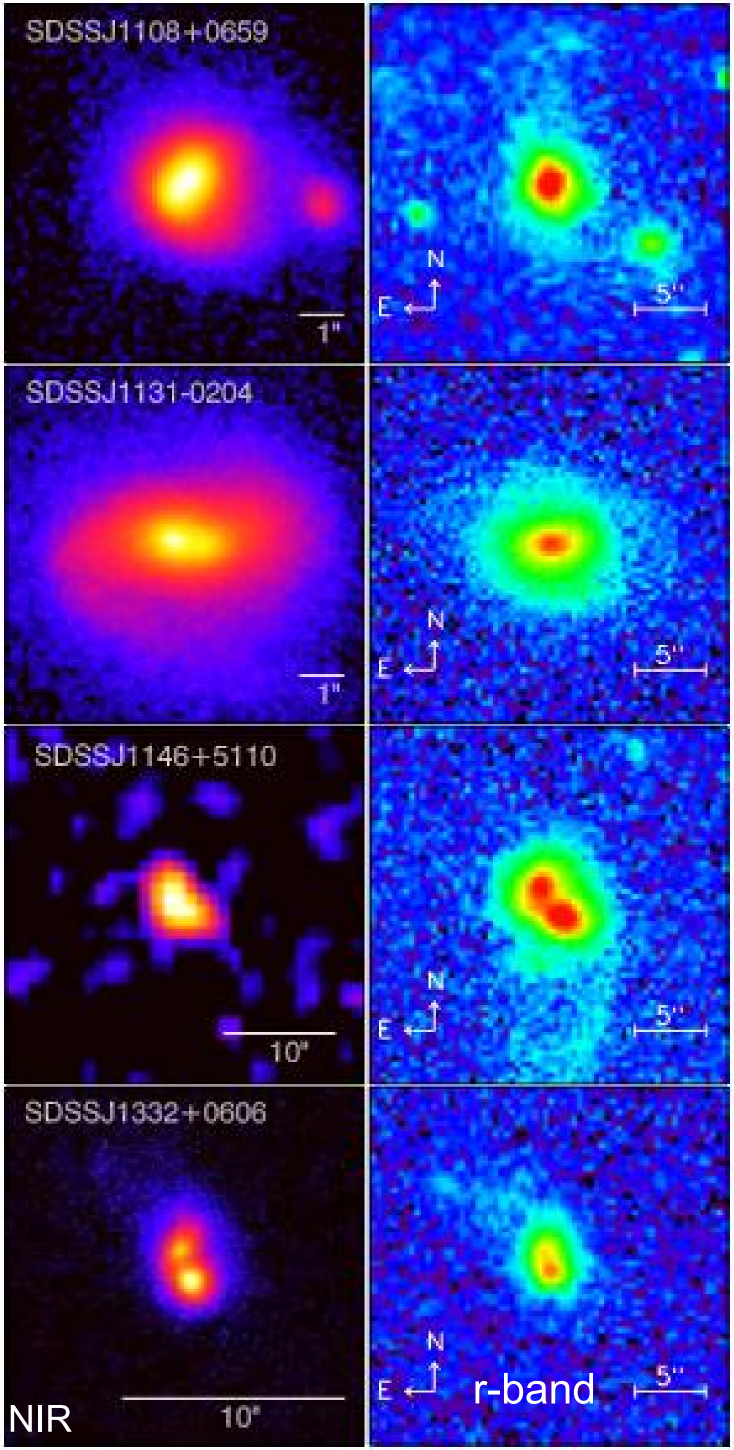
binary AGN

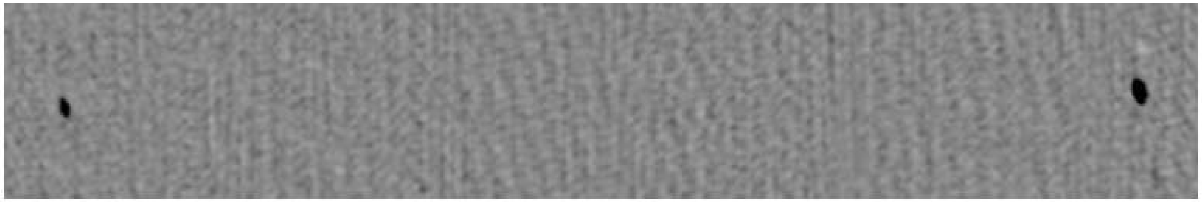


Detection of binary AGN : two examples

• binary AGN are expected to result from galaxy mergers
• difficult to detect
• systematic search for objects with double-peaked OIII emission lines in Sloan Digital Sky Survey

=> detection of 4 binary AGN (Seyfert 2)
=> drawn from a sample of only 43 candidate objects

Xin Liu et al., ApJ Letters 715 (2010) L30-L34

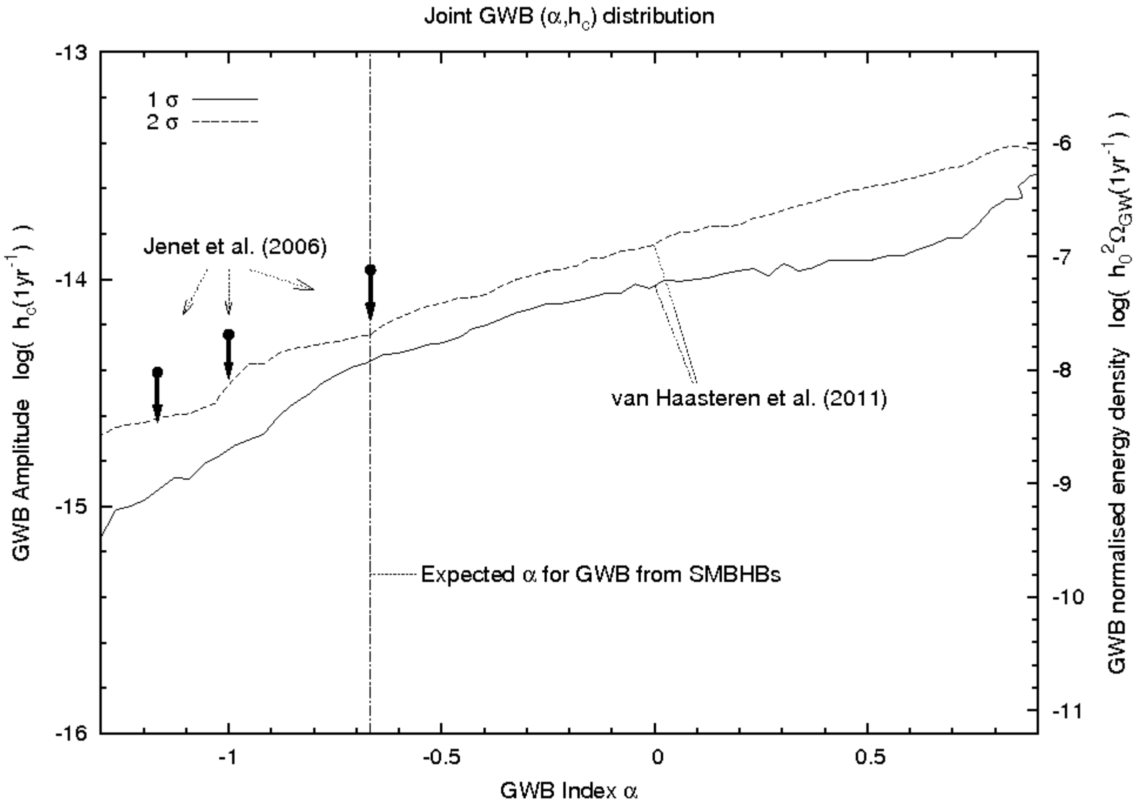


VLBI detection of an AGN pair in the binary black hole candidate SDSS J1536+0441, M. Bondi, M-A. Perez-Torres, ApJ

