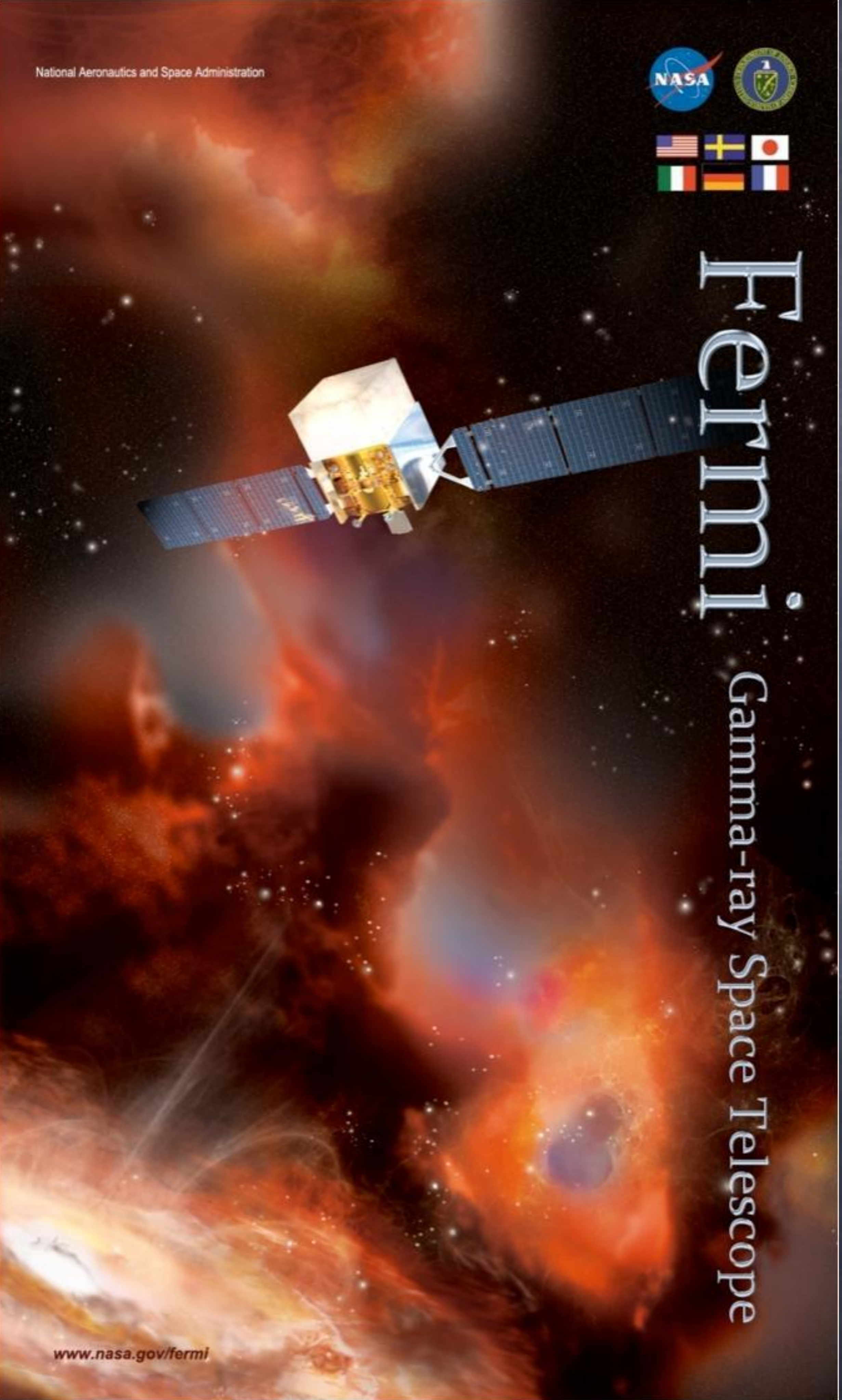


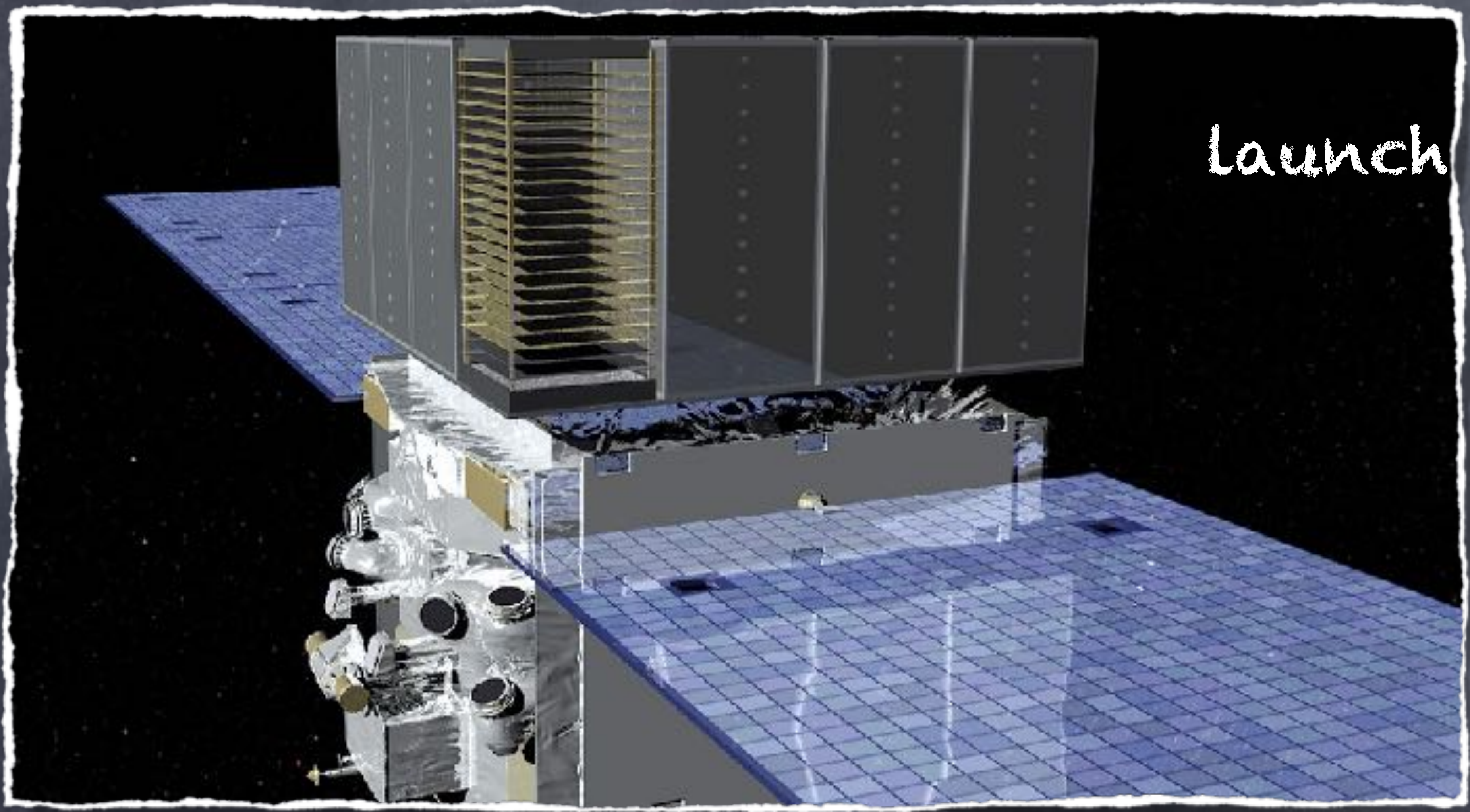
10 years of observations of the extragalactic sky with Fermi-LAT

Elisabetta Cavazzuti
on behalf the Fermi-LAT collaboration

Italian Space Agency

RICAP 2018

Fermi Large Area Telescope



launch June 11, 2008

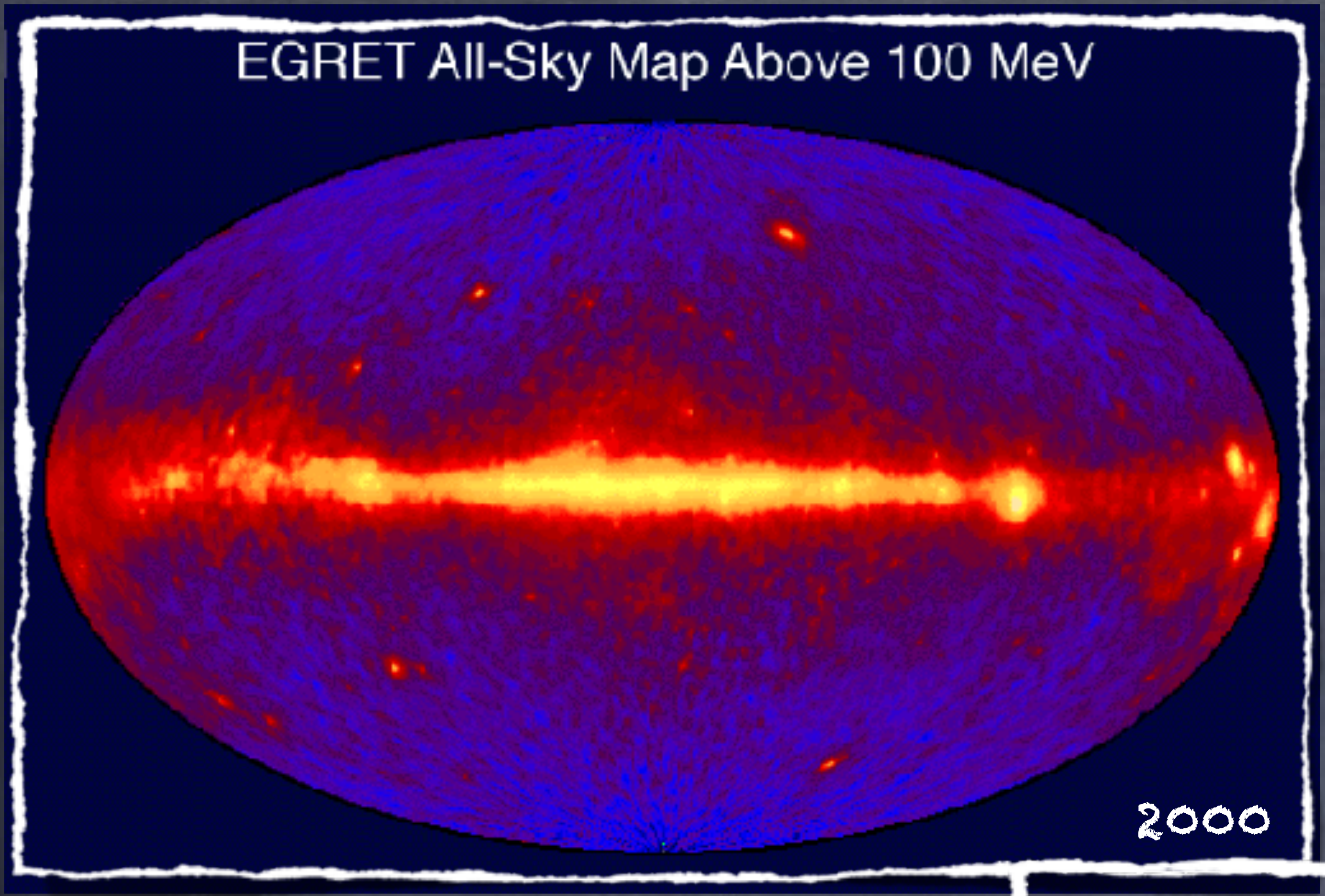
1- Converting and tracking system:
- convert an incident γ-ray to an e^+e^- pair
- reconstruct the γ-ray direction from the tracks of the pair

2- Calorimeter:
- measure the photon energy

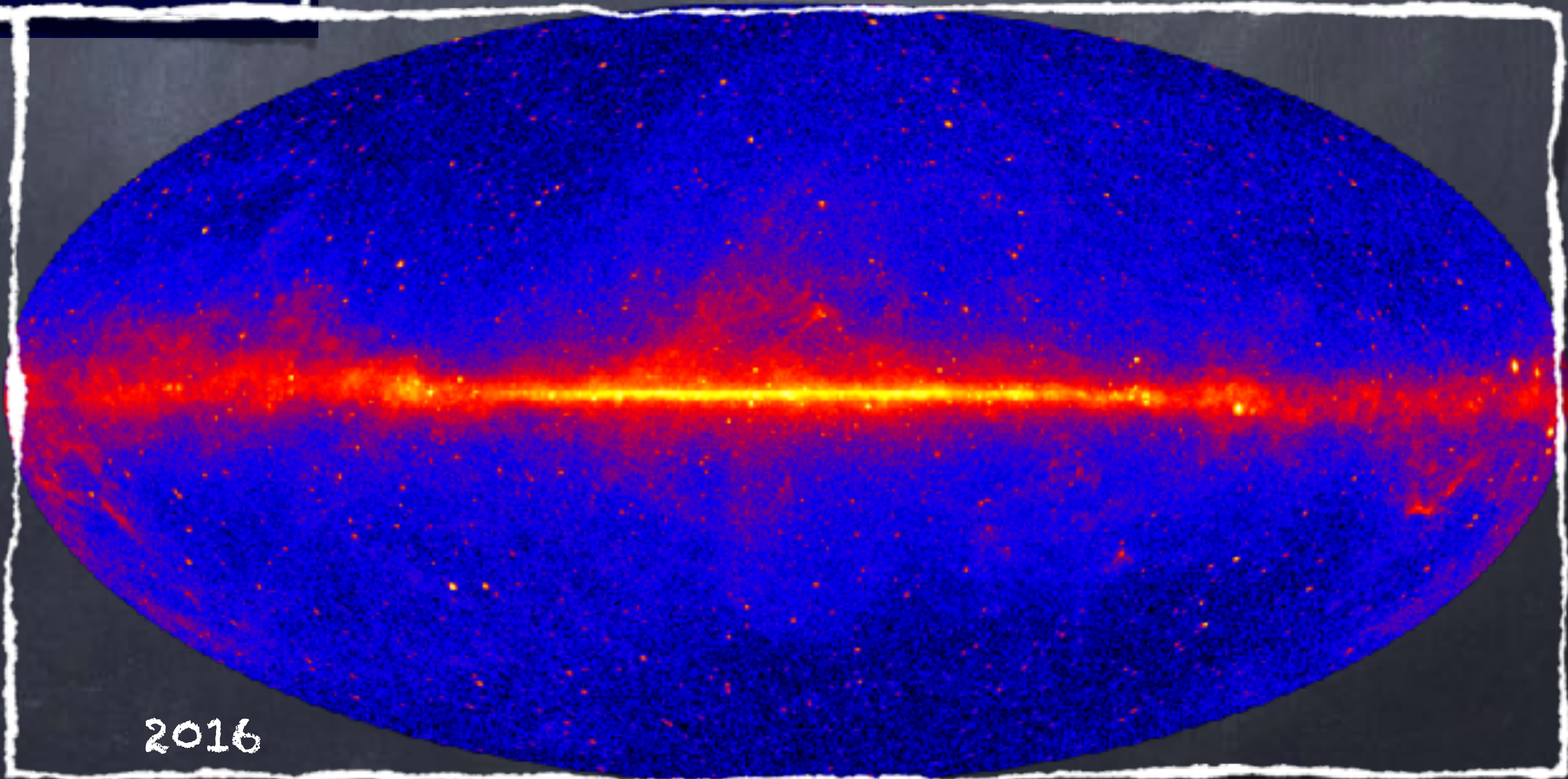
3- Anti-coincidence detector:
- limit the cosmic-ray background

