# Calculating Upper Limits with the Fermi/LAT

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Why would you want upper limits?

- **Exploratory: start off looking for a new source, settle for upper limits**
  - i.e., "better than nothing" SED constraints
  - Possibly help characterize the low state of a previously flaring source
- **Test/rule-out a model which predicts gamma-rays**

# Fermi Upper Limits on Magnetars
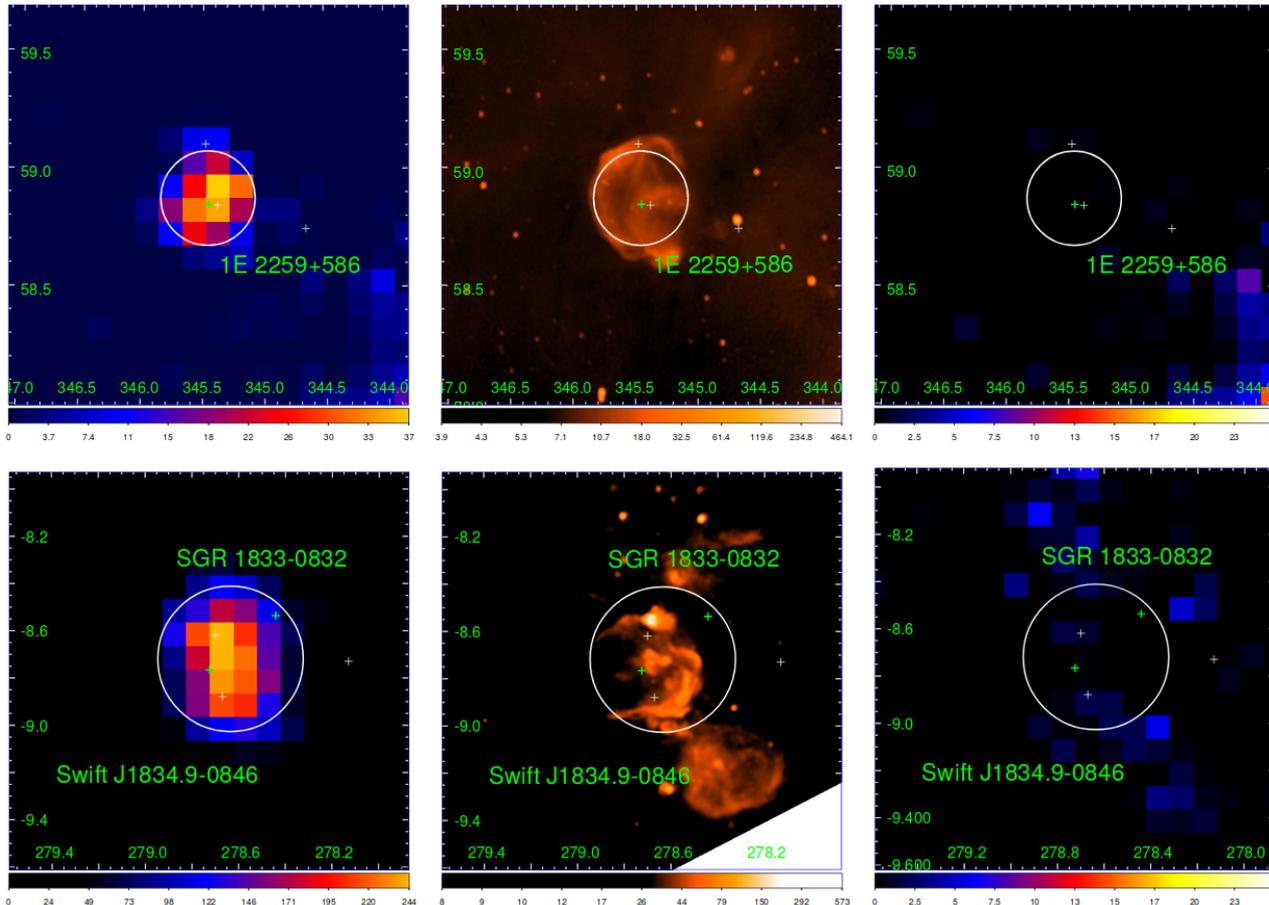
These sources have regular pulsations and huge flares previously detected in hard X-rays with Nustar

After carefully modeling the SNR emission (seen in TS Map at left), there was no remaining signal, pulsed or otherwise, from the Magnetars.