resolution of two radio cores at the pc scale for the first time => two compact (radio-quiet) AGN

Upper limits on the GW background

Upper limits on the GW background from pulsar timing array *(R. van Haasteren et al., 2011)*



- European Pulsar Timing Array (including Nançay radiotelescope)
- signal from extragal. GW at low frequencies (10^{-9} to 10^{-8} Hz) from delays in millisecond pulsar signals
- new upper limit on GW amplitude for the case of a background from SMBH binaries 6×10^{-15}.

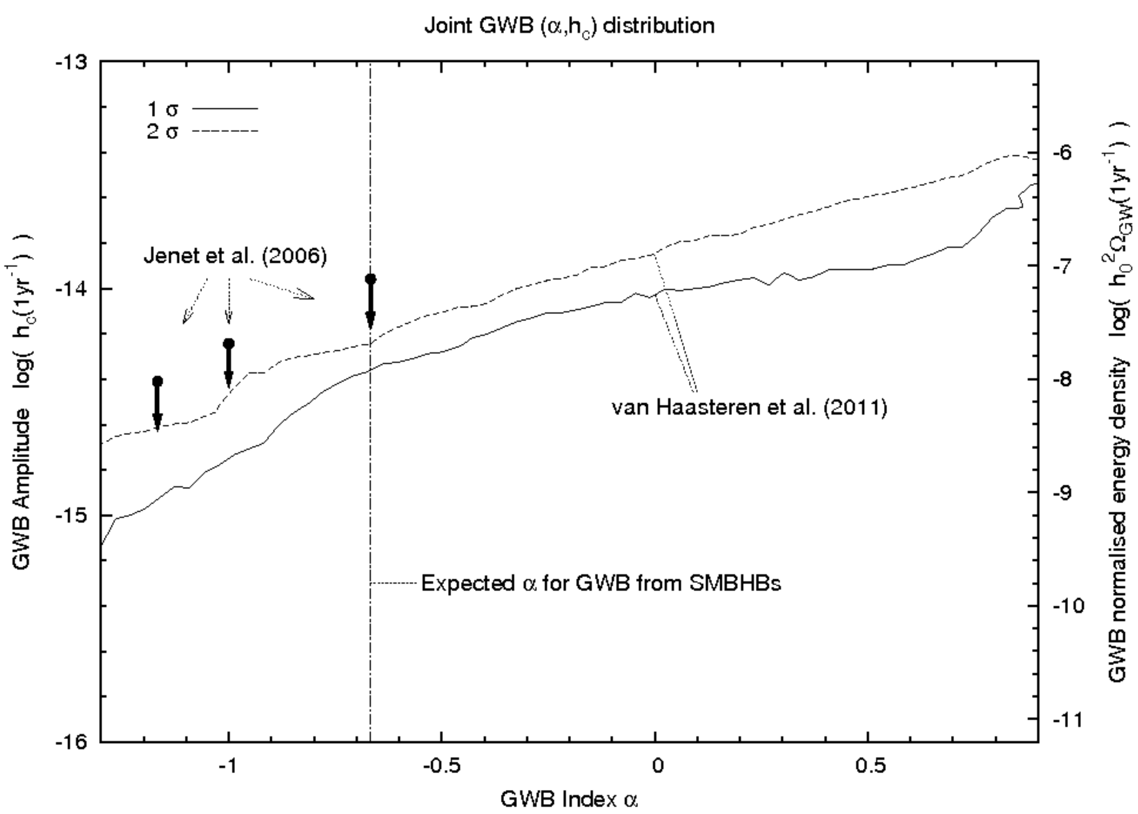
GW from SMBH binaries: predictions & upper limits

Predictions for gravitational wave detection (*M. Preto et al., 2011*)

- N-body simulations of galaxy mergers
- non-axisymmetries in galaxies after merger lead to coalescence within Hubble time

=> 10 to a few 100 events / year would be detectable by LISA

Upper limits on the GW background from pulsar timing array *(R. van Haasteren et al., 2011)*