* Large effective area (~ 0.9 m2 above 1 GeV)
* Low dead time (~27 μs)
* Wide field of view (2.4 sr, i.e. 20% of the sky)

Fermi Large Area Telescope



Fermi-LAT All-Sky Map Above 1 GeV



Fermi Gamma-ray Space Telescope

Catalogs drive other studies

logN-logS

Long term studies

γ-ray vs non γ-ray sources

LF

MW timing correlation

catalog

EBL

new SNR

EGB

new PSR

unresolved Galactic sources

new generation of diffuse Galactic emission

LAT general catalogs (FGLs, FHLs)

* Purely gamma-ray based (associations only post facto)
* Detection over time-integrated data set (scanning the sky permanently)
* 0/1/2/3FGL: full energy range (> 100 MeV)
* 1/2/3FHL: high-energy only (> 10 / 50 GeV)
* Each generation has used improved data/calibration: P6 -> P7 -> P7Rep -> P8

FGLs and FHLs

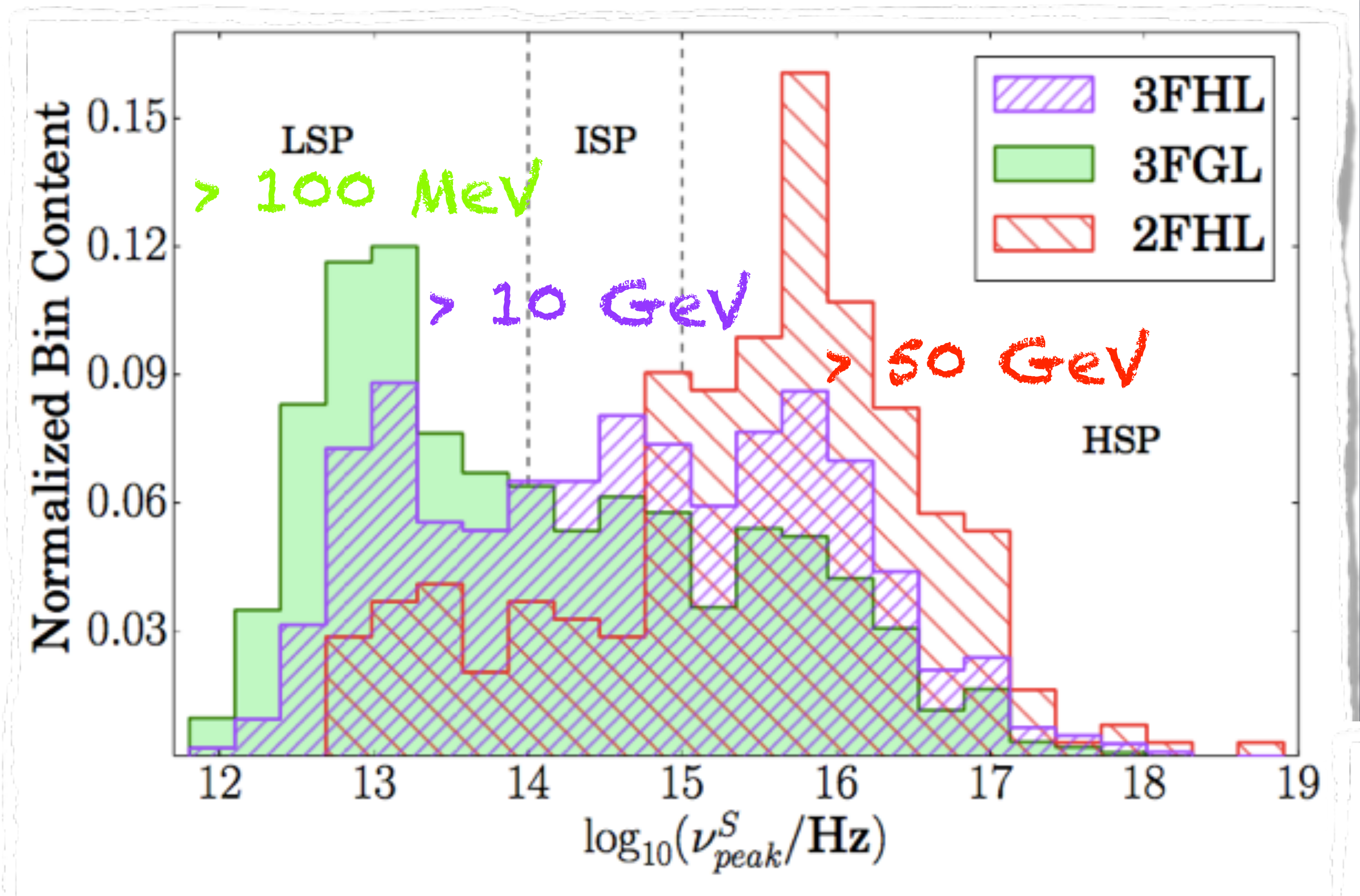
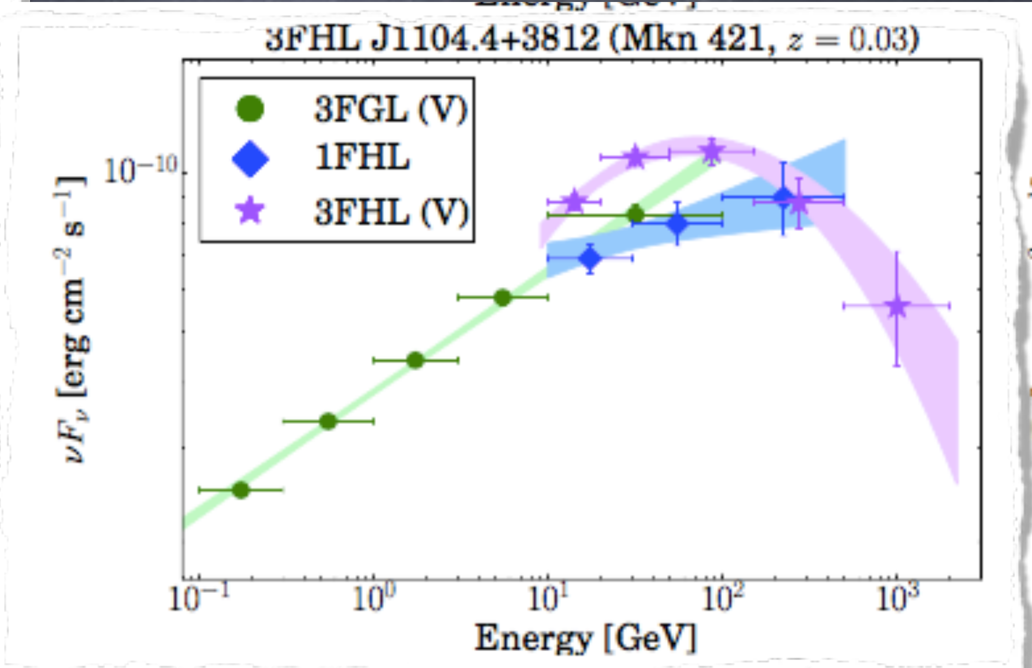
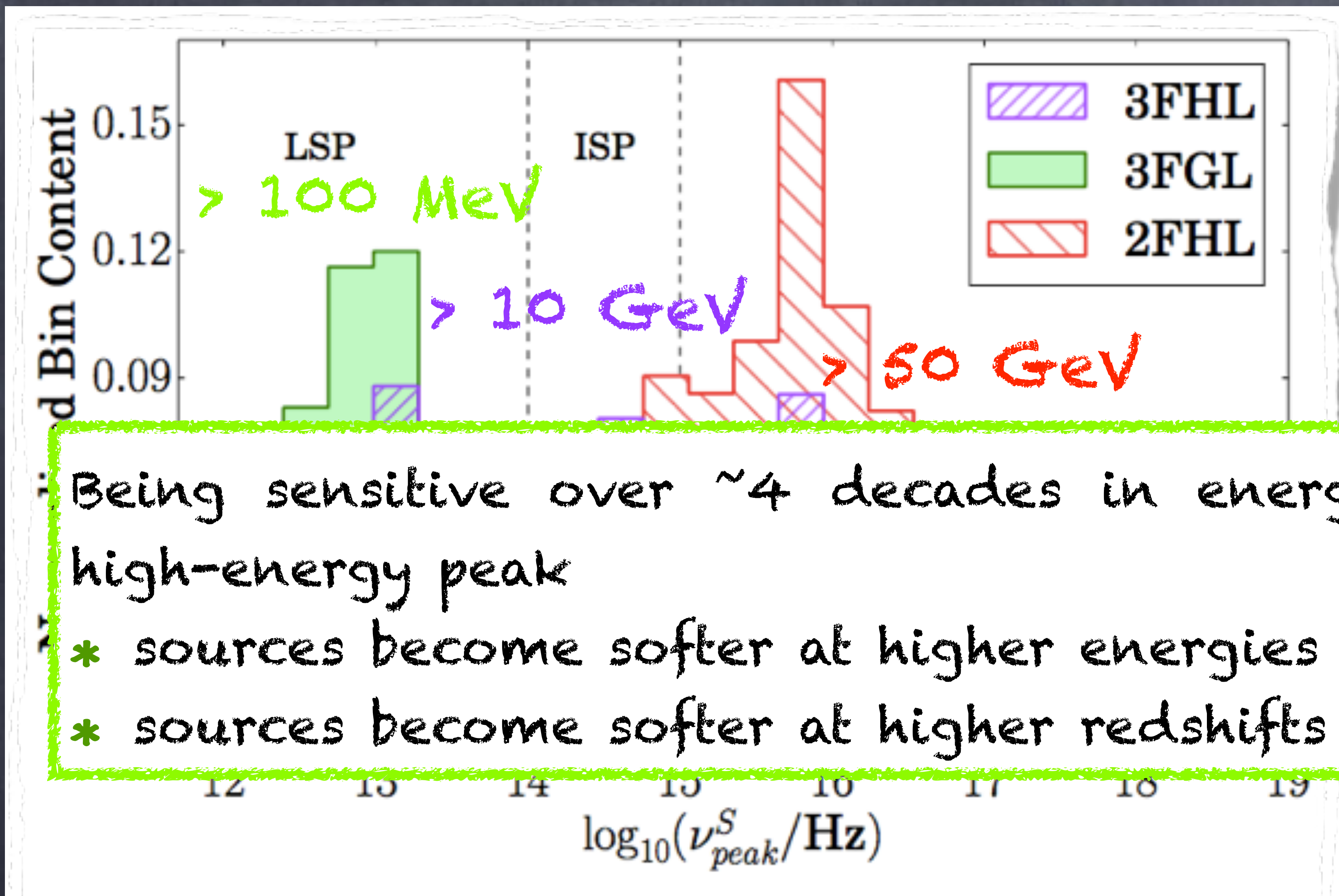


Fig. 14.— Normalized distributions of the frequency of the synchrotron peak for the blazars detected in th 3FGL (0.1–300 GeV), 2FHL (50 GeV–2 TeV), and 3FHL (10 GeV–2 TeV) catalogs.



