ACTIVE GALACTIC NUCLEI: SOURCES FOR ULTRA HIGH ENERGY NEUTRINOS!

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Sources of ultra high energy cosmic rays

- Three candidate source classes:
- **(I) Radio galaxies, and their jets**, drawing from the ISM and IGM, mostly Hydrogen and Helium
- **(II) Radio galaxies**, and their jets, plowing through **Wolf Rayet star explosion** regions full of new highly enriched cosmic rays
- This is the currently best bet to explain the **observed ultra high energy cosmic rays**
- **(III) Starburst galaxies** and their **GRBs**
- and as a subset, the starburst phase usually preceding the activity of a freshly fed supermassive black hole
- In all cases, there should be high energy neutrinos from interaction, and decay

Ultra high energy neutrinos?

BUT:

- If most ultra high energy cosmic rays heavy ions
- First interaction does not produce neutrinos so directly
- Only multiple stage interaction gives neutrinos
- How do we get a large flux of ultra high energy neutrinos?

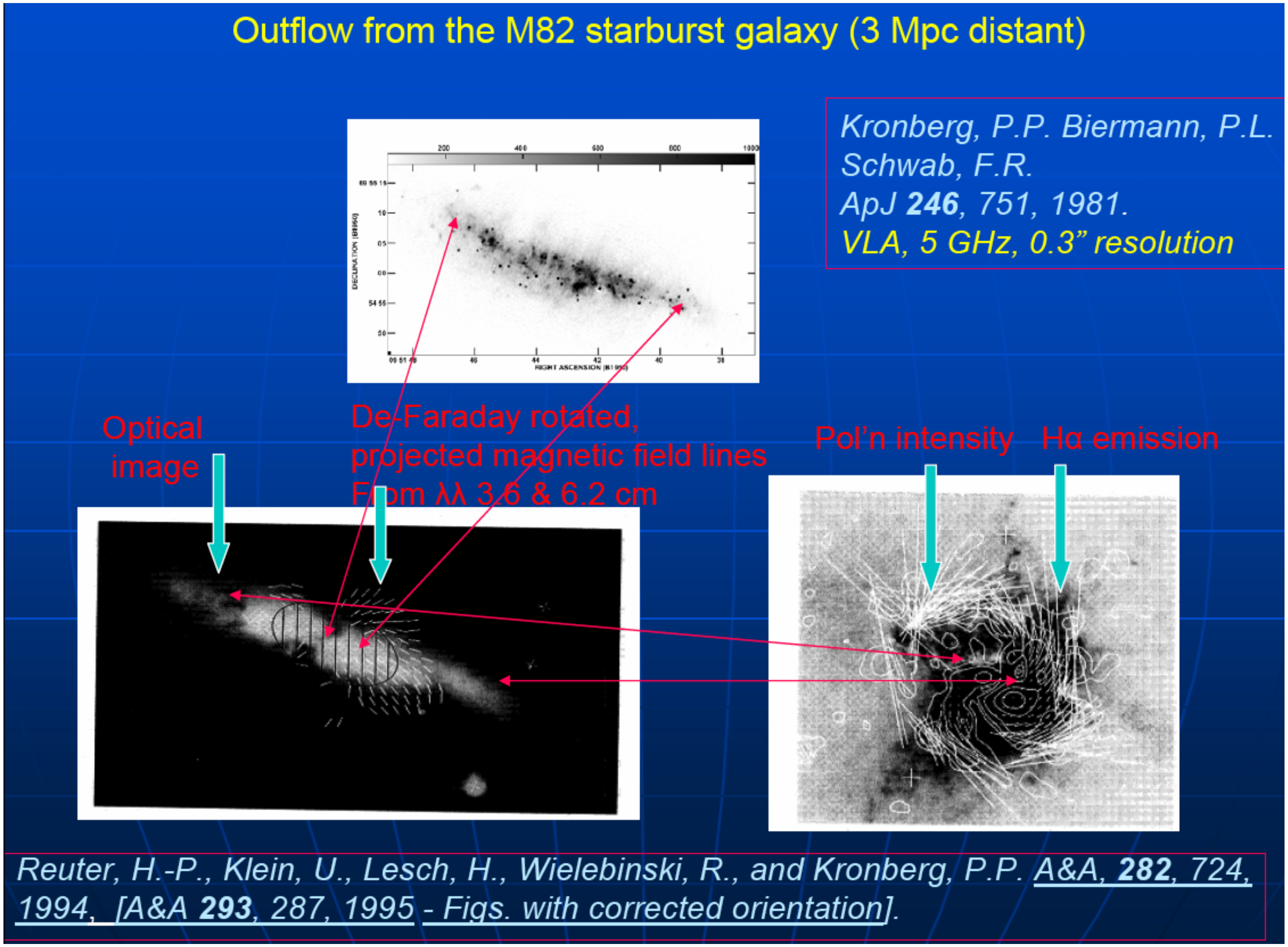


Figure 1 WR star explosions in other galaxies. Source P.P. Kronberg 2008

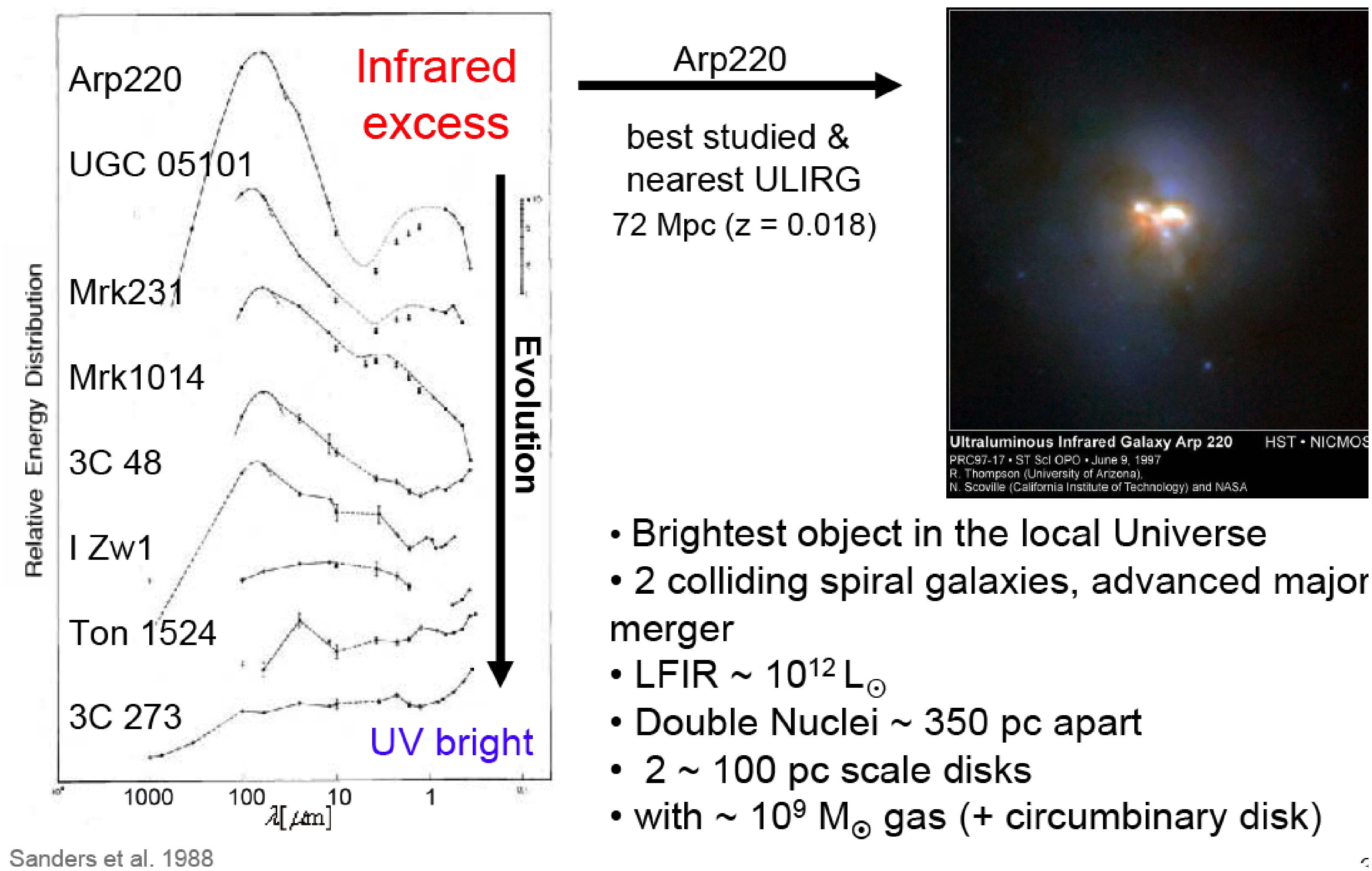
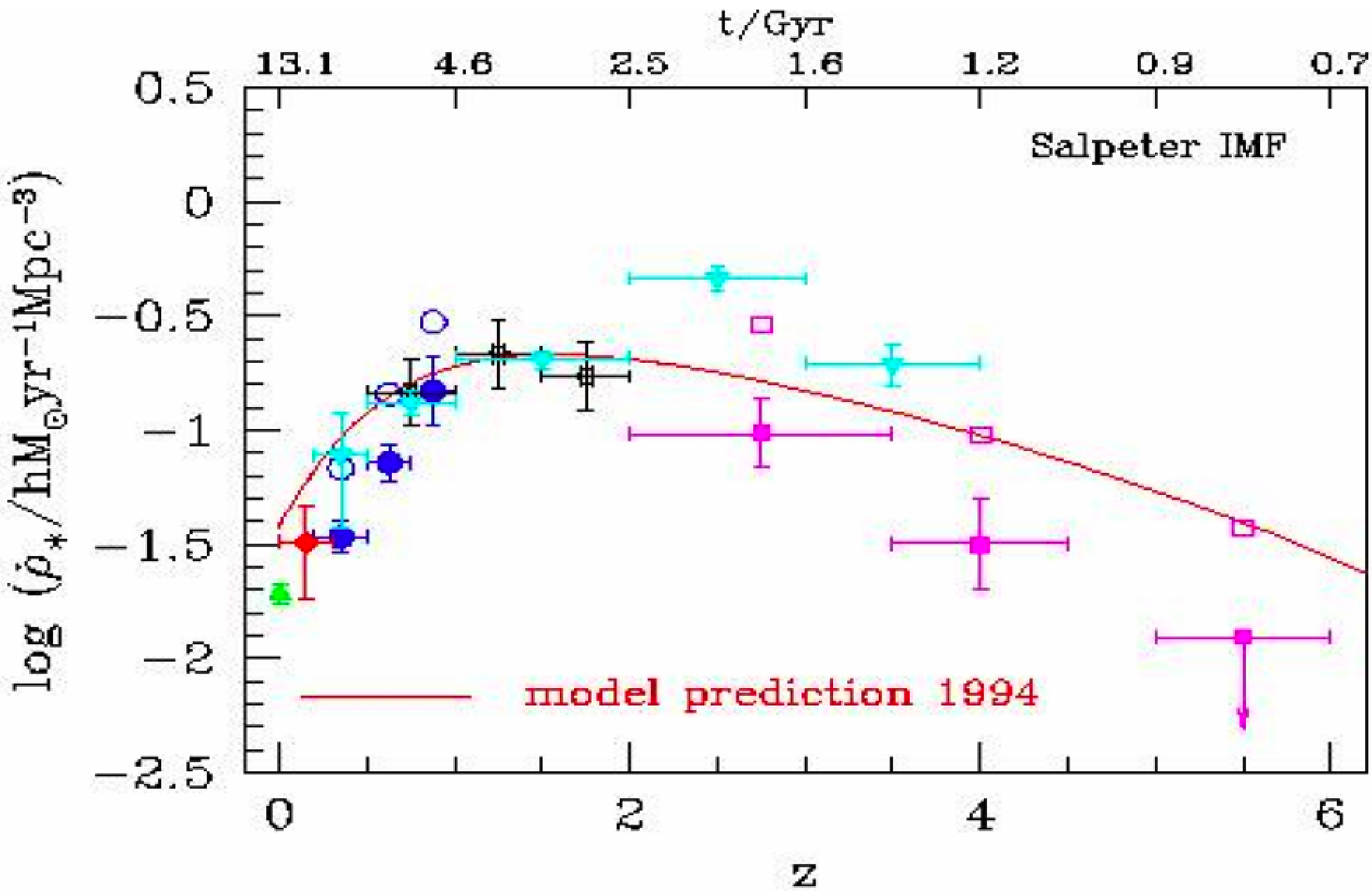


Figure 2 The radio galaxy Arp220 and evolution. Source Lecture S. Britzen



(Baugh et al. 1998)