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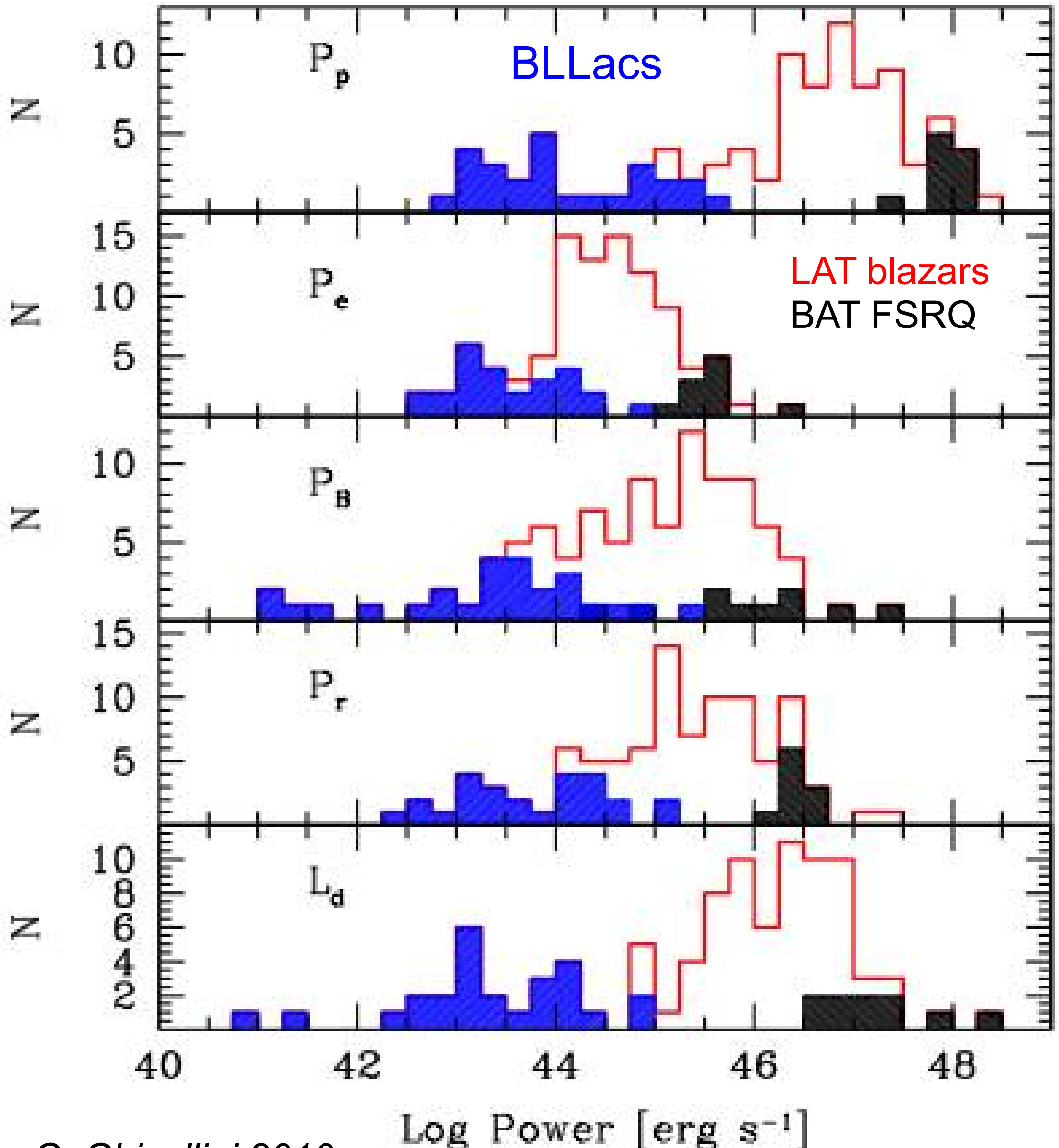
Proton content in jets

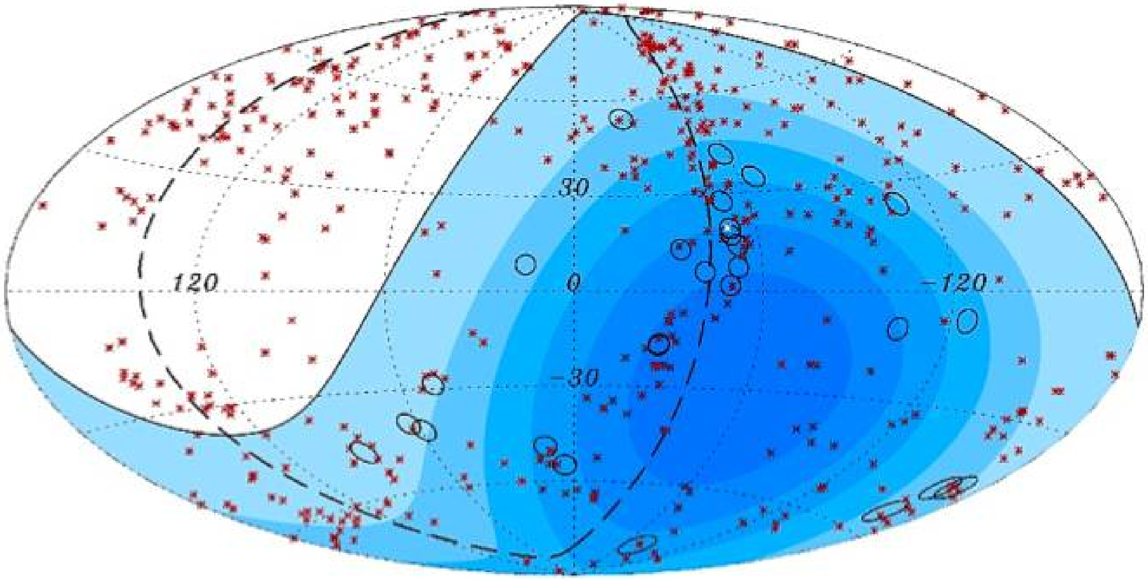


G. Ghisellini 2010

There is evidence that jets carry a fraction of (cold) protons. Kinetic energy in protons is needed to account for the total jet power and to explain the power in radio lobes etc.

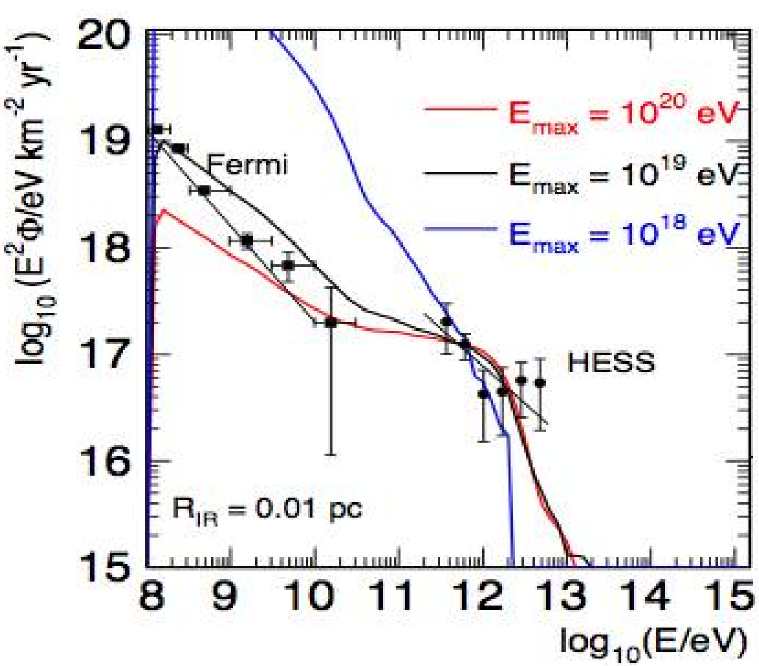
"(...) *as indicated by several independent observations, protons are present in AGN jets and presumably play **key role in dissipation processes in shocks**. In particular, they **transfer a fraction of the dissipated energy to electrons/positrons** helping them to reach threshold energies for further acceleration by stochastic mechanisms and produce the observed γ-ray spectra via the ERC and SSC scenarios.* "
(M. *Sikora, 2010*)

UHECR emission from Cen A ?