Ajello, M. et al 2017

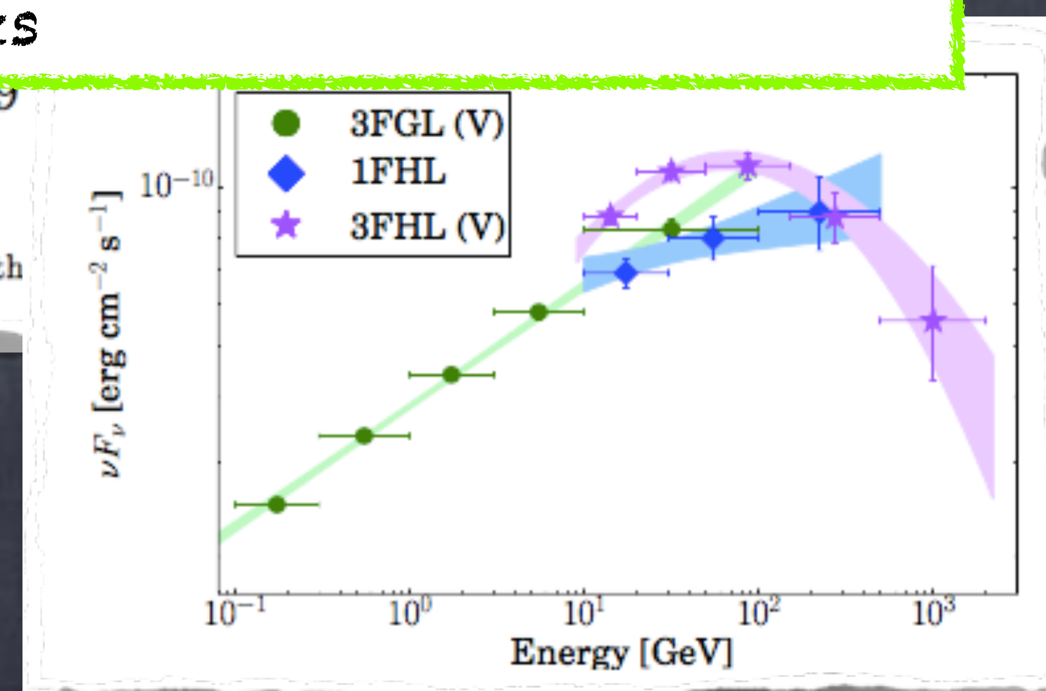
FGLs and FHLs



Being sensitive over ~4 decades in energy, the LAT resolves the high-energy peak

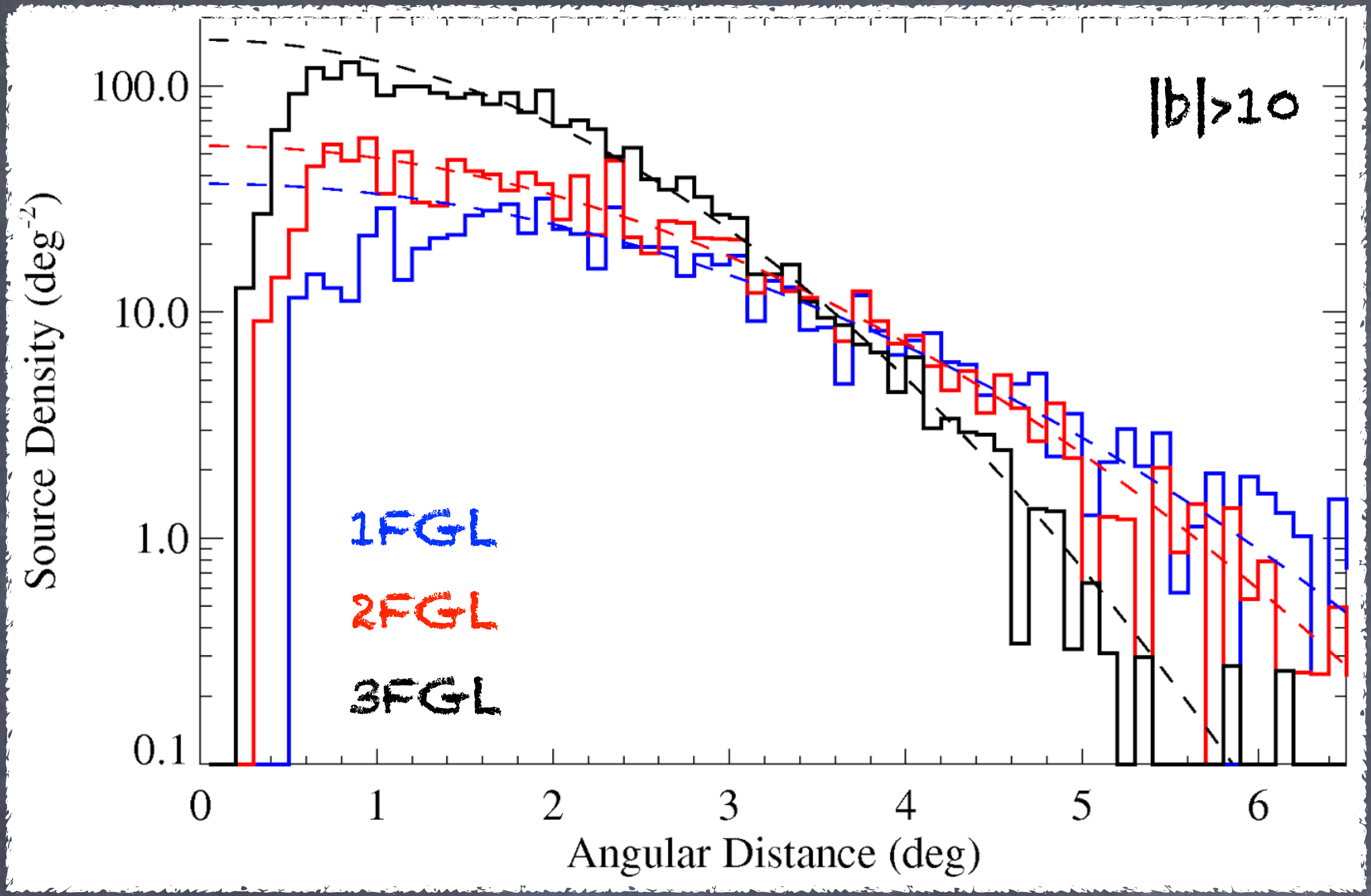
- sources become softer at higher energies
- sources become softer at higher redshifts

Fig. 14.— Normalized distributions of the frequency of the synchrotron peak for the blazars detected in th 3FGL (0.1–300 GeV), 2FHL (50 GeV–2 TeV), and 3FHL (10 GeV–2 TeV) catalogs.



Ajello, M. et al 2017

Distance to the nearest neighbors

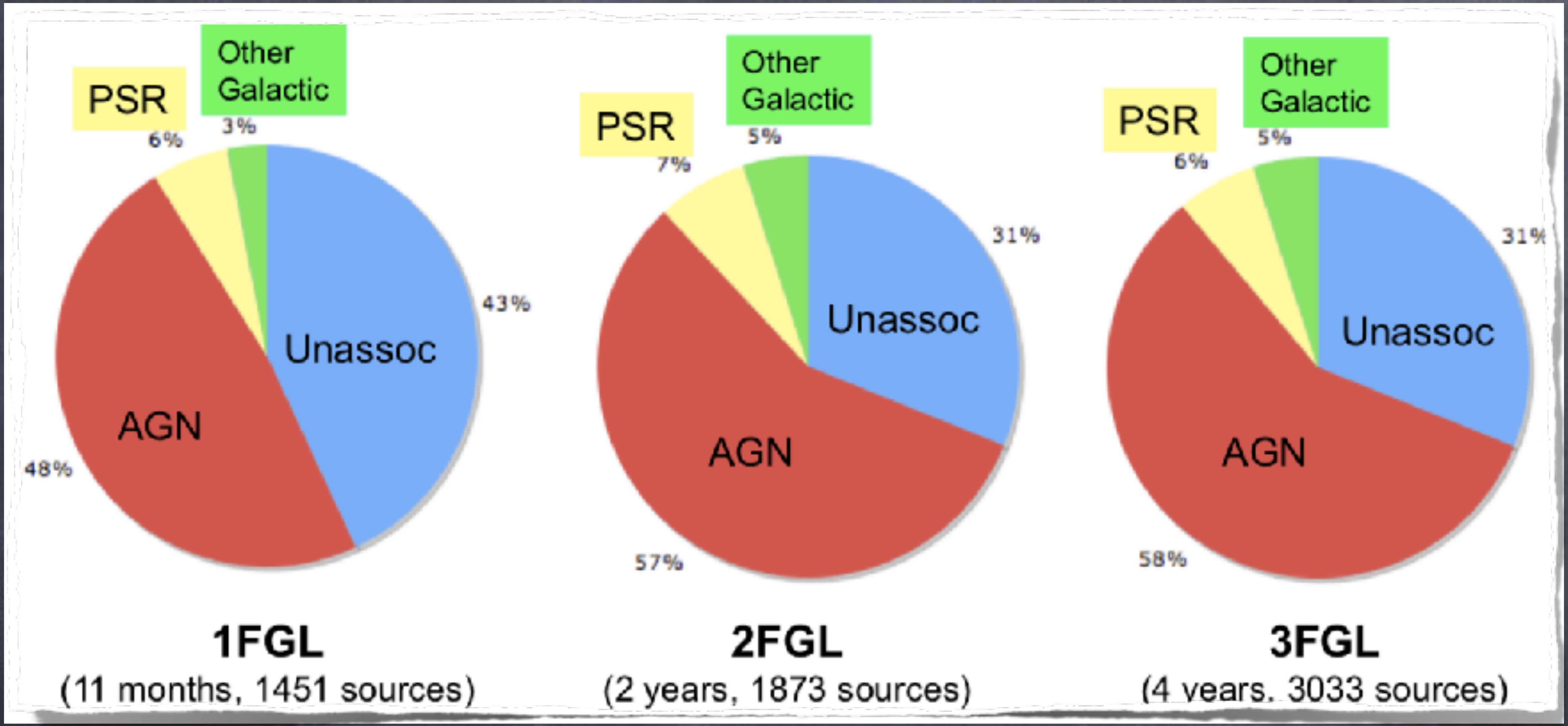


3FGL - number of missing closely-spaced sources is ~6% of the estimated true source count. For the 2FGL catalogue the fraction was only 3.3%.

Despite the reconstruction improvements, the larger number of detected sources is now pushing the main LAT catalogues into the confusion limit even outside the Galactic plane.

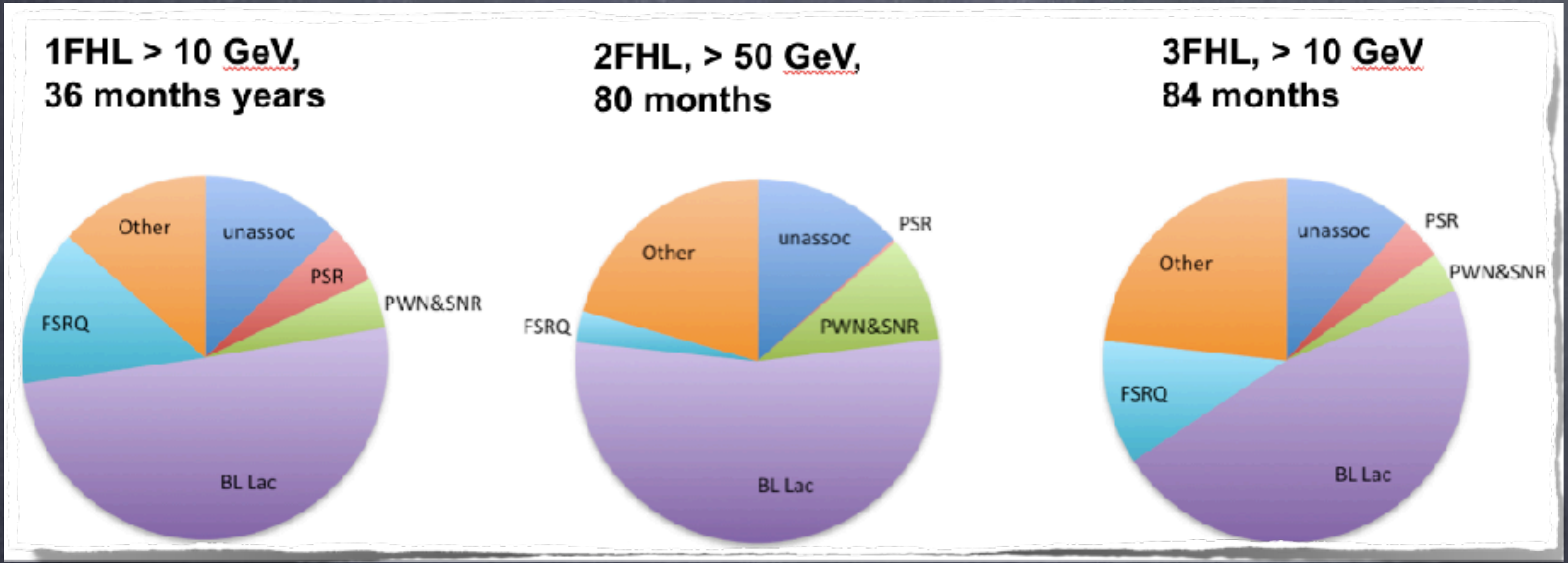
Because the effect of confusion goes as the square of the source density, the expected number of sources above the detection threshold within 0°.5 of another one (most of which are not resolved) has increased by a factor 3 between 2FGL and 3FGL.

Source association - FGLs



ongoing effort on deepening counterpart catalogs

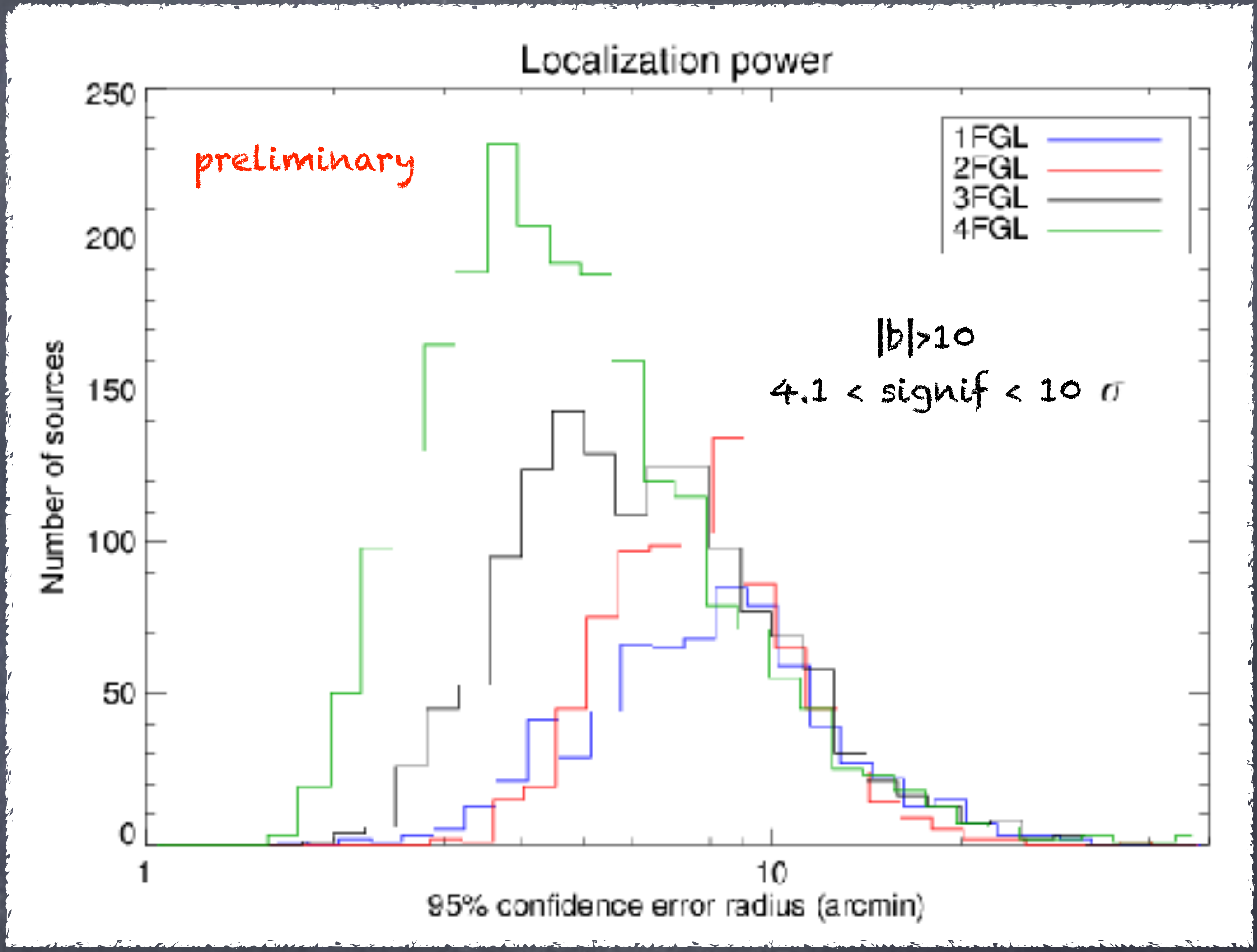
Source association - FHLs



much fewer unassociated sources in FHLs wrt FGLs

Toward 4FGL

- Localization of faint sources (critical for associations) continues to improve
- Median error radius at 25 < TS < 100 is 4.5 arcmin
- Systematic factor 1.05 on error radius (as in 3FGL)
- Absolute 95% systematic error: 27 arcsec (as in 3FHL)