Figure 3 Star formation as function of redshift. Source Lecture S. Britzen

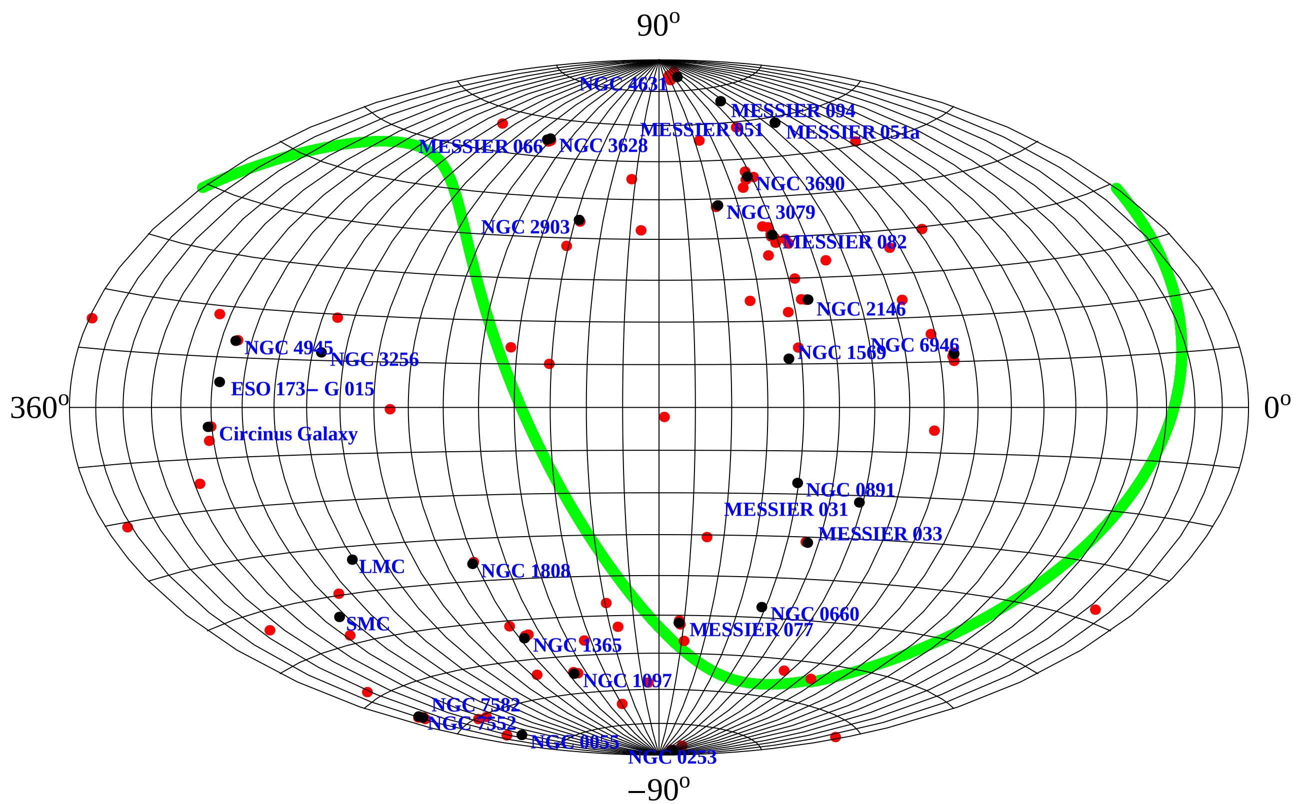
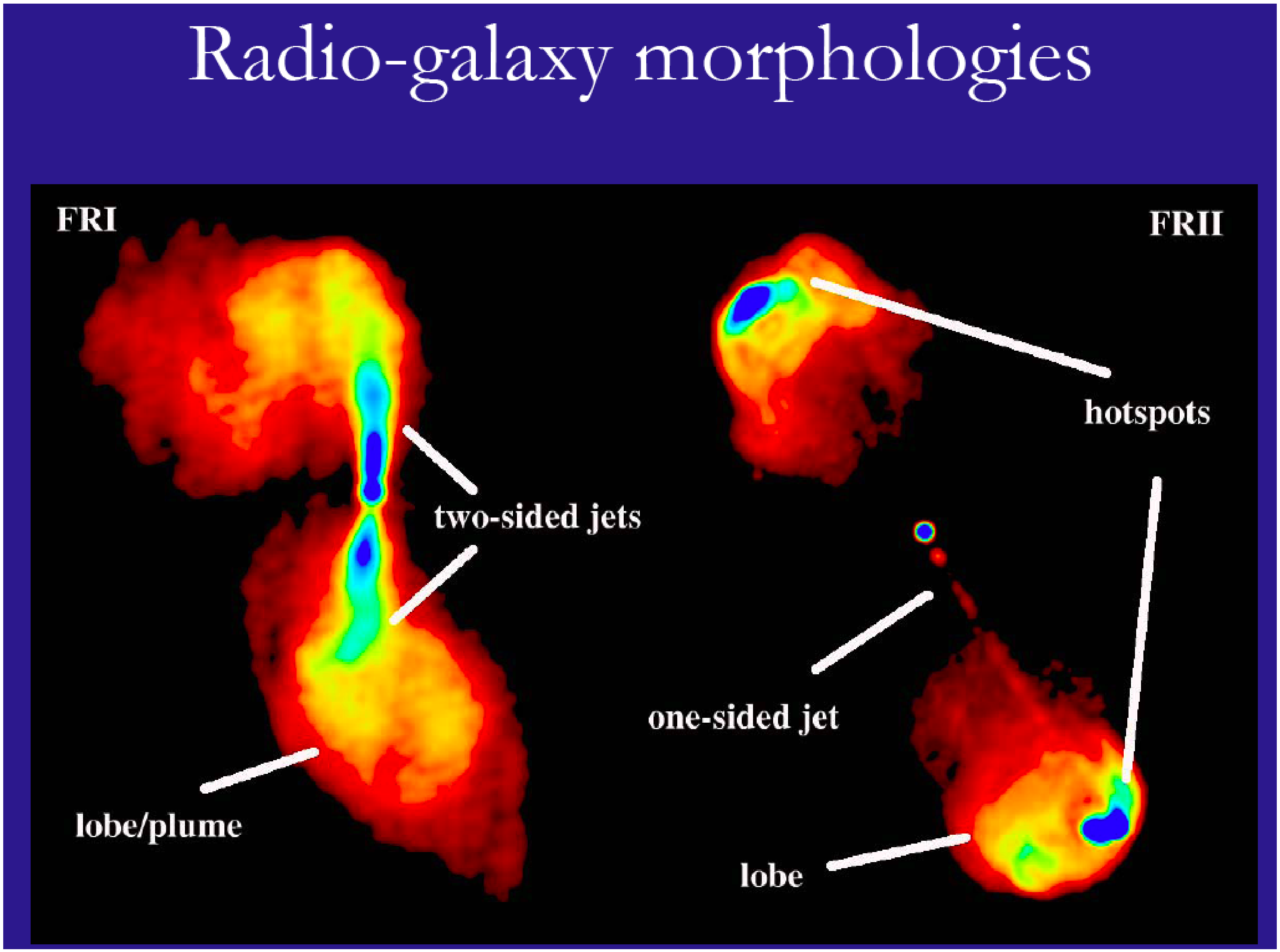