'Outer Gap' model of Cheng & Zhang (2001) had predicted Fermi detection in the first year.

Li et al., 2016

Colliding Wind Binaries
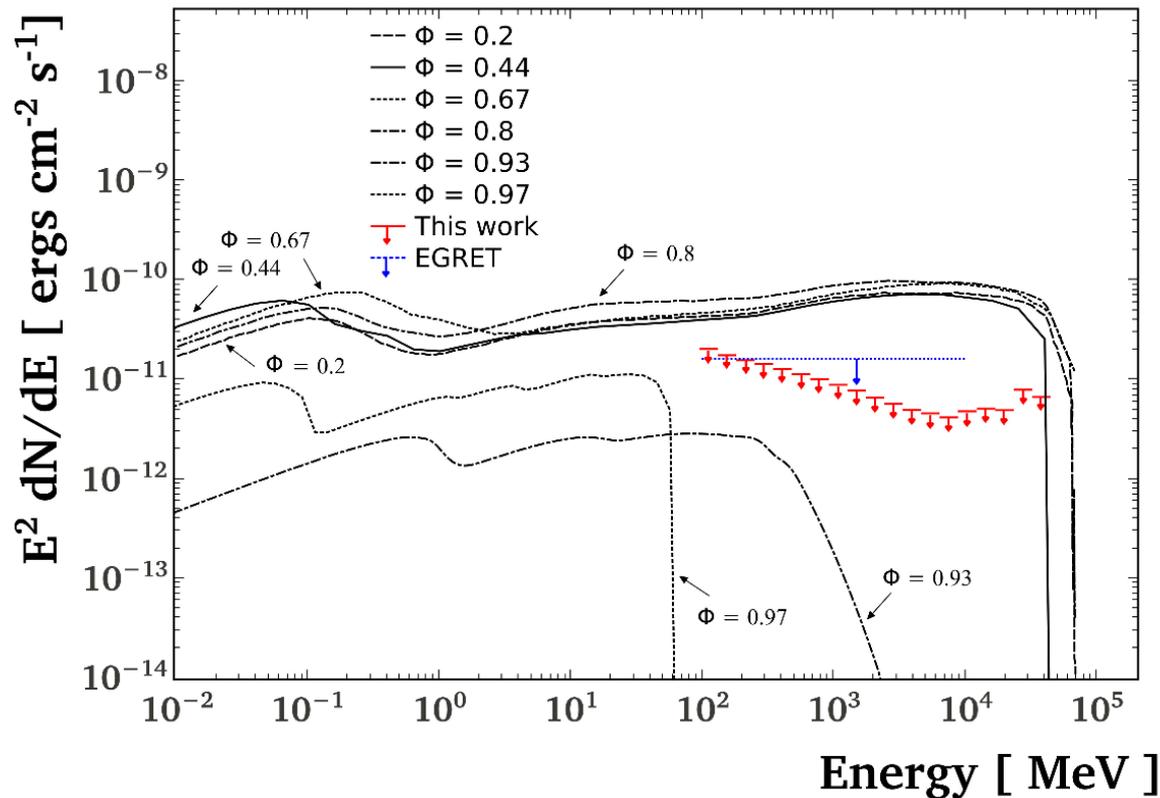
Wolf-Rayet stars are extremely massive, luminous stars with strong stellar winds.

With an OB binary companion = CWB

Wind shock region contains relativistic electrons → synchrotron emission

Several theoretical models **predict gamma-ray emission** via inverse Compton, Bremmstrahlung, and π^0-decay.