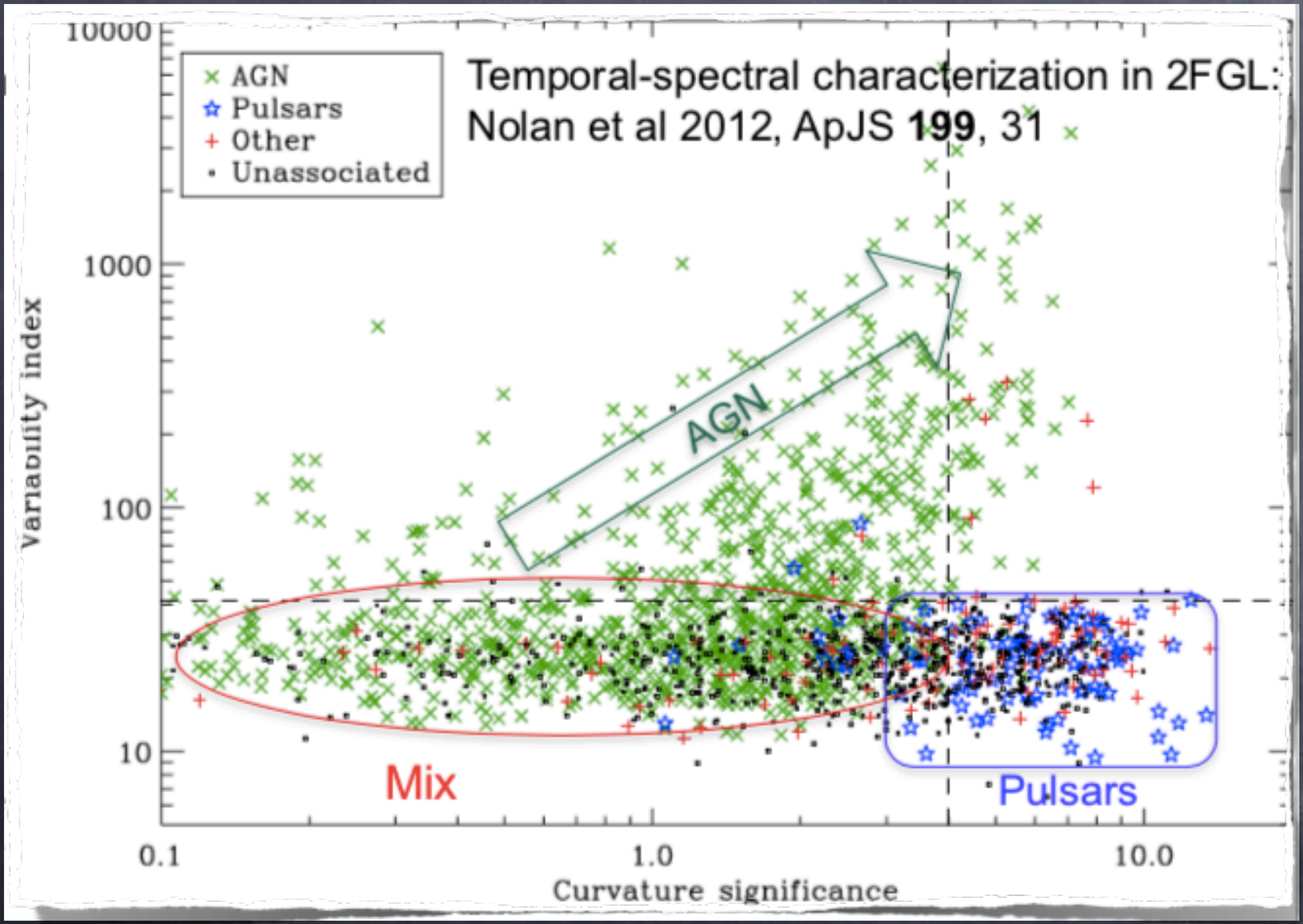


Detection uses TSmap assuming several spectral shapes

> 13,000 seeds with TS>10

FL8Y (and 4FGL) contains ~ 5000 TS>25 sources

Statistical assessments of UNASSOC



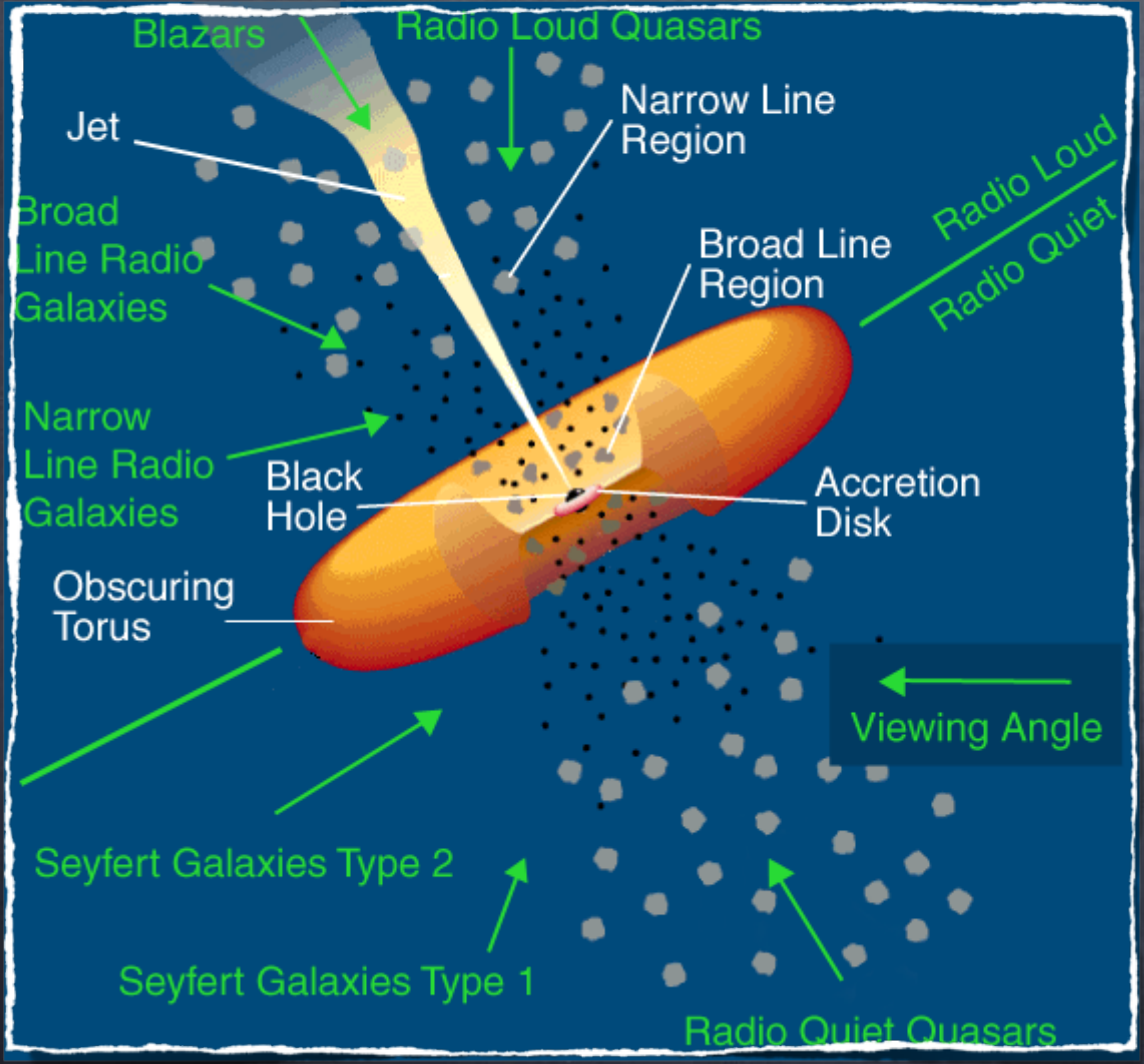
* Concentrate MW efforts on what is most promising
* Use all γ-ray information (particularly variability, spectral curvature) to feed classification algorithms,
* learning from known associations

Difficulty: Training sample (brighter) has smaller error bars than most UNASSOCs

Catalog-driven studies in the extragalactic sky

AGN UNIFIED SCHEME

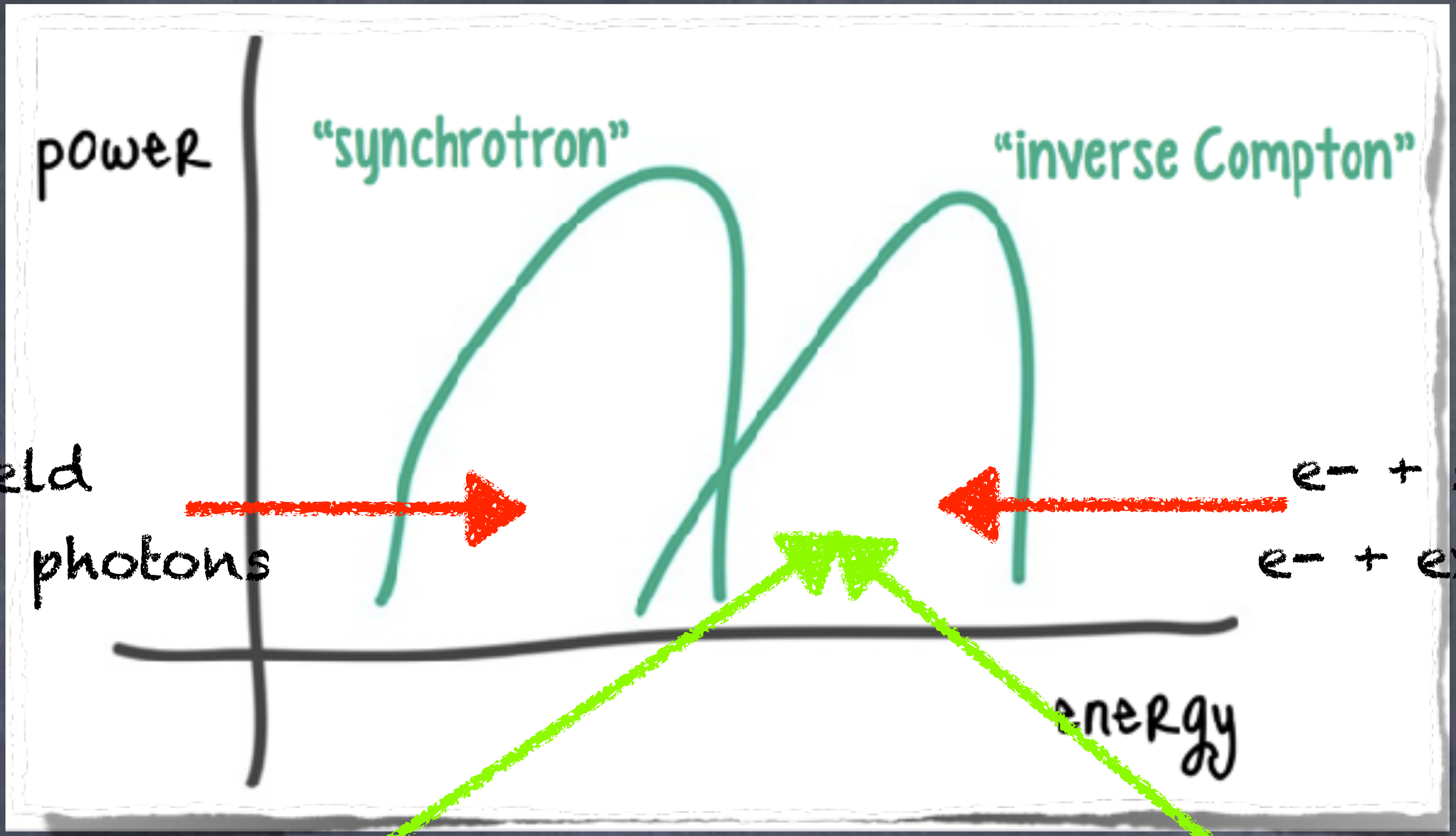
~ 1995



blazars dominate the extragalactic sky in a number of observational windows (u-wave, hard X-ray, γ-ray, TeV)

Urry, Padovani 1995

EMISSION MODELS



e- + B field
=> synchrotron photons

e- + synch. photons
e- + external photons

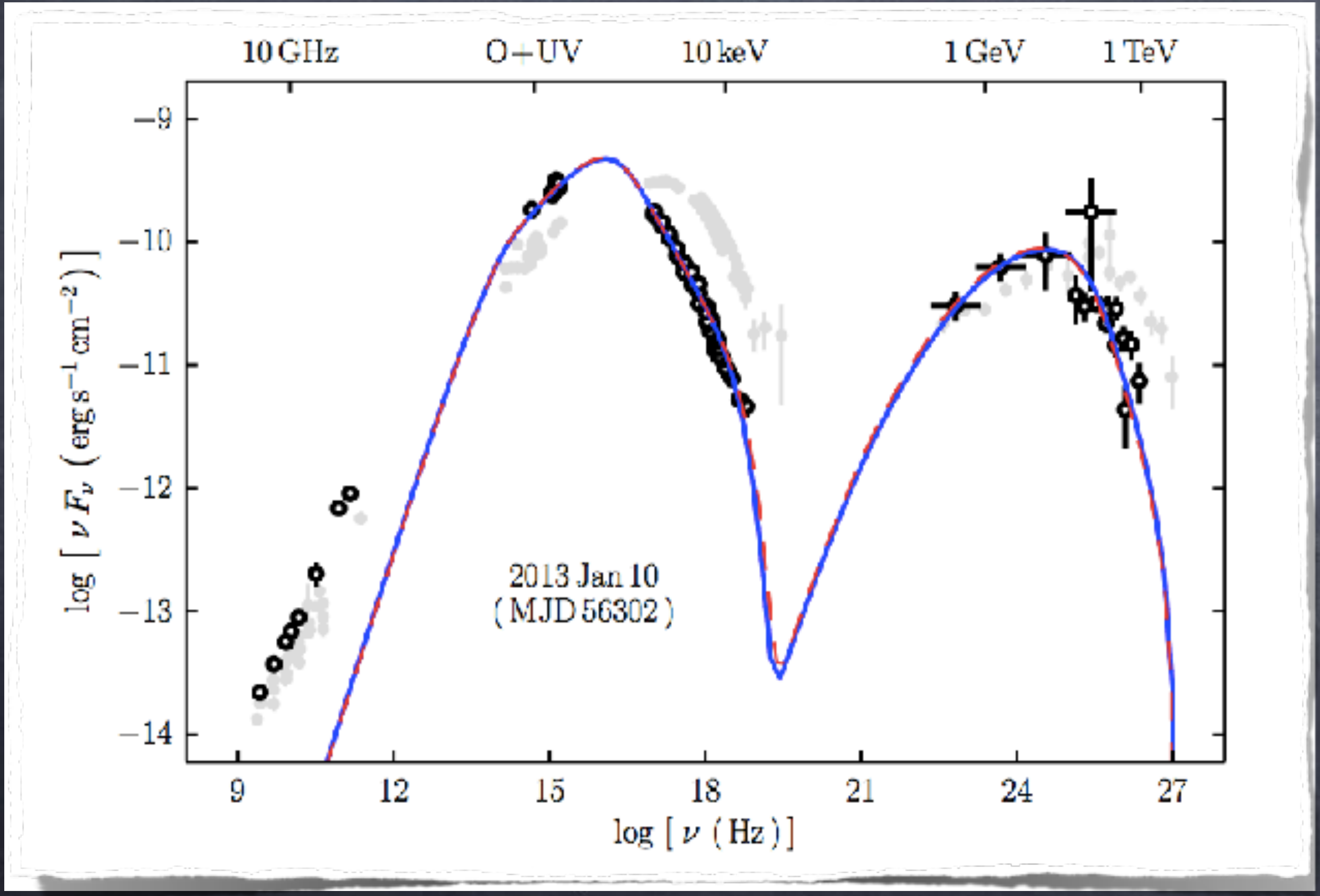
LEPTONIC

radiative output dominated by e^-/e^+ high-energy photons most likely the result of inverse Compton scattering by the same e- that produced the synchrotron

HADRONIC

both e^-/e^+ and p accelerated to ultra-relativistic energies
p's exceed threshold for pγ photo-pion production on soft photon field in emission region