Acceleration sites for UHECR protons

- large-scale jet ? (shear acceleration) (*Rieger & Aharonian, A&A, 506, 3, L41,2009*)
- radio lobes ? (*Hardcastle, MNRAS,405,4,2810,2010, Moskalenko et al. 2008*)
- acceleration near the AGN core ? (*Sol & Istomin, 2009, Ap&SS, 321, 57*)
- more possibilities for heavy UHECR



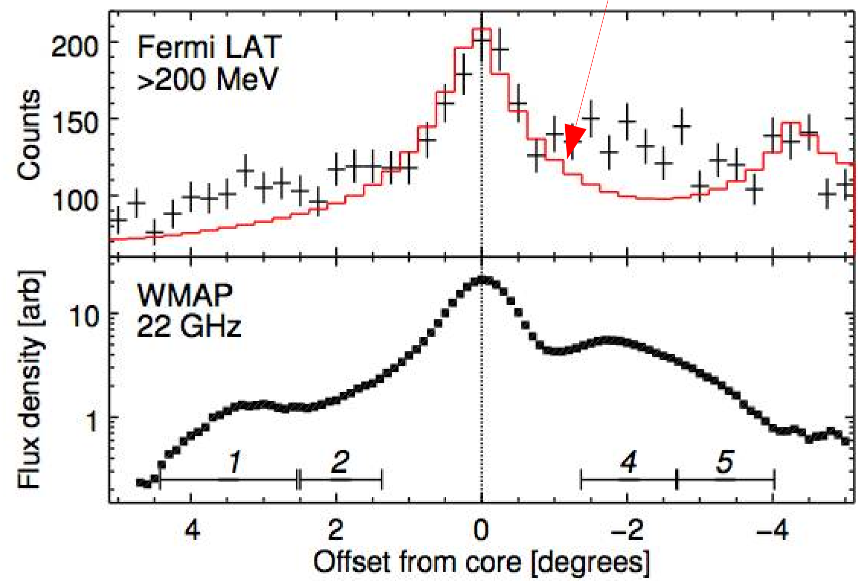
e.g. hadronic emission mechanisms for TeV γ-rays with acceleration near the core:

- *UHE muons* can escape emission zone
- *UHE photons* interact very little in emission zone (Klein-Nishina effect)

Kachelriess et al., astro-ph/1002.4874

HE γ-ray emission from radio lobes (Cen A)

point source + diffuse background



- Particle acceleration to very high energies (electrons of 0.1-1 TeV) in the giant radio lobes of Cen A.

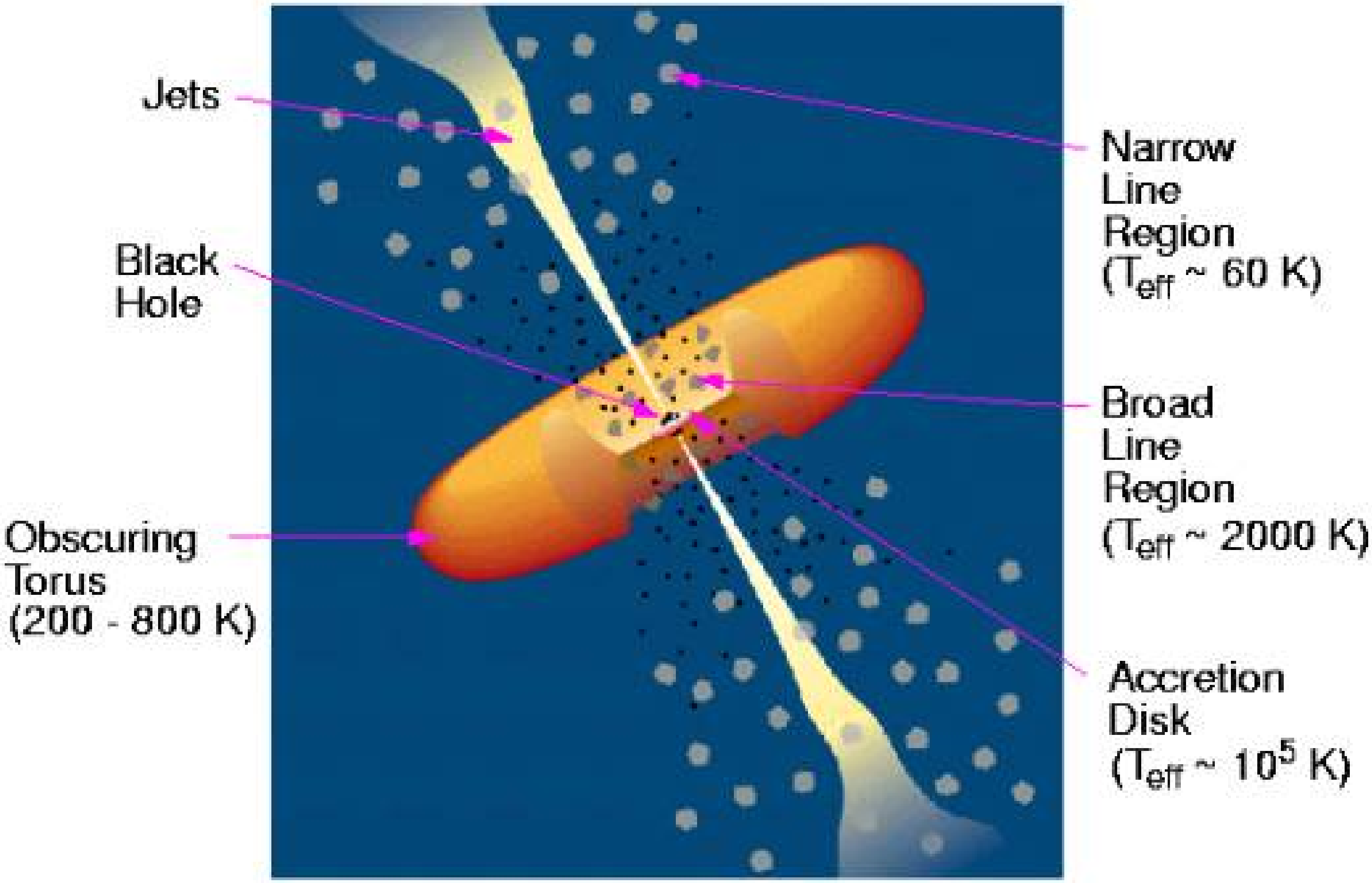
- HE emission dominated by Inverse Compton on the CMB.