Werner+ 2013 found no gammay-ray emission from any CWB
(η Car is the only exception, and is considered "exceptional")
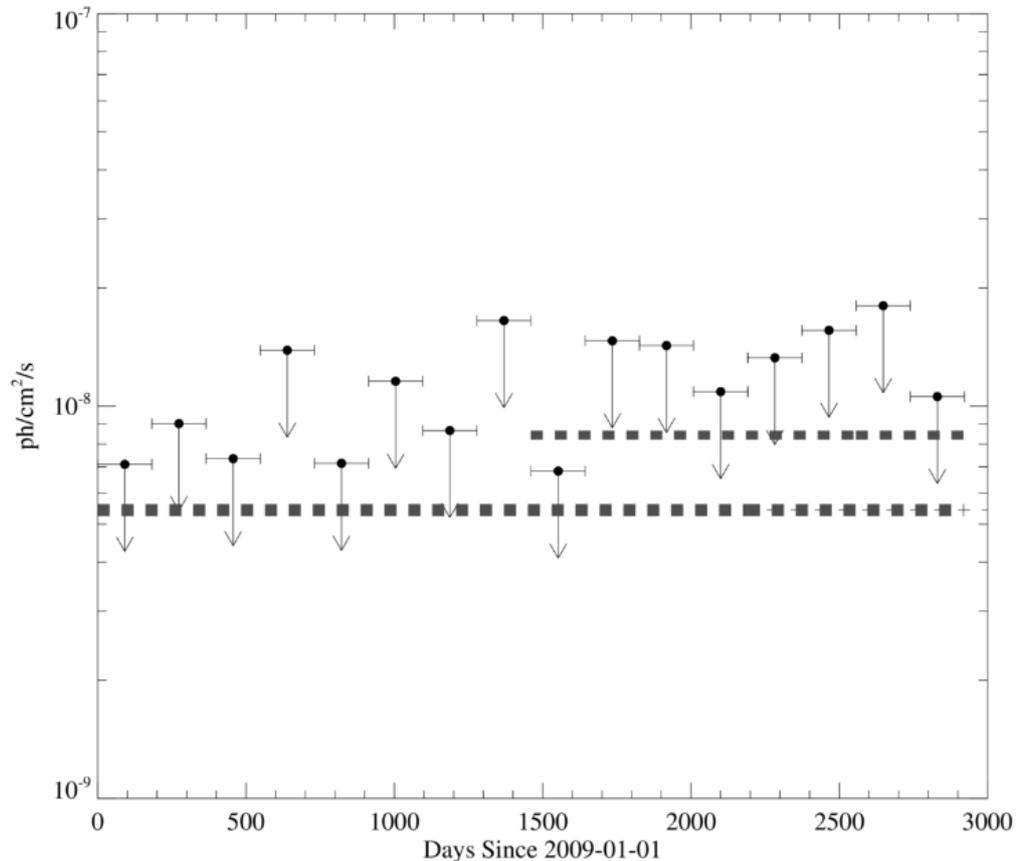
Fast Radio Bursts

FIG. 1.— The photon flux upper limits of 100 MeV-10 GeV LAT band emission of FRB 121102 in the 8-year time span. Each down arrow denotes flux limit for each 6-month time bin; the short and long dashed lines represent the 4-year and 8-year up-limits, respectively.

FRBs are bursts of radio emission lasting milliseconds. Some, like FRB 121102 are repeating and known to be extragalactic.

← Most popular explanation is that this is a new-born magnetar with a very large spin-down power

Could expect gamma-rays from either magnetosphere or shocks in the wind associated with the magnetar

Exploratory search with Fermi/LAT (Zhang & Zhang 2017) Found no gamma-ray emission

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Dark Matter!