Figure 4 Aitoff projection in galactic coordinates of the selection from NED in 60μm, redshift $z \leq 0.0125$, flux density brighter than 50 Jy, starburst selected, sample of 32 candidate sources and 100 virtual events from this sources and weighted contribution. Double Monte-Carlo to simulate the intermittent nature of Gamma Ray Bursts

Evolution of an activity episode:

- Two galaxies merge, both may have a central supermassive black hole
- stage I: Feeding a central starburst, the starburst dominates the energetics of the emission; this is accompanied by the formation of many massive stars, Wolf Rayet stars, their explosions and many gamma ray bursts
- stage II: Feeding the central black holes, the black holes takes over
- stage III: The black holes merge, induce a spin-flip: for a while both jet directions are visible
- stage IV: The activity dies down, reaching a limit when just one red giant star feeds the black hole

Radio galaxies, jets, hot spots, shocks and shear-flows as accelerators and phase mixers



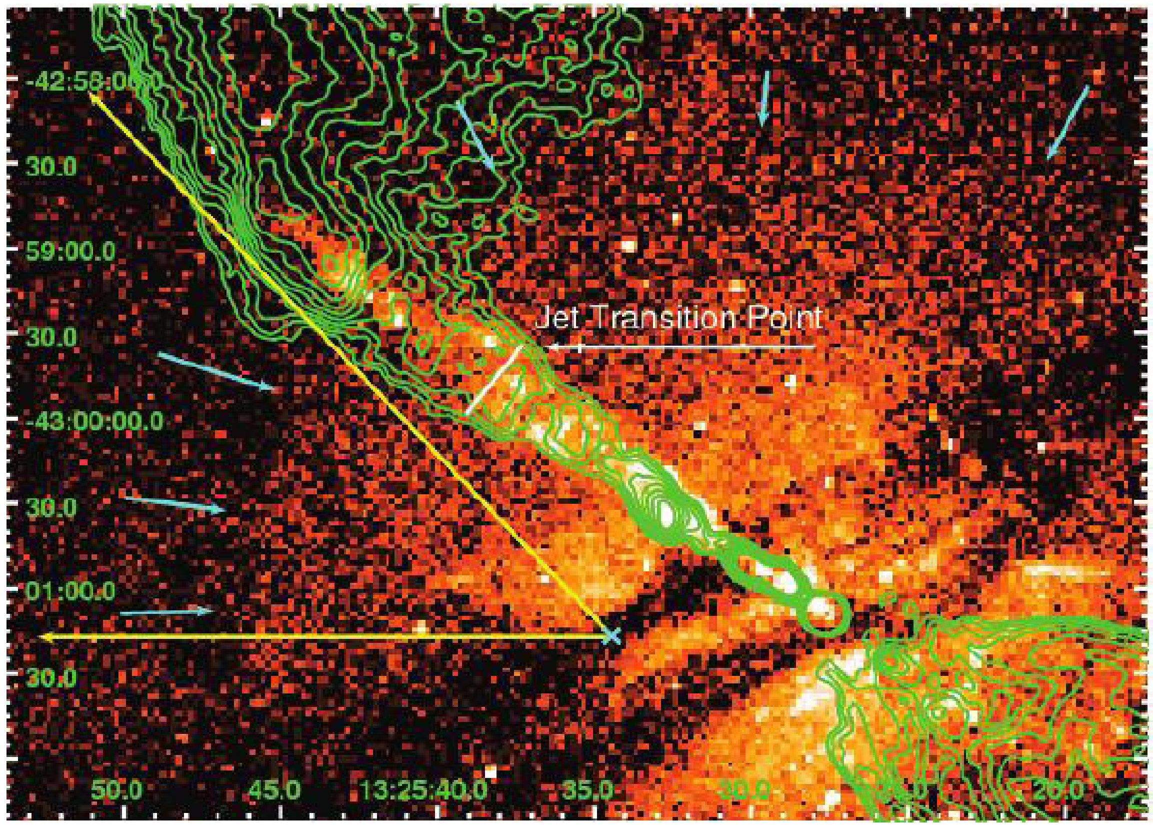


FIG. 2.—Raw *Chandra*/ACIS-I image of Cen A in the 0.5–1.0 keV band. The light blue arrows denote the approximate position of the surface brightness discontinuity in the gas. The light blue cross and yellow lines denote the wedge in which the surface brightness profile in Fig. 3 was created. The approximate position of the transition region of the jet (where the width of the X-ray jet narrows) is also labeled.