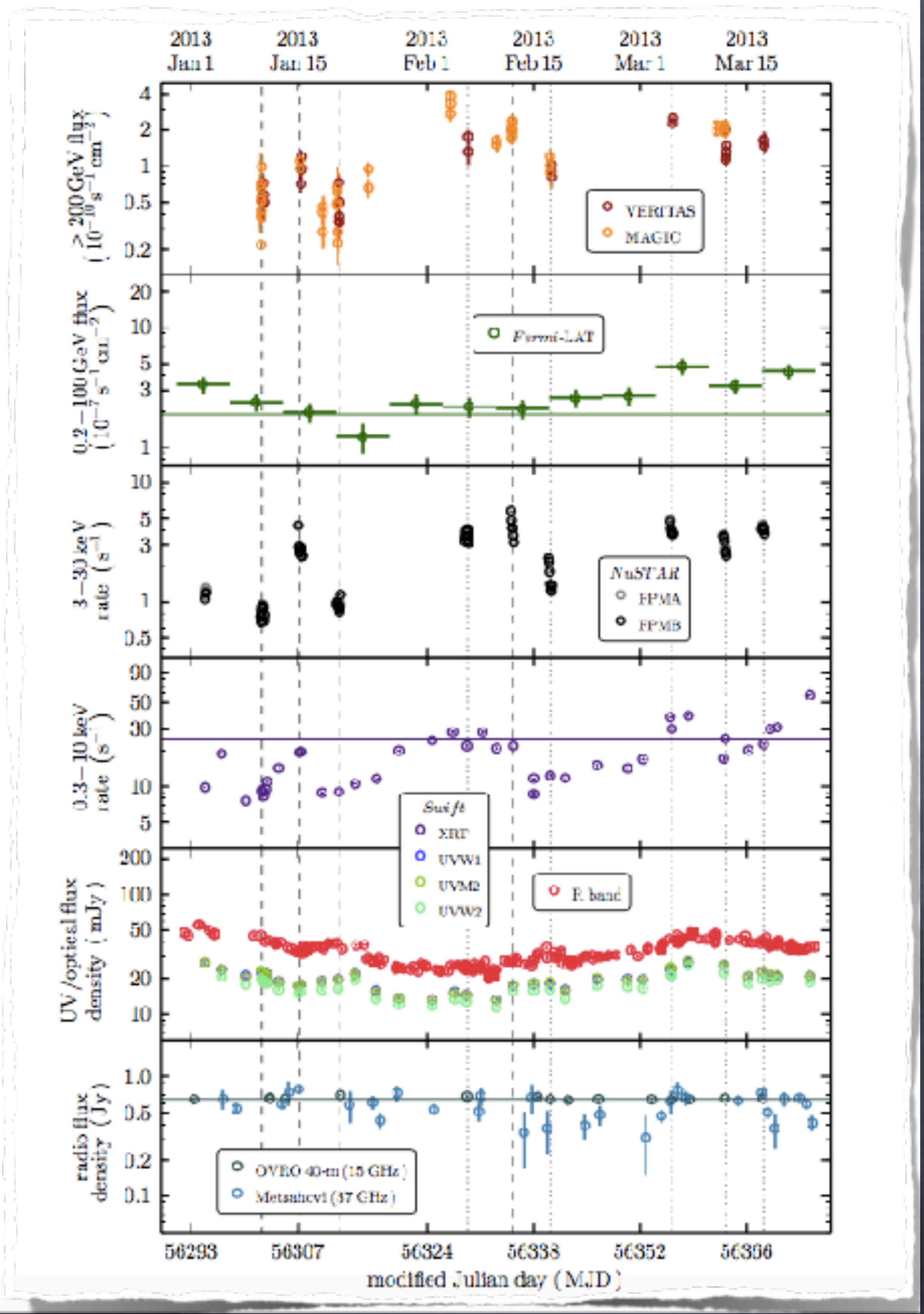
leptonic models provide good fits to many blazars



Mkn 421
HSP BL Lac

Bolokovic et al 2016, ApJ 819, 156

EMISSION MODELS vs OBSERVATIONS



- leptonic models provide good fits to many blazars
- X-ray and γ-ray emission often correlated - a fact naturally explained by SSC models

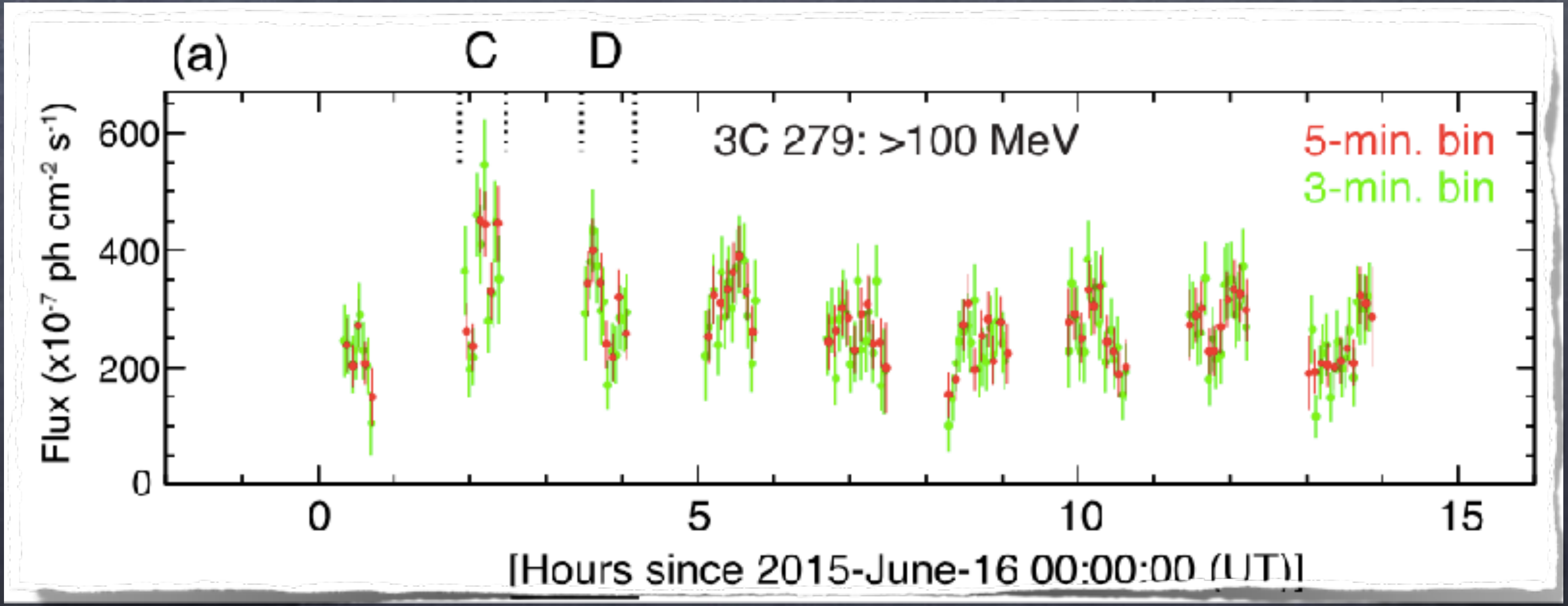
Mkn 421
HSP BL Lac

Bolokovic et al 2016, ApJ 819, 156

EMISSION MODELS vs OBSERVATIONS

- in hadronic models, the cooling times are longer, which makes it more difficult to explain the rapid variability often seen in blazars
- proton synchrotron can produce rapid variability with very high energy protons in extremely magnetised, compact regions

3C 279
FSRQ



Ackerman+ ApJL, 824, L20 2016

EMISSION MODELS vs OBSERVATIONS

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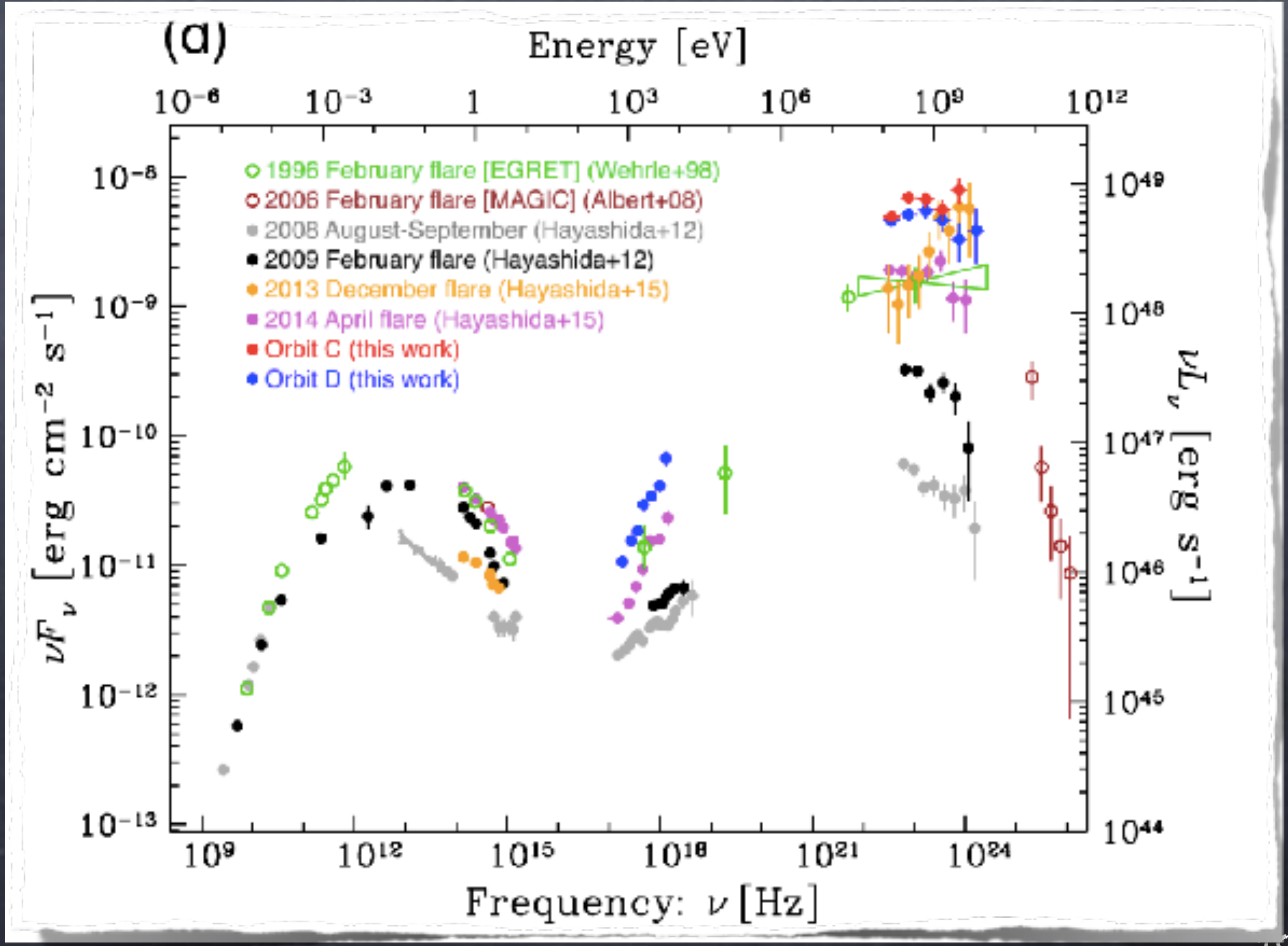
3C 279
FSRQ



Ackerman+ ApJL, 824, L20 2016

EMISSION MODELS vs OBSERVATIONS

in many cases leptonic and hadronic models can produce equally good fits to SED

possible diagnostic: variability, X/gamma polarization, neutrinos

-> time dependent leptonic one-zone models produce correlated synchro-gamma variability (eg Mkn 421), X-ray behind gamma-ray by few hours, optical lead gamma-ray by few hours

-> time dependent hadronic models can produce uncorrelated variability, orphan flares