Limits to dark matter annihilation cross-section from a combined analysis of MAGIC and Fermi-LAT observations of dwarf satellite galaxies
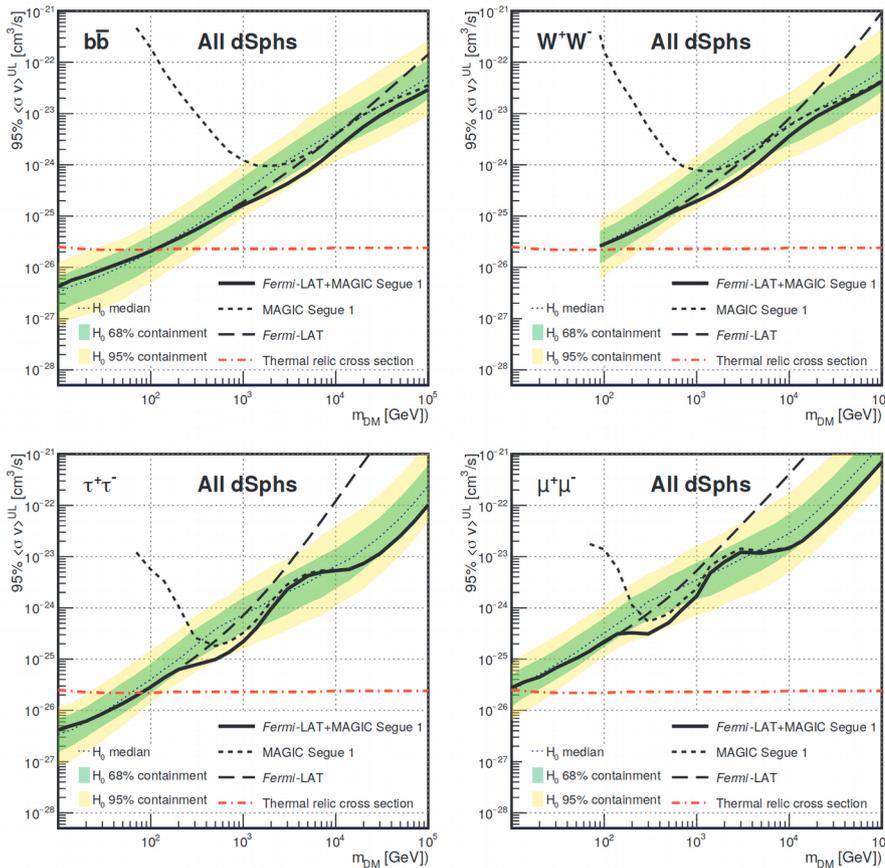
Fermi/LAT has been instrumental in ruling out DM decay signals in several contexts.
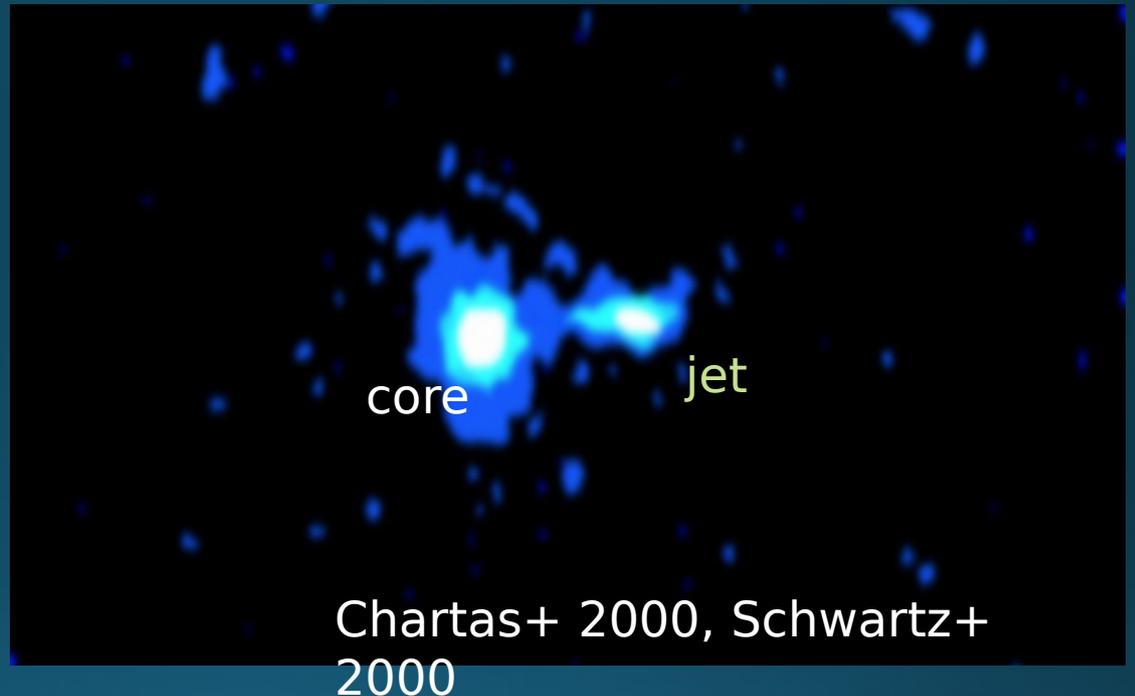
Fermi Limits on Large-Scale Quasar Jets