Figure 6 Cen A in X-rays. Source Hardcastle papers

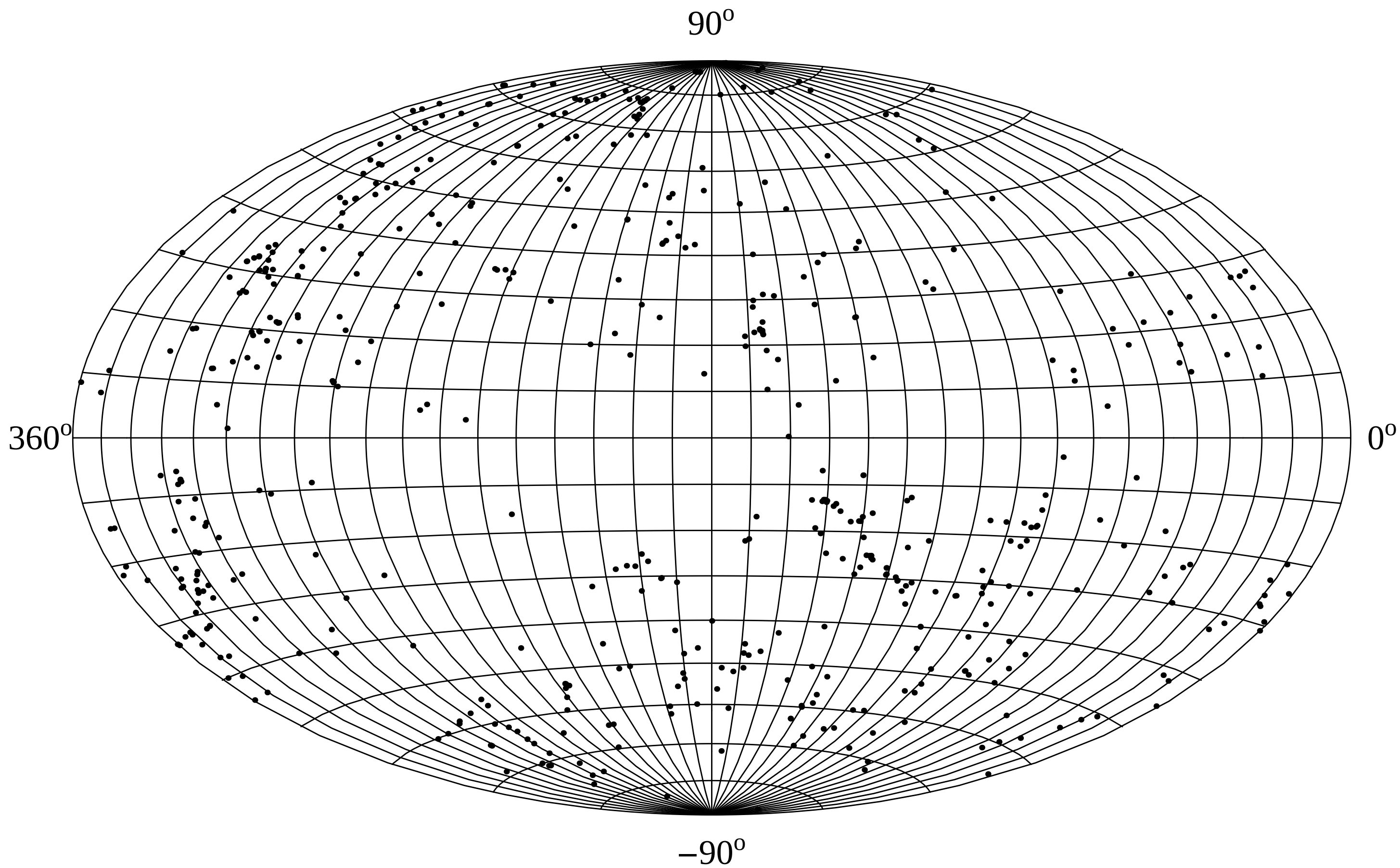


Figure 7 The sky in super-massive black holes, $> 3.10^8\ M_\odot$: Aitoff projection in galactic coordinates of 528 NED candidate sources in the case of a complete sub sample, massive Black Hole($M_{BH} > 3 * 10^8 M_\odot$). The choice was made from a complete sample of 10,284 candidate brighter than 0.03 Jy at 2 micron, and selected at z< 0.025: source L. Caramete

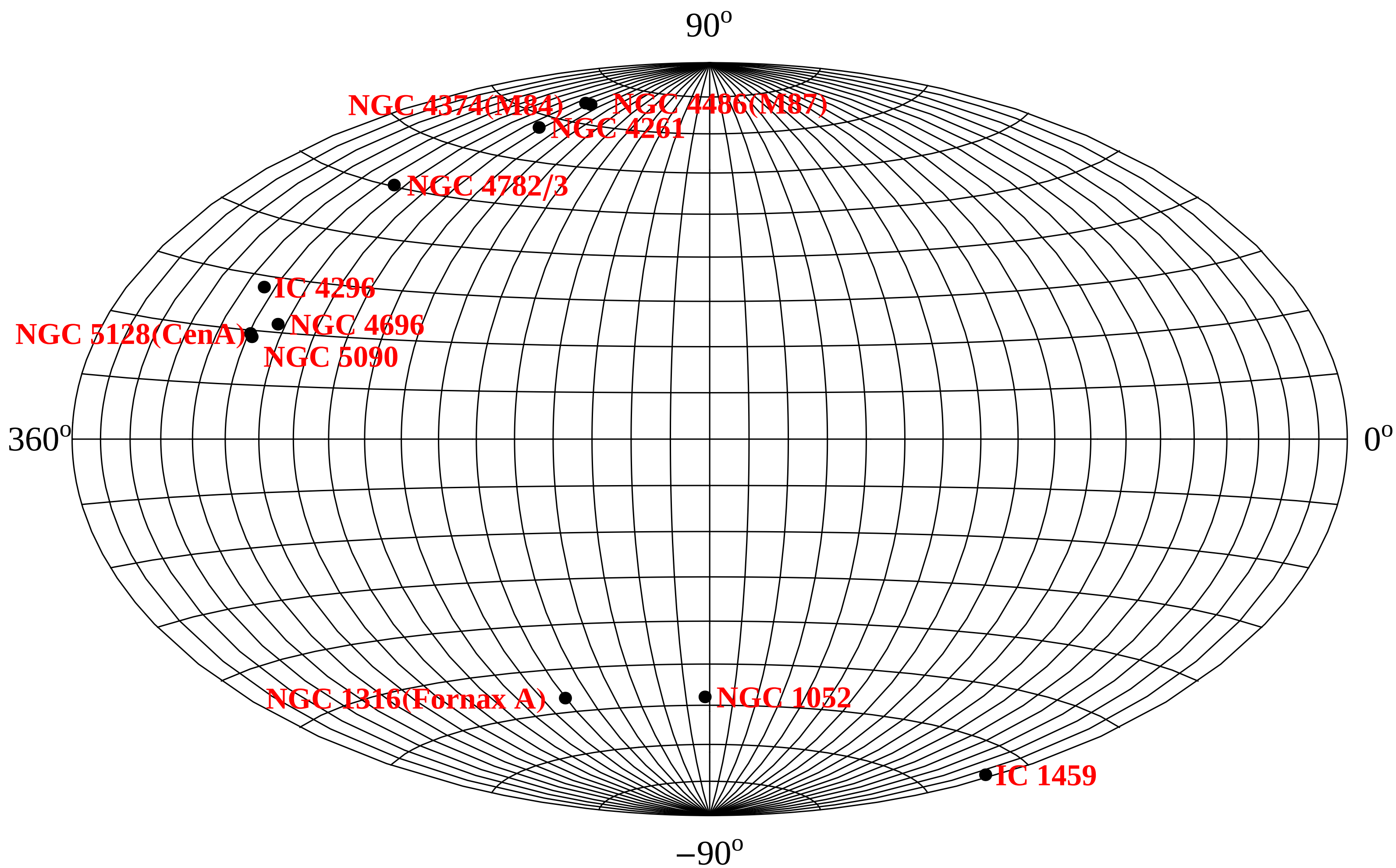


Figure 8 Aitoff projection of galactic coordinates of NED sample of 11 candidate sources from complete samples at 5GHz and 2 micron; this is our best estimate at present for the strongest sources of ultra high energy cosmic rays. The strongest contributors in such an all-sky survey are predicted to be Vir A (M87 = NGC4486), Cen A (NGC5128), and For A (NGC1316): source L. Caramete