(white: optical, orange: radio, purple: gamma)

Abdo et al. (Fermi), Science 2010:Vol. 328 no. 5979 pp. 725

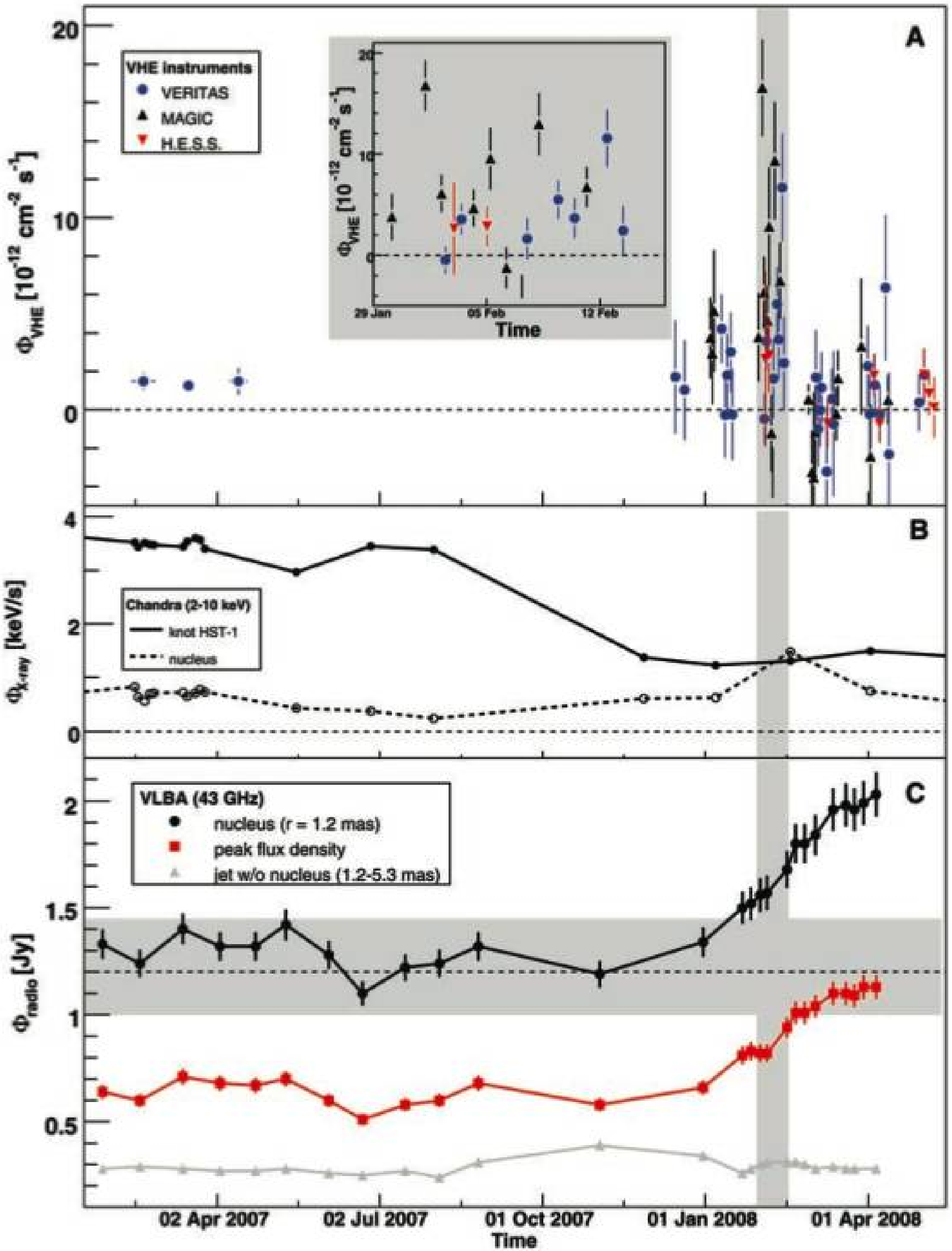
schematic view of AGN

(Diagram from Urry & Padovani 1995)



Annotated by M. Voit

VHE γ-ray emission from a radio galaxy (M87)



Joint MWL campaign (H.E.S.S., MAGIC, VERITAS; Chandra; VLBA) observes flare in 2008:

- strong VHE γ-ray outbursts over a few days
- simultaneous X-ray flare from the nucleus (and NOT from HST-1)
- coincides with rise in the radio flux from the nucleus

=> **common origin for the flare emission from the nucleus very likely**

=> possible interpretation:

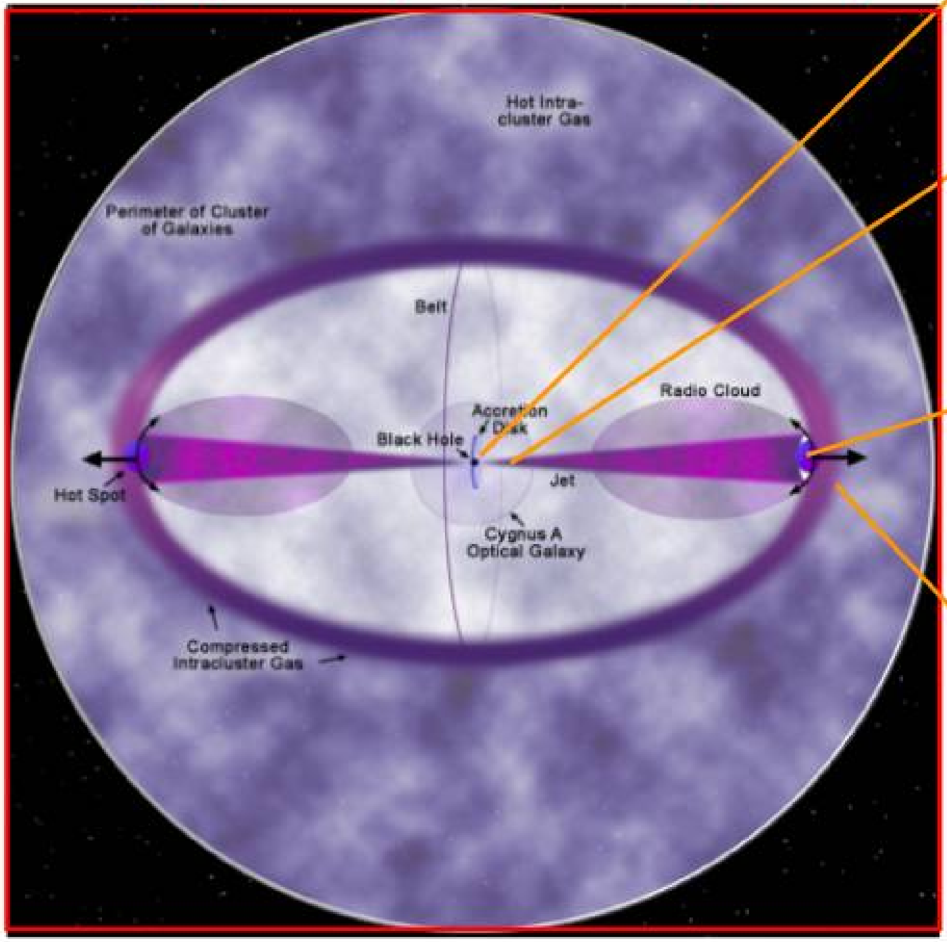
- VHE & X-ray flare in the jet collimation region
- radio emission initially hidden by self-absorption, becomes visible as the plasma travels along the jet

Science 24 (2009) 444-448

Where to accelerate cosmic rays ?