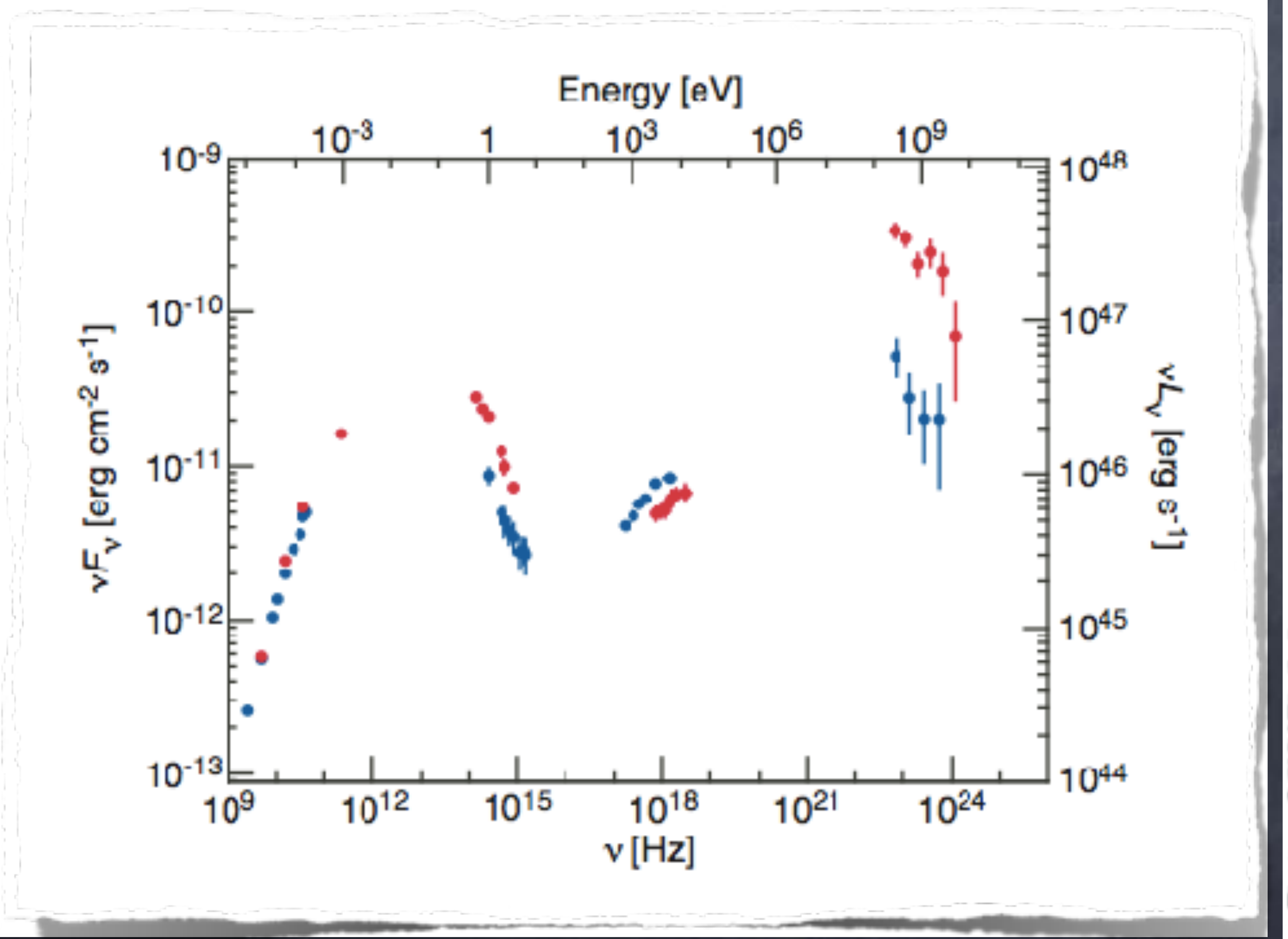
EMISSION MODELS vs OBSERVATIONS

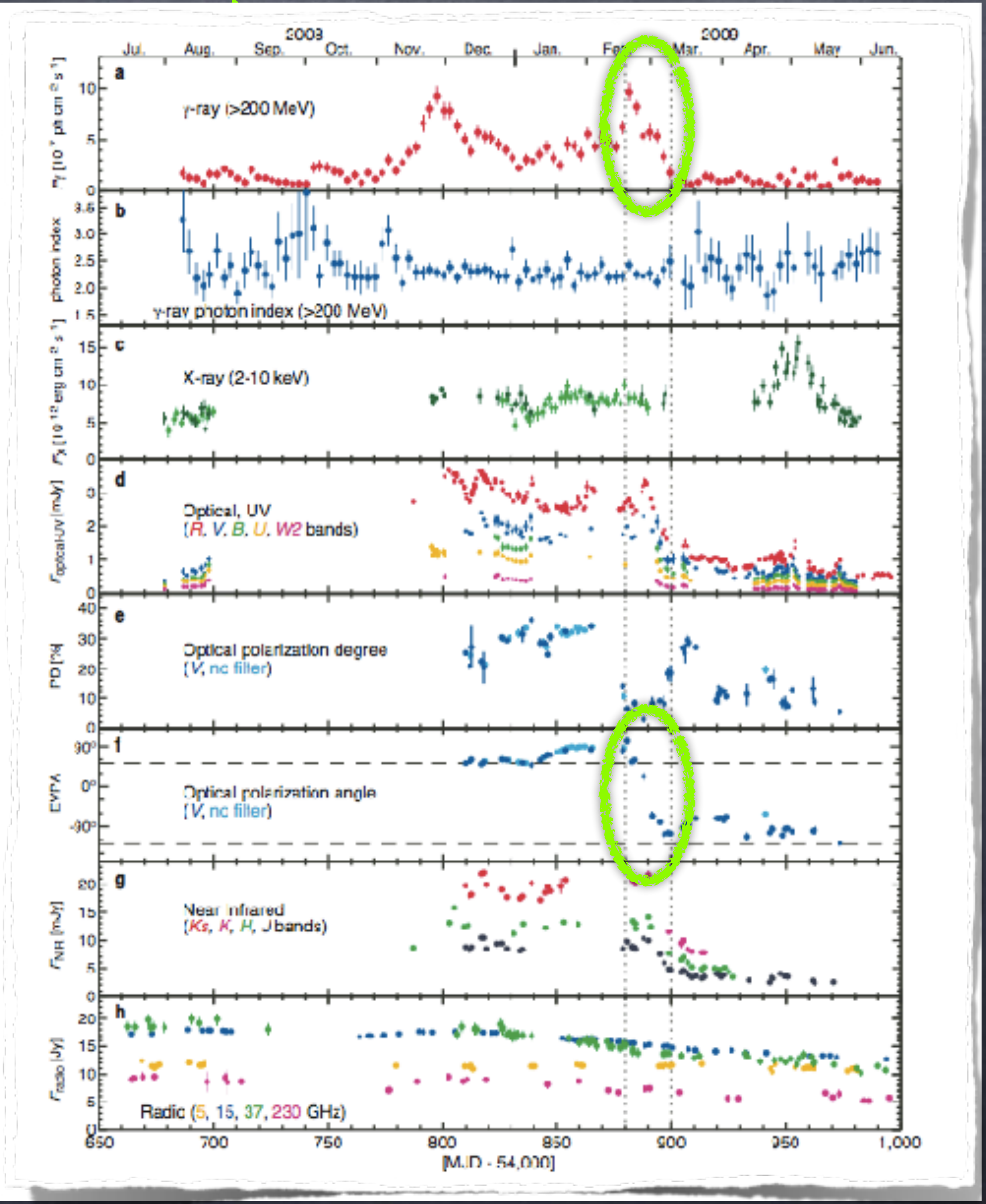
possible diagnostic: variability, X/gamma polarization, neutrinos

polarisation swing

co-spatial optical and γ-ray emitting regions

3C 279



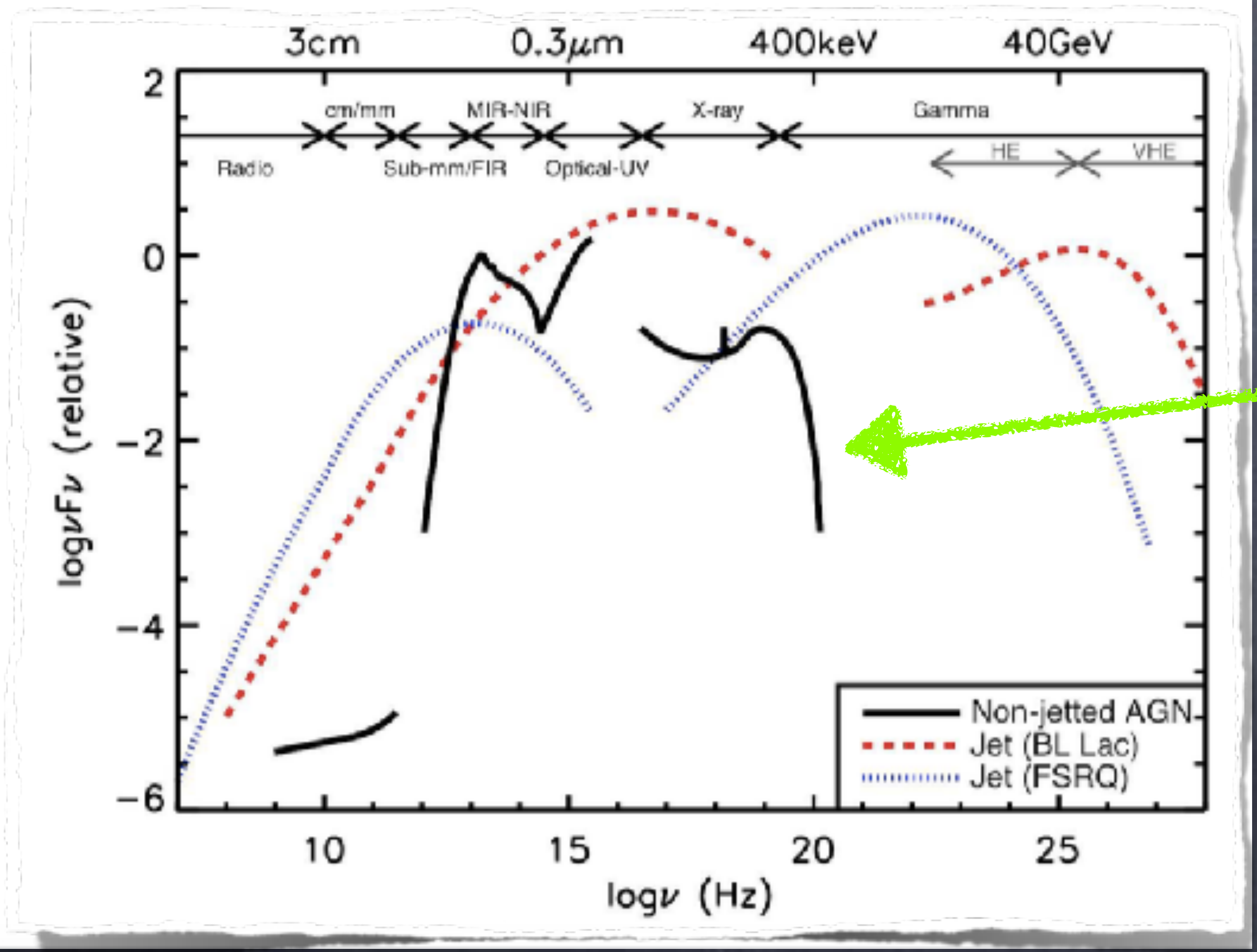


Abdo+ Nature, 2010

~ 2017

all this might be superseded by a better knowledge of the sky thanks to more sensitive instruments, such as Fermi, deep radio surveys and hopefully soon X-ray surveys based on a fundamentally physical rather than just an observational difference, => the presence (or lack) of strong relativistic jets

"jetted" and "non-jetted" AGN



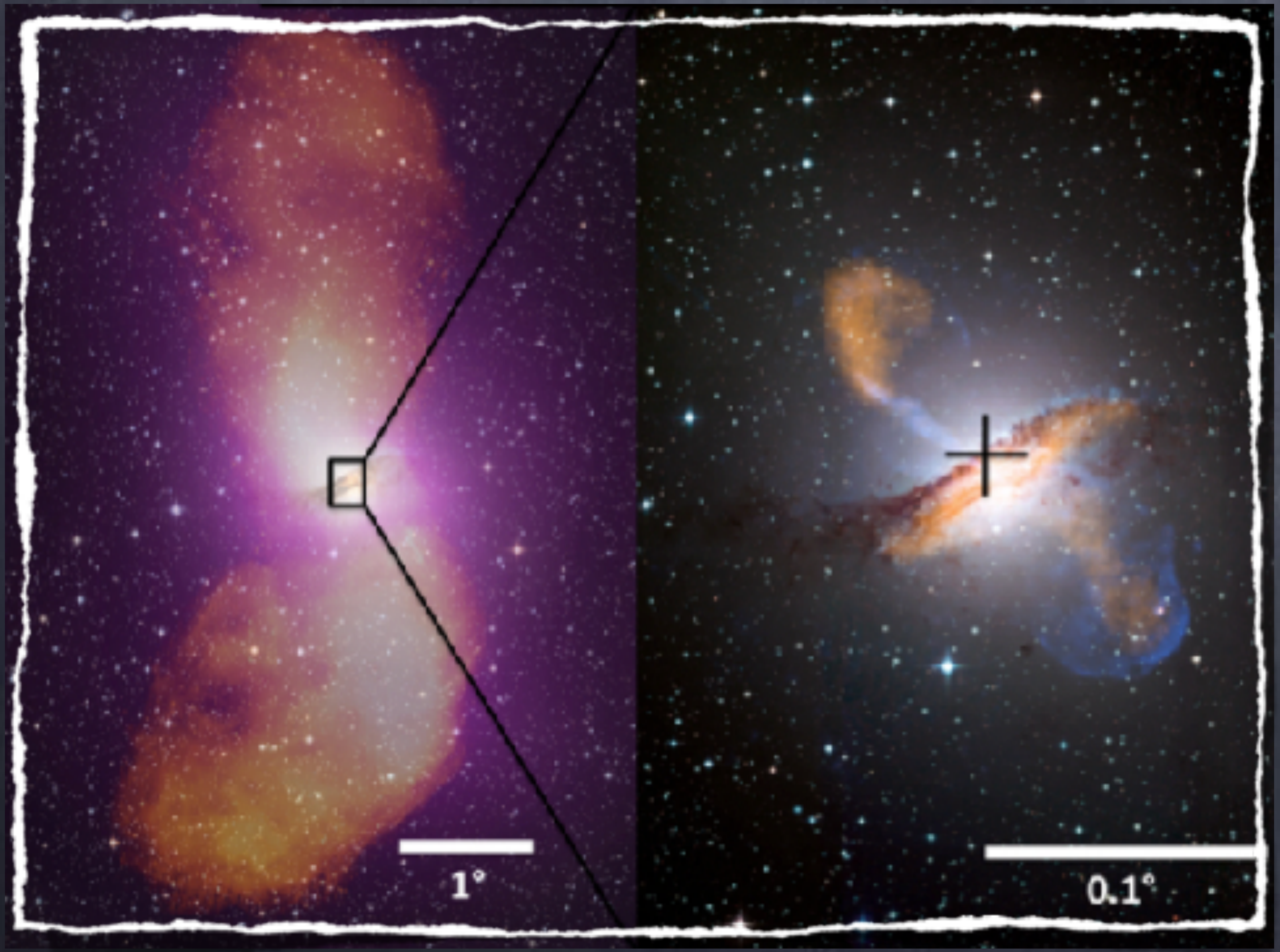
the SED of non-jetted AGN has a cutoff at much lower energies than those of jetted AGN

credit: C. M. Harrison

Padovani 1707.08069v1
Nature Astronomy, 1, 0194 (2017)

NEW CLASSIFICATION

- jetted AGN are characterised by strong, relativistic jets
- non-jetted AGN can also have radio structures similar to collimated outflows but these "jets" are small, weak, and slow compared to those of jetted sources



Centaurus A - RL

Mrk 573 - RQ

NEW CLASSIFICATION

How to distinguish between the two classes RL / RQ ?

1. Direct evidence of a strong jet

2. γ-ray (1 MeV) emission: only jetted AGN manage to reach these energies

3. Radio-excess (RL AGN) off the far infrared-radio correlation (RQ AGN)

JET-DISC CONNECTION

Connection between accretion rate and relativistic jet power in AGN

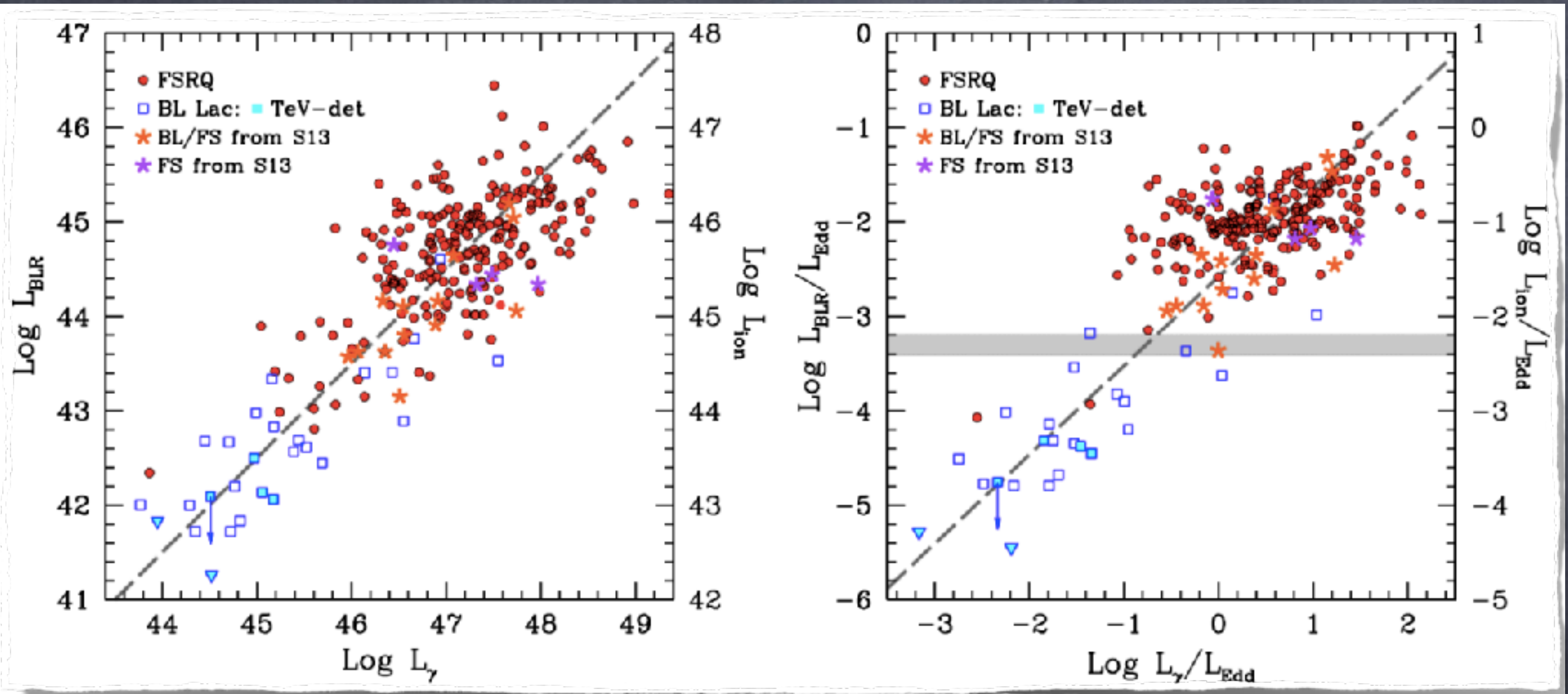
- The jet power can be traced by γ-ray luminosity in the case of blazars, and radio luminosity for both blazars and radio-galaxies.
- The accretion disc luminosity is instead traced by the broad emission lines.