Accretion vs. Spin-down: powering the jet

- Two limits to connecting relativistic jets to the central black holes:
- The accretion limit, when the magnetic field is governed by current accretion
- This approach describes well all active binary stars with black holes, low luminosity AGN, and some high activity AGN
- The spin-down limit, when the magnetic field is governed by past activity
- This seems to cover the vast majority of black holes - and observationally they are all active
- This pertains to extremely low levels of accretion
- The Poynting flux is the lower limit to the energy flow along jets, valid in the limit of negligible baryonic load

The baryonic load

- Energy flow over mass flow gives Lorentz factor: Today we think of typically 50 for AGN jets, but consider structured jets
- Example: 10^{45} erg/s, and $3 \cdot 10^{-4}\ M_{\odot}/yr$ imply a Lorentz factor of 50: single star wandering into jet?
- At such a Poynting flux, charged particles can be confined up to $Z\,10^{20}\,\mathrm{eV}$, where Z is their charge.
- Baryons from nearby star with wind can also feed accretion disk, probably a red giant star: believed to happen in our Galactic center
- Baryons from accretion disk, at about $0.1\,M_{\odot}/yr$ (efficiency for jet powering assumed at 10 percent) for this power

Deterministic chaos in emission?

- Jet as well as background stars (spectral peak at 2 μ) produce radiation field: photons
- Shocks in jet produce high energy ions, protons
- Interact with photons: producing new leptons of much higher energy than possible by straight acceleration
- Interact with magnetic fields and photons, make further leptons, further photons, cascade down in energy
- Basic exemplary equation (May *Nature* **261**, 459, 1976)

$$X_{i+1} = a\,X_i\,(1 - X_i) \qquad (1)$$

- X_i could be very high energy leptons at time i
- Chaotic region: $a = 3.57$ to $a = 4$
- One possible reason for extreme short term variability

Attempt to scale the neutrino production from the sources of ultra high energy cosmic rays (J. Becker):

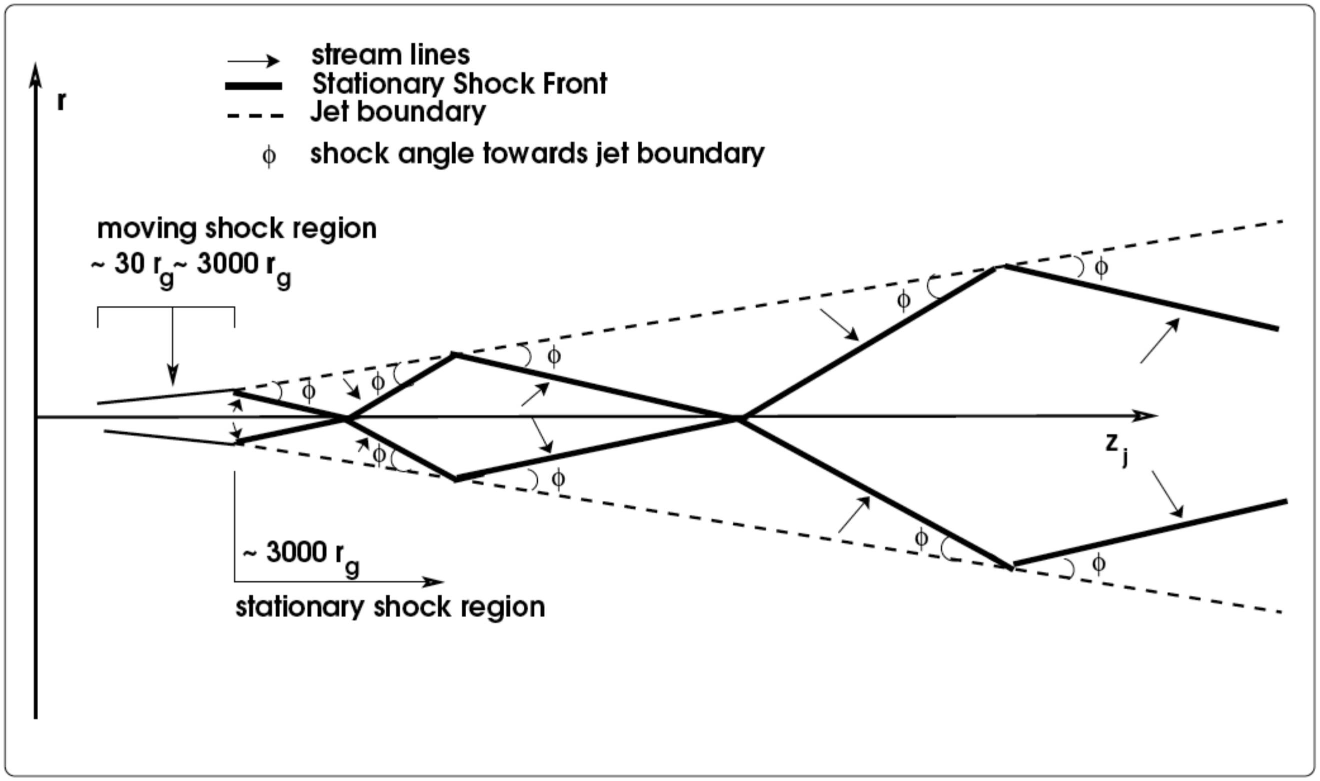


Fig. 1. Proposed conical shock structure in AGN jet.