AGNs: acceleration sites

high power (FR 2) radio galaxy



from Chandra webpage

near-nucleus

highest E not expected

inner jet (blazar)

E_{max}~$E_{p\gamma}$~<10^{20}eV

accel./escape nontrivial

hot spot

R~10^{21} cm   B~1mG

E_{max}~E_{esc}~$10^{20\text{-}21}$eV

accel./escape easier

bow shock

R~10^{23} cm   B~0.1mG

E_{max}~E_{esc}~10^{20}eV

Berezhko 08

accel. nontrivial

OK IF B field amplified
escape easiest

S. Inoue

How to accelerate protons in Cen A ?

Acceleration in the large-scale jet ?

"From a theoretical point of view and based on conventional acceleration concepts, it seems challenging to account for a possible production of UHECR protons beyond 10^{19} eV. On the other hand, (...) **shear acceleration** along the large-scale jet in Cen A may help to overcome this problem by increasing the en-ergy of shock-accelerated seed particles by a factor of some tens (...)"

rieger
aharonian
0910.2327v1

If UHECR are heavy beyond 1019 eV, other mechanisms might work (Blandford-Znajek?).

Acceleration in the radio lobes ?

hardcastle: http://arxiv.org/pdf/0901.1346

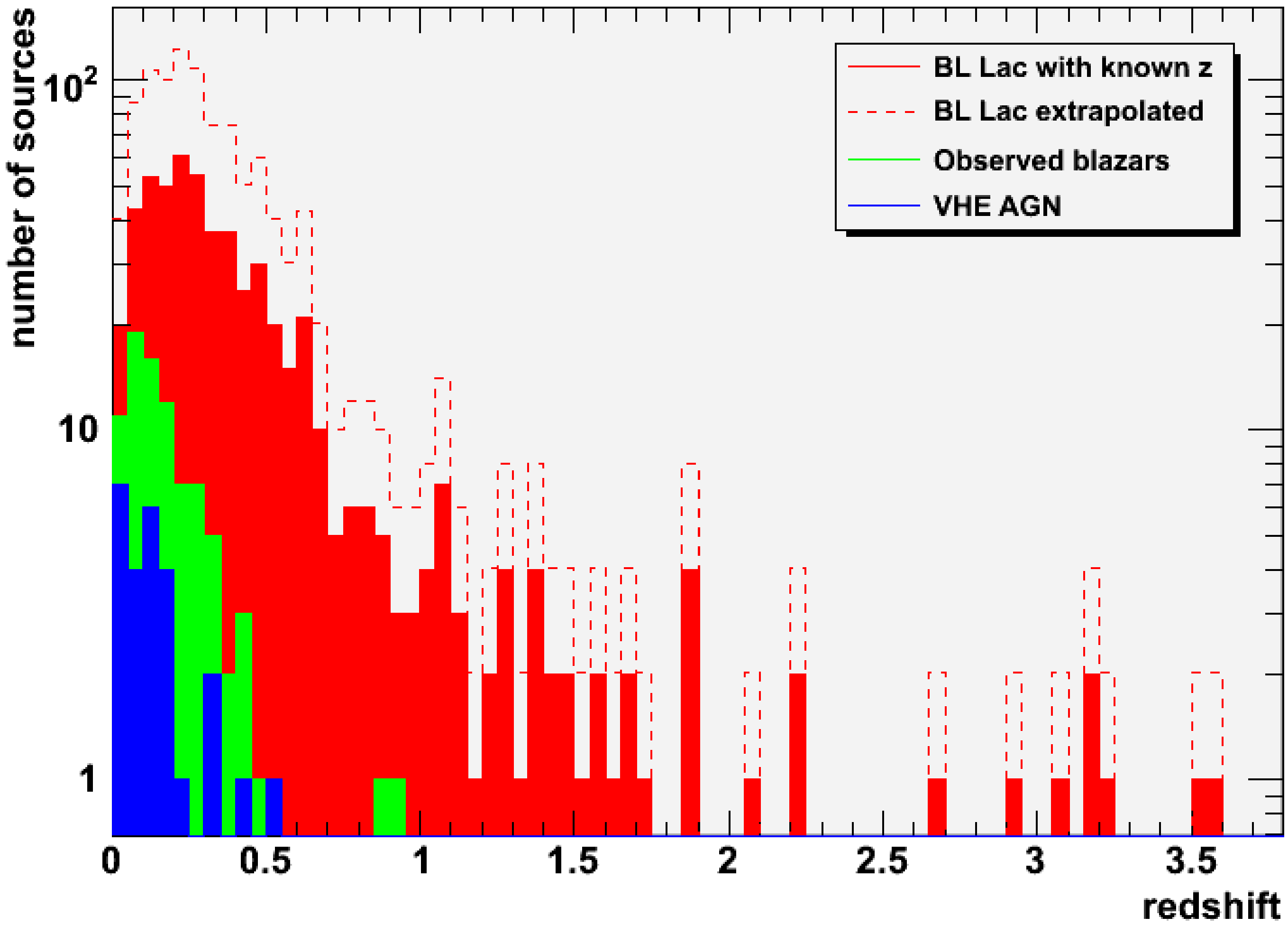
By the criterion of Hillas (1984),(...) magnetic fields significantly higher than equipartition (e.g. ~ 400μG) would be required for the shock front to accelerate cosmic rays to 10^{20} eV. There is considerable evidence that magnetic fields can be amplified by large factors at the forward shocks of SNRs (e.g. Berezhko & Völk 2004; Ellision et al. 2004) (...) and so if similar processes were operating at the Cen A shock front then UHECR energies could be achieved.

The Cen A shock front appears resolved in our *Chandra* observations, with a width of ~ 2 arcsec (corresponding to ~ 3 5pc). (...This implies) magnetic field strengths of ~ 1μG, (...) much lower than would be required to accelerate UHECRs.

The ~ **600-kpc-scale giant outer lobes of Cen A may be a more likely candidate for the origin of the UHECRs apparently associated with Cen A** (e.g. Moskalenko et al. 2008; Hardcastle et al. 2008).