collected all the blazars that show broad emission lines in their optical spectra, with gamma and radio data

based on 2nd LAT AGN Catalog

Sbarrato+ 2014

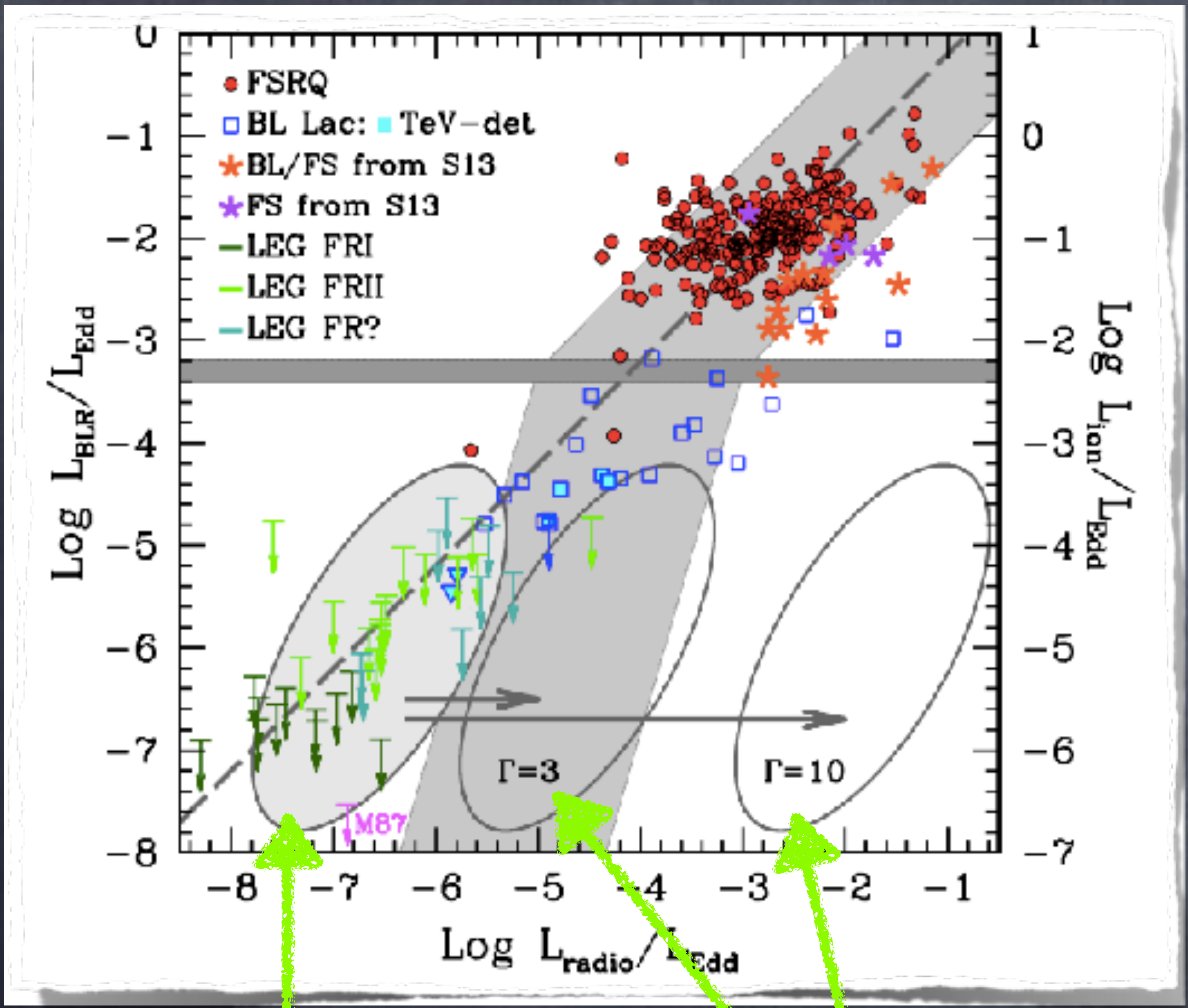
JET-DISC CONNECTION



strengthens the hypothesis of a tight relation between the accretion rate and the jet power in blazars.

Sbarrato+ 2014

JET-DISC CONNECTION



adding the radio galaxies identify the transition between efficient and inefficient accretion structures

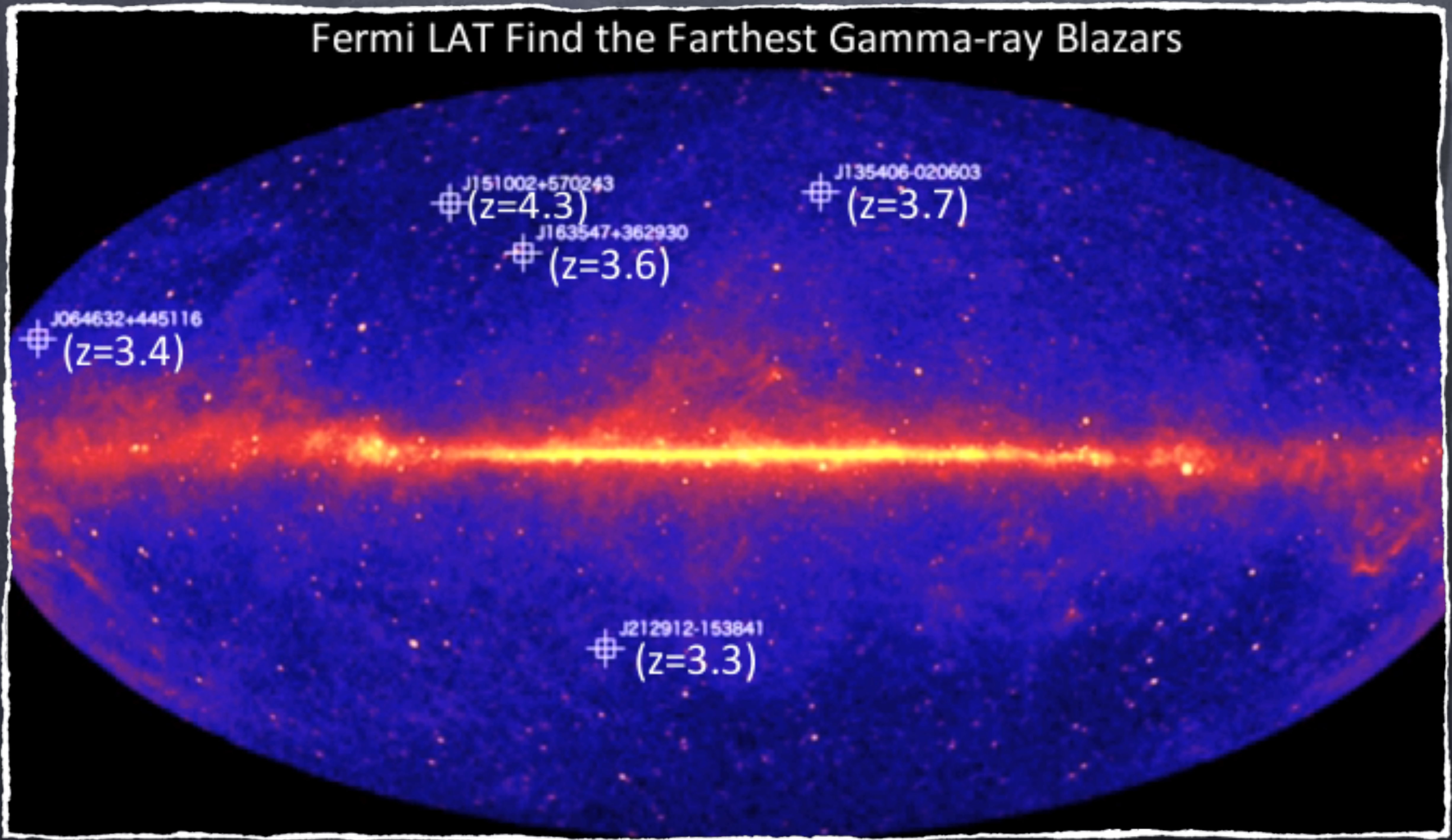
- only blazars -> no very low-accreting objects, since they would be line-less and dominated by the jet non-thermal emission, and without a redshift estimate.
- LEG radio-galaxies -> the only mean to study the radiatively inefficient accretion regime

include the core of the radio-galaxies

show where the radio-galaxies would be located if they were beamed according to Lorentz factors Γ = 3 or 10, respectively

Sbarrato+ 2014

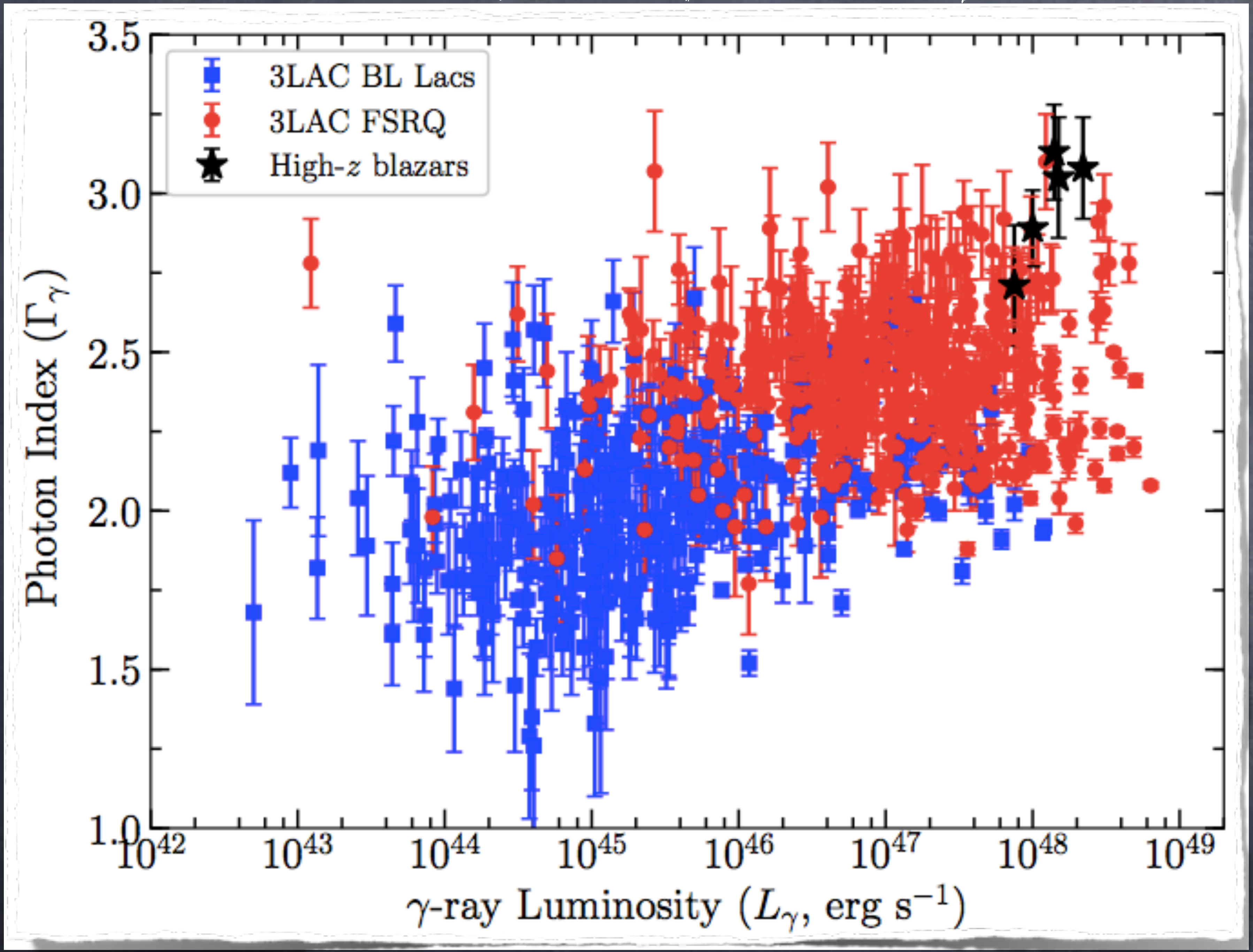
AT THE DAWN OF THE UNIVERSE



Ackermann, M. et al. 2017, ApJL, 837, L5

AT THE DAWN OF THE UNIVERSE

NVSS J151002+570243 (z = 4.31) is now the farthest known γ- ray emitting blazar

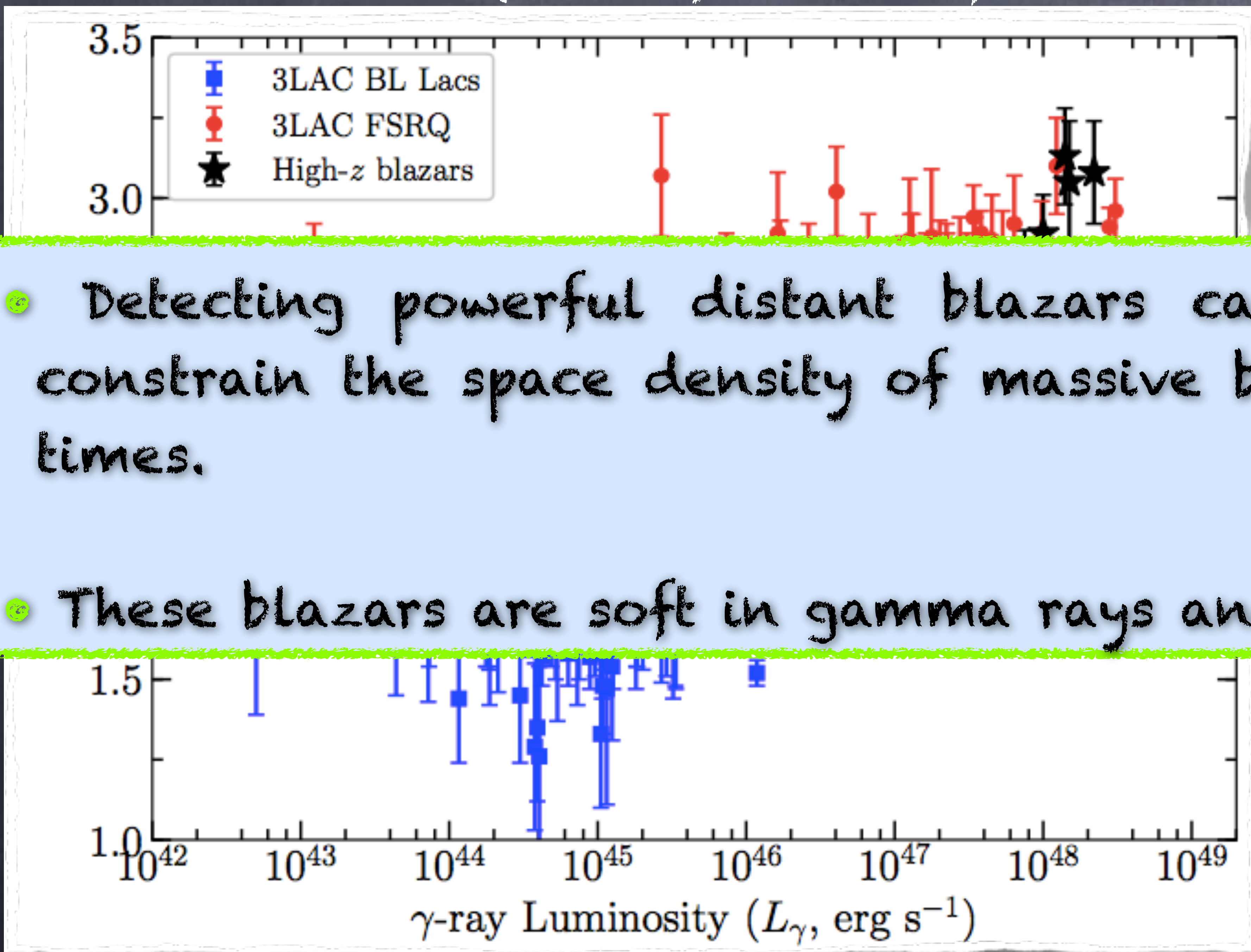


- cosmic evolution of blazars from high power distant sources into nearby low luminous objects
- 10 years of LAT observations -> lower flux threshold -> fainter objects
- ~1.4million quasars included in the Million Quasar Catalog (MQC; Flesch 2015)