Figure 9 A model for the compact jet structure. Source Becker & Biermann 2009

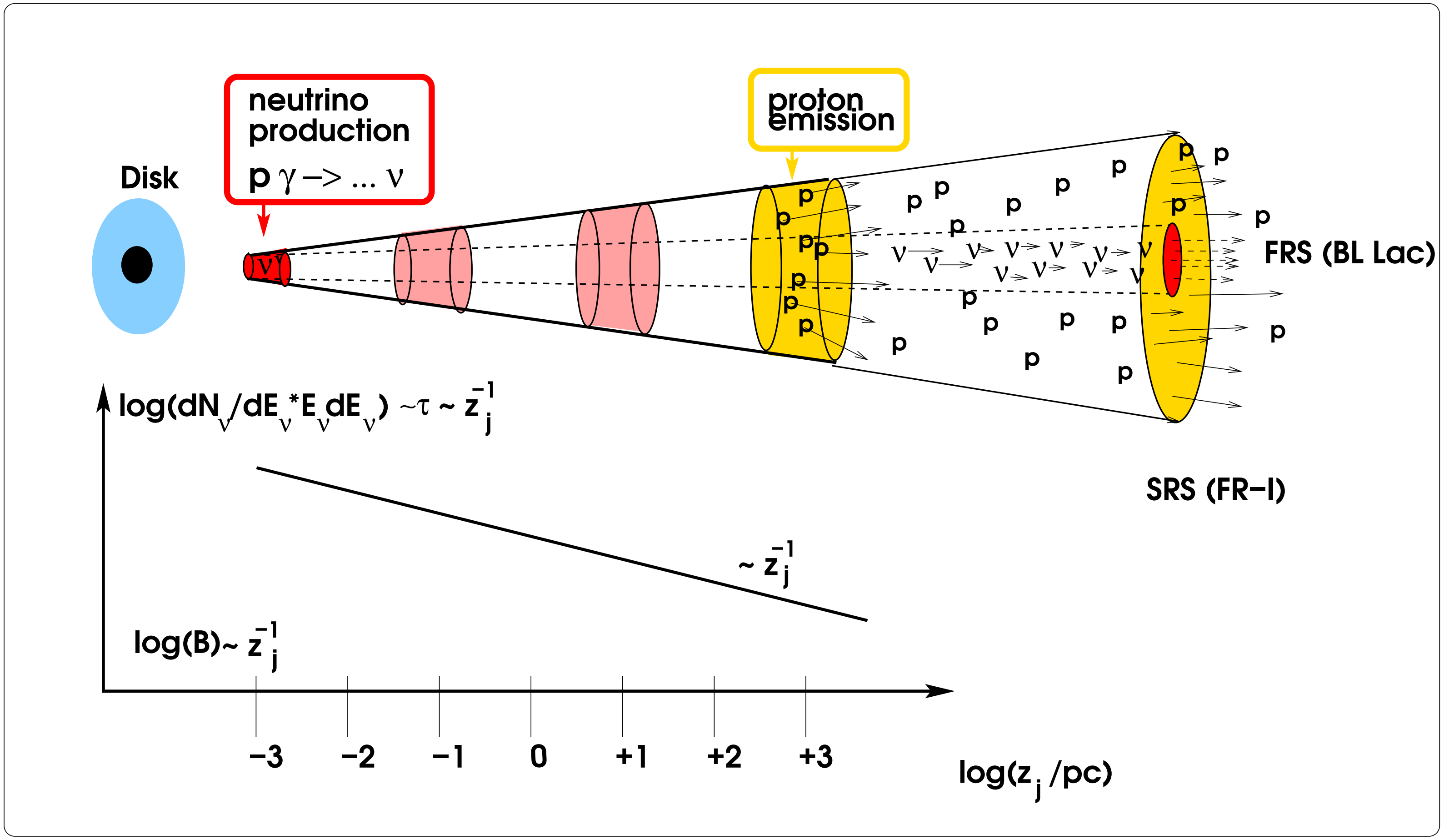


Figure 10 Neutrino production in AGN. Source Becker & Biermann 2009

- The largest interaction for ultra high energy **protons and ions** is at the first strong shock, near about 3000 r_g
- Ion-γ leads to single nucleons, second stage p-γ: Luminosity scales with $\tau_{ion\,\gamma} \times \tau_{p\,\gamma}$, so accentuates **flaring**!
- Charged pion decay also leads to very energetic electrons and positrons, that themselves also emit photons, covering a different photon energy range
- The resulting flux should scale with the **square** of the photon field. One could imagine a third stage, with IC on the resulting leptons, so third power possible
- In fact, all strong GeV and TeV sources are flat spectrum radio sources: all **highly variable**