e.g. Centaurus A

Veron-Cetty catalog



Unification by viewing angle

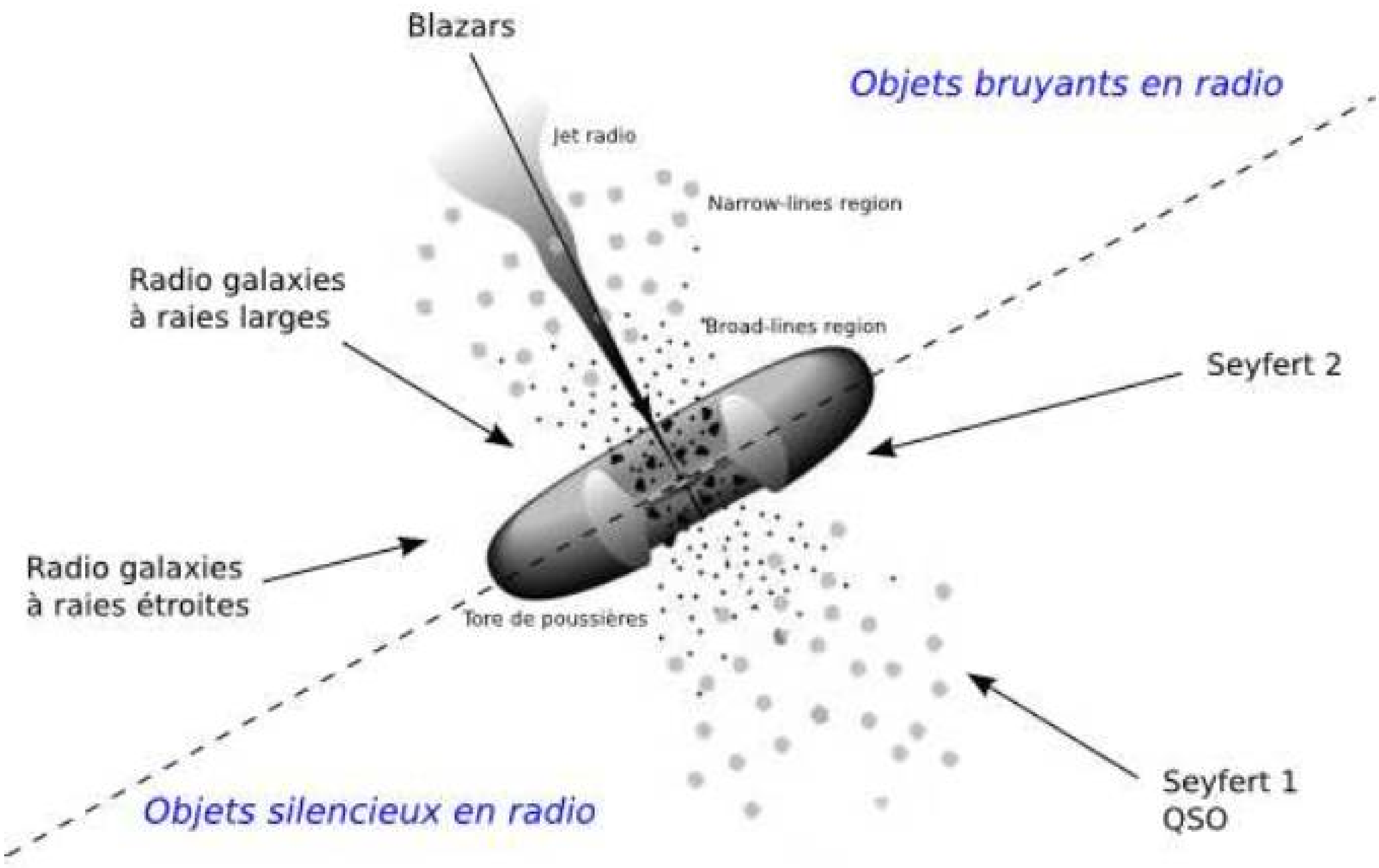
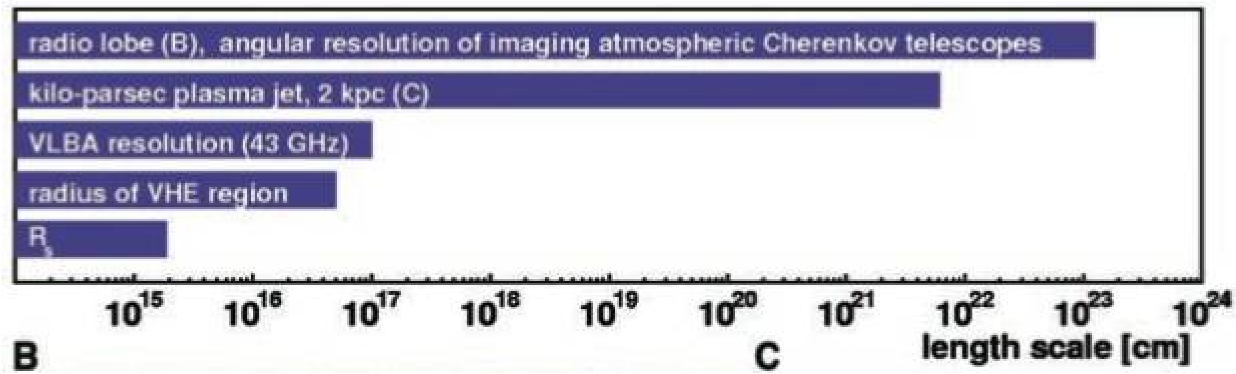
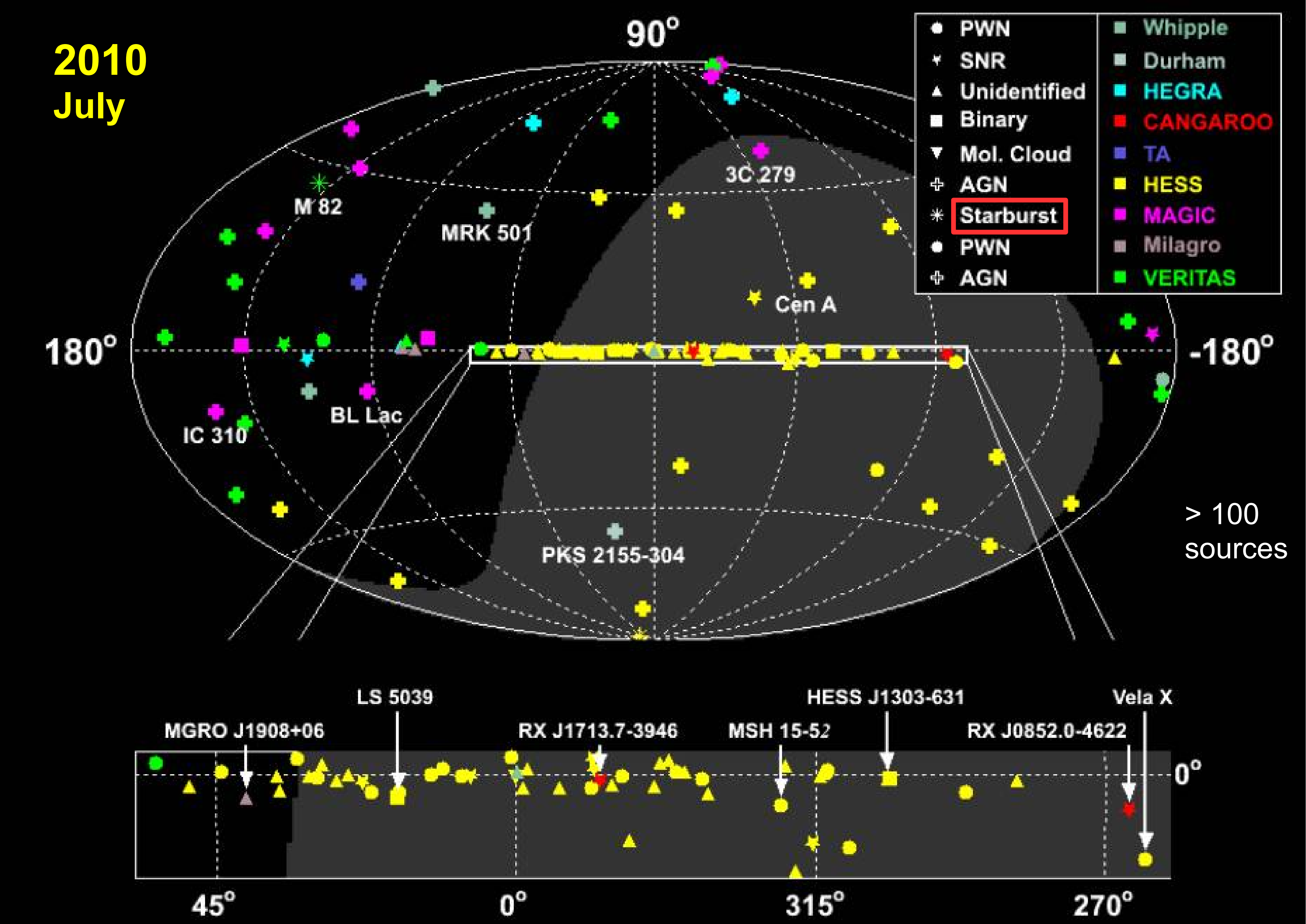