Ackermann, M. et al. 2017, ApJL, 837, L5

AT THE DAWN OF THE UNIVERSE

NVSS J151002+570243 (z = 4.31) is now the farthest known γ- ray emitting blazar



- cosmic evolution of blazars from high power distant sources into

- Detecting powerful distant blazars can be important to constrain the space density of massive black holes at early times.

- These blazars are soft in gamma rays and hard in X-ray

- ~1.4million quasars included in the Million Quasar Catalog (MQC; Flesch 2015)

Ackermann, M. et al. 2017, ApJL, 837, L5

IC170922A

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
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
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STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
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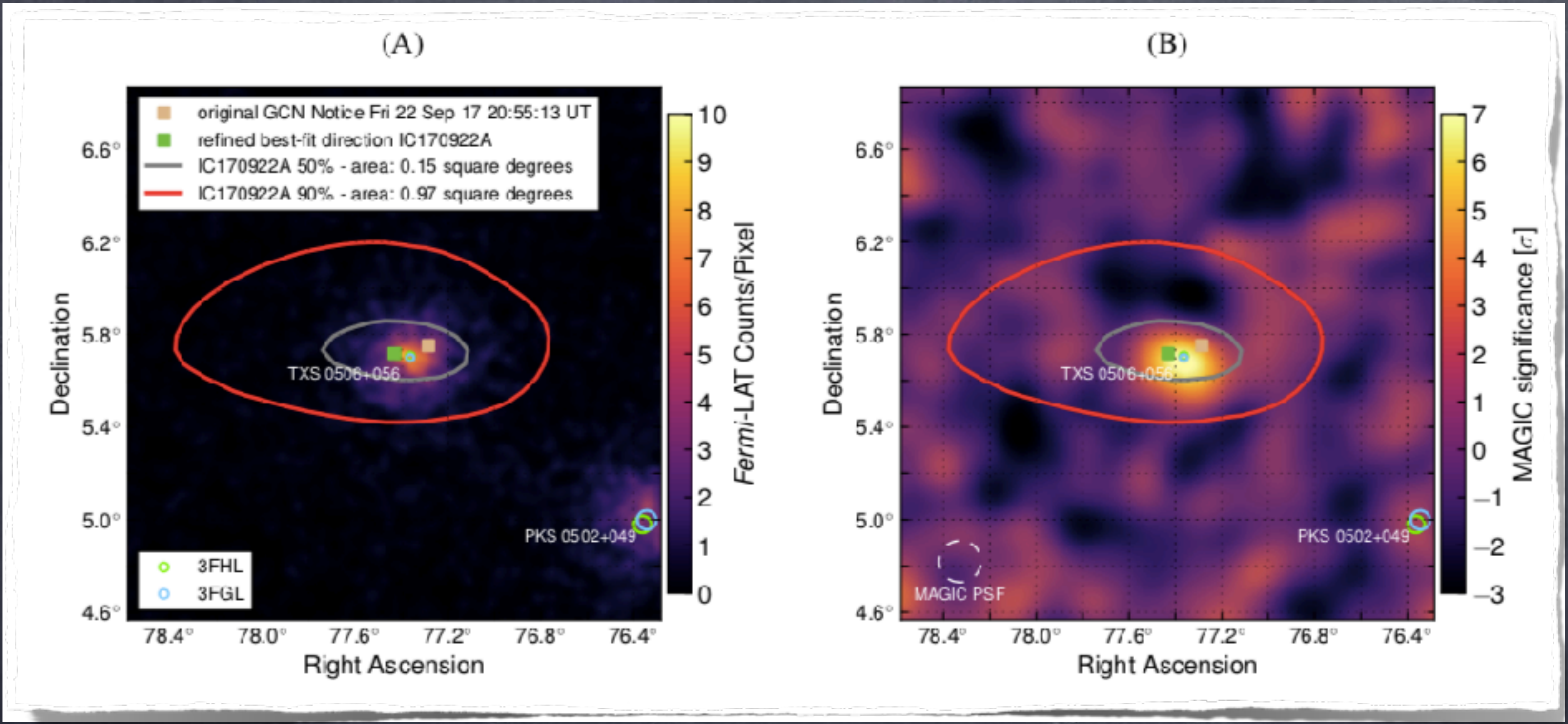
MULTI-MESSENGER ERA HAS STARTED



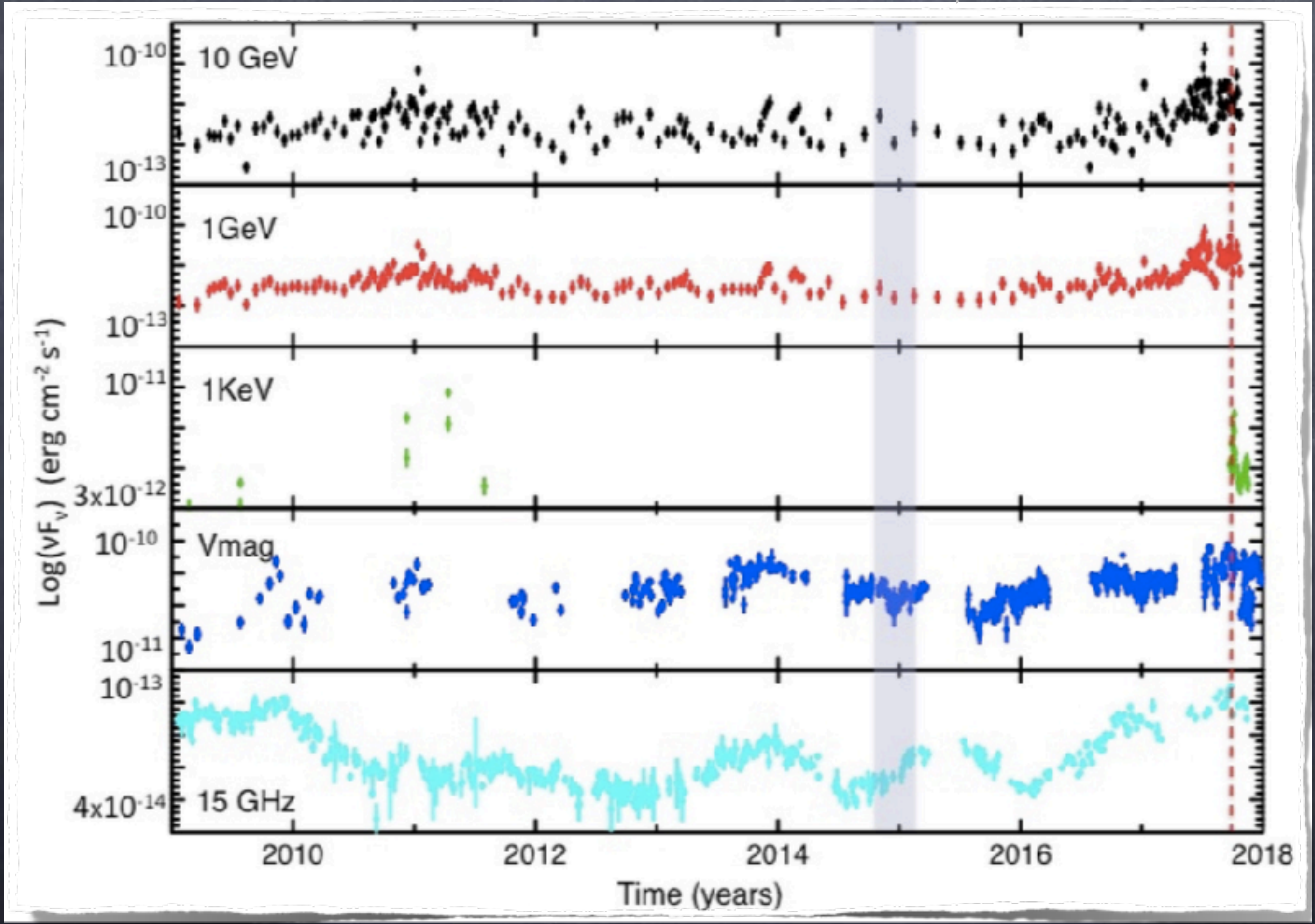
3-sigma post-trial probability of association with the flaring blazar TXS 0506+056

Science 361, eaat1378 (2018)

MULTI-MESSENGER ERA HAS STARTED

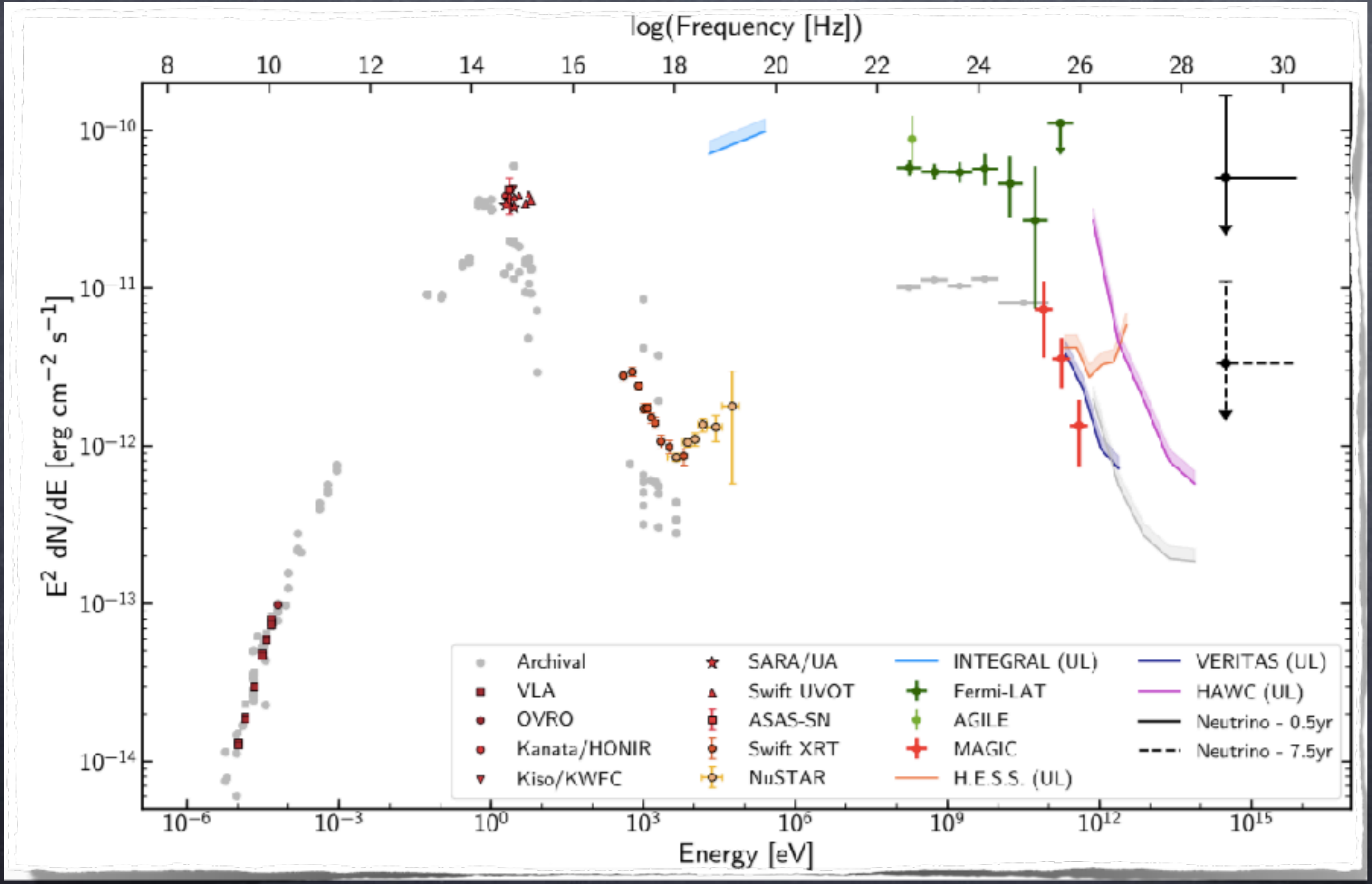
2014-2015 neutrino flare

IC170922A



Padovani et al. MNRAS 2018

MULTI-MESSENGER ERA HAS STARTED



Science 361, eaat1378 (2018)

MULTI-MESSENGER ERA HAS STARTED

* TXS0506+056 -> brightest Fermi source in the region of interest at energies above 1GeV during the IceCube-170922A event but only above 2-5 GeV during the neutrino flare.

* Both the lack of a correlation between the γ-ray and radio/optical flux and the SED shape of TXS0506+056, which is unusual in terms of its Compton dominance, appear not to be consistent with simple leptonic models.

=> hadronic flare during the neutrino detections ?

(Padovani et al. MNRAS 2018)

MULTI-MESSENGER ERA HAS STARTED

spatial, timing, and energetic multi-messenger diagnostics point to TXS0506+056 as the only counterpart of all the neutrinos observed in the vicinity of IceCube-170922A and

the first non-stellar neutrino (and hence cosmic ray) source, (at 3 sigma level of confidence, ndr)

Emerging picture -> extreme blazars, i.e., strong, very high energy γ-ray sources with the peak of the synchrotron emission > 10^{14} – 10^{15} Hz, are the first class of sources with evident contribution to the IceCube diffuse signal.

(Padovani et al. MNRAS 2018)

Thanks