Flat spectrum radio sources

predicted to be strong flaring neutrino emitters

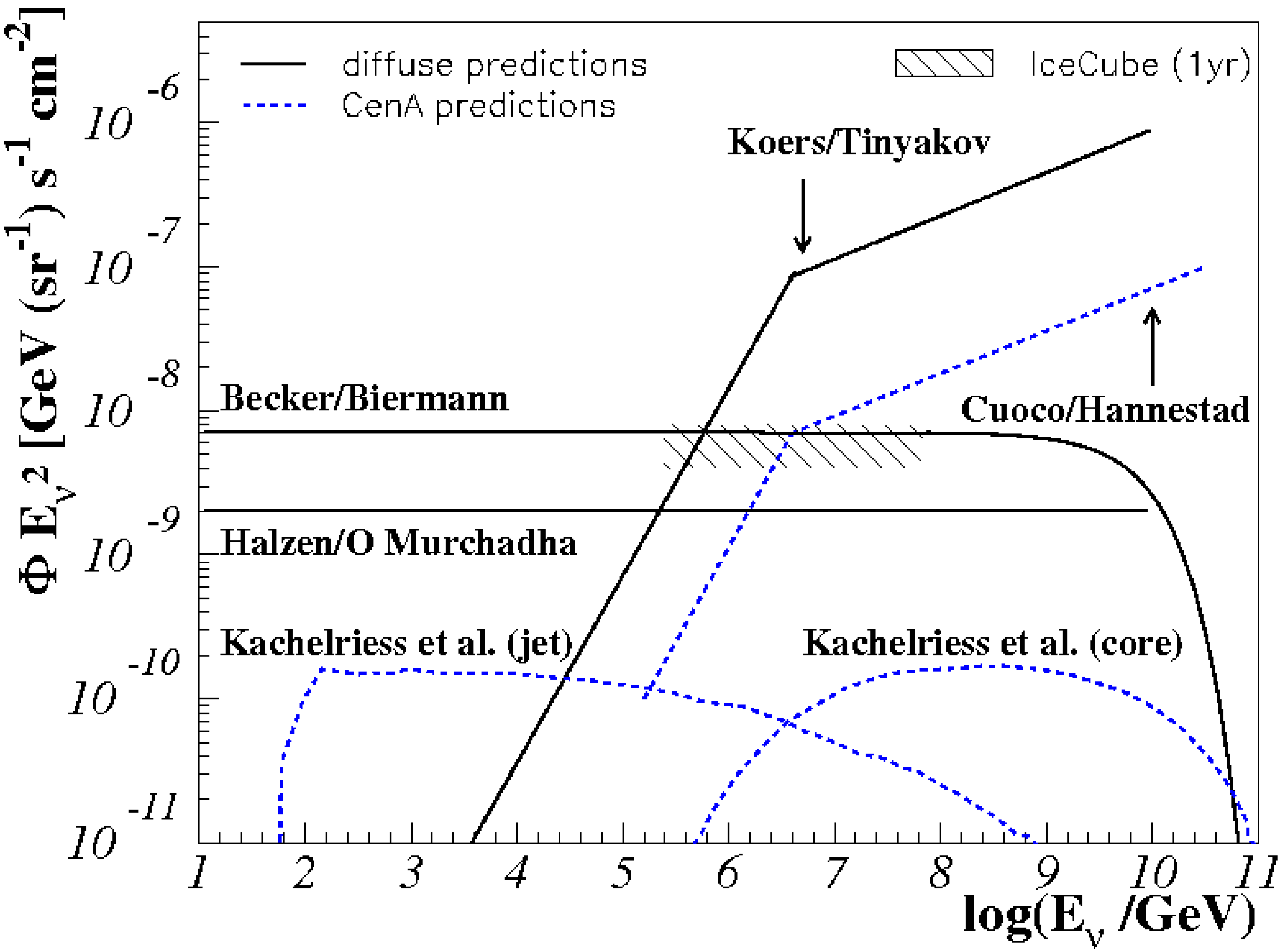


Figure 11 Predictions of extragalactic neutrinos

Ultra high energy neutrino source candidates

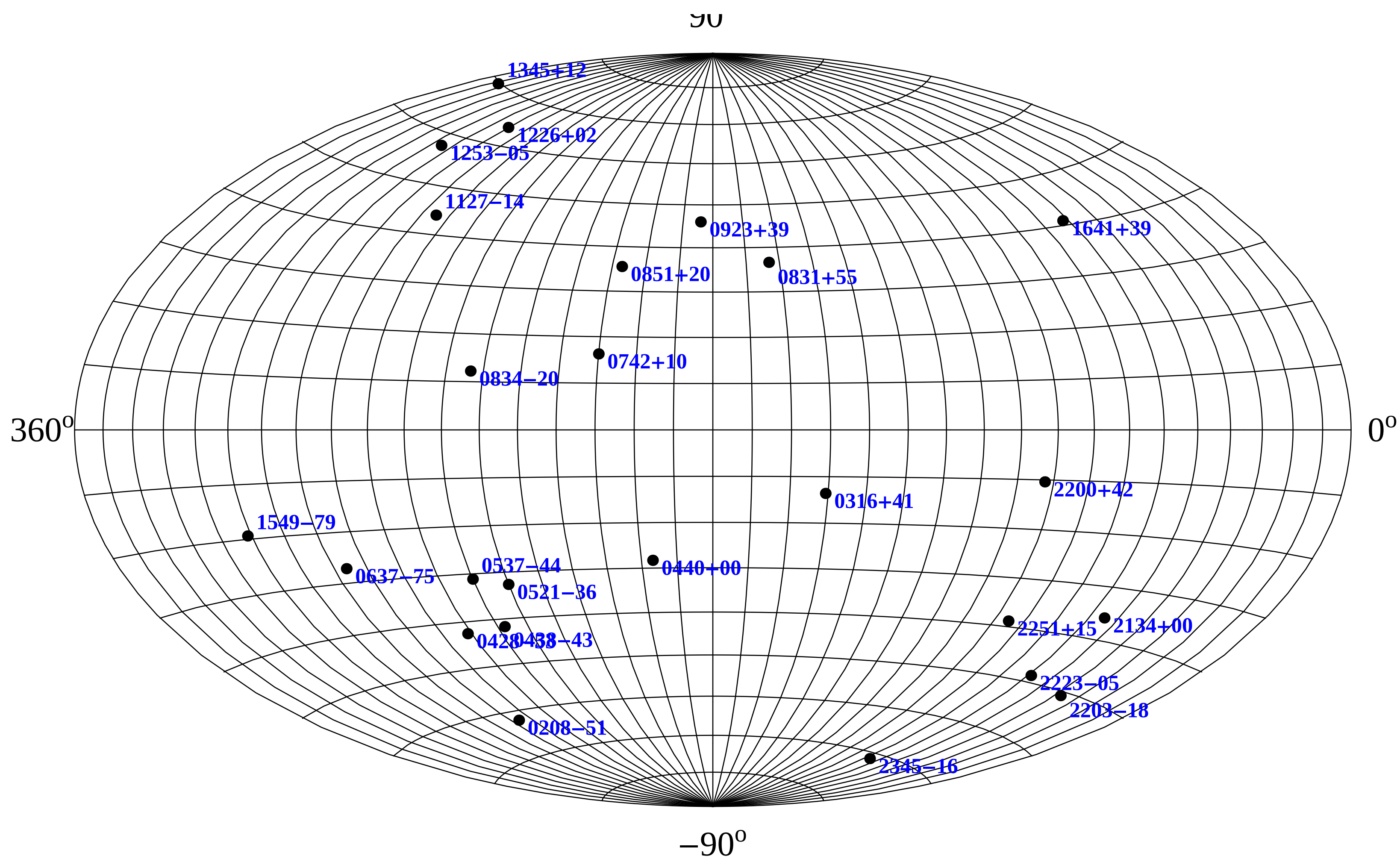


Figure 12 Aitoff projection in galactic coordinates of the 25 flat and inverted radio spectrum sources highest in flux density at 2.7 GHz. These sources are prime candidates to be ultra high energy neutrino and photon sources. 3C279 = 1253-05, see Mannheim et al. 1992

Key Concepts

- Three main source classes:
- 60 μ-selected sources, with FIR/Radio $\simeq$ 250, starbursts with lots of GRBs: prime example M82
- 5 GHZ selected radio sources with steep spectrum: UHECR source candidates: prime example Cen A
- 5 GHz selected flat spectrum radio sources: HE neutrino candidate sources: prime example 3C279
- Sources will be extremely variable, with spikes

Best bet: Flaring neutrino emission from

flat radio spectrum AGN

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