Fig. 1.6: Schéma d'unification des NAG. Adapté de Urry & Padovani (1995).

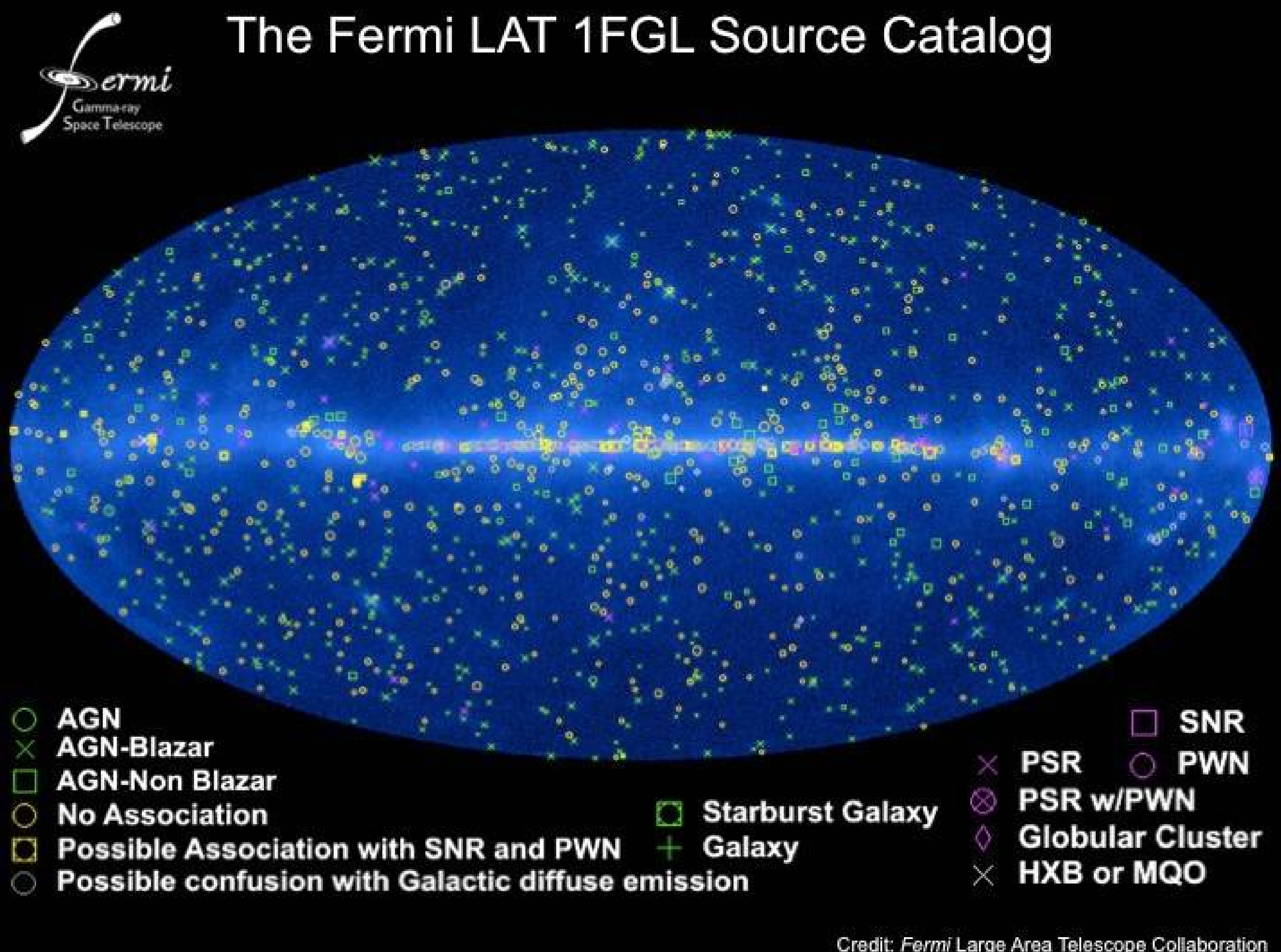
e.m. emission from AGN

- **radio lobes:**
  radio to HE (synchrotron, bremsstrahlung, IC...)
- **host galaxy:**
  optical, IR emission (thermal, absorption lines)
- **torus:**
  dominates in IR
- **jet:**
  radio to VHE (synchrotron, IC or hadronic processes)
- **accretion disk, broad-line/narrow-line region:**
  optical, UV, X-ray (thermal, emission lines)
- corona:
- nucleus:


radio lobe (B), angular resolution of imaging atmospheric Cherenkov telescopes
kilo-parsec plasma jet, 2 kpc (C)
VLBA resolution (43 GHz)
radius of VHE region
R
10^15 10^16 10^17 10^18 10^19 10^20 10^21 10^22 10^23 10^24
B
C
length scale [cm]


2010
July
90°
180°
-180°
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Starburst
PWN
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
M 82
MRK 501
3C 279
Cen A
BL Lac
IC 310
PKS 2155-304
> 100
sources
LS 5039
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
315°
270°

a look at lower energies: HE γ-ray astronomie in 2010



E>100 MeV

> 1400 sources in 11 months