July 1999: Chandra X-ray Observatory Launched

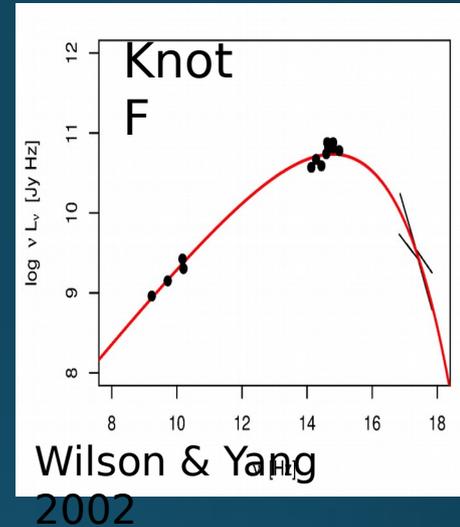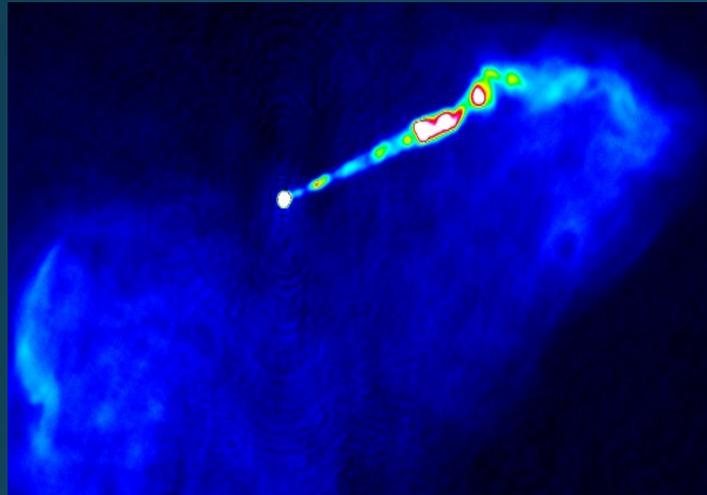# Fermi Limits on Large-Scale Quasar Jets

July 1999: Chandra X-ray Observatory Launched

August 1999: Chandra discovers the extended kpc-scale jet of PKS 0637-752 during orbital activation and checkout phase
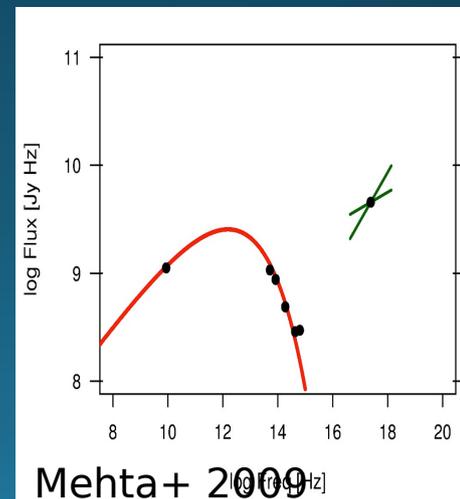

core   jet

Chartas+ 2000, Schwartz+ 2000

Fermi Limits on Large-Scale Quasar Jets

Low-power Jets: synchrotron spectrum producing soft X-rays

Knot F

Wilson & Yang 2002

High-power Jets: synchrotron spectrum producing no X-rays (turnover is before optical)


Godfrey+ 2012

Mehta+ 2009

Fermi Limits on Large-Scale Quasar Jets

September/October 2000: Chartas et al. & Schwartz et al. discovery & discussion papers on PKS 0637-752 manage to rule out:

- Thermal Bremstrahlung (electron density required far too high)

- Synchrotron self-compton (requires a "gross departure from equipartition)

- Inverse Compton off the CMB (off by orders of magnitude)

- A Single Synchrotron Spectrum
  - A second, co-spatial synchrotron spectrum was considered, but deemed unlikely because no known reason for it, and co-spatial with first synchrotron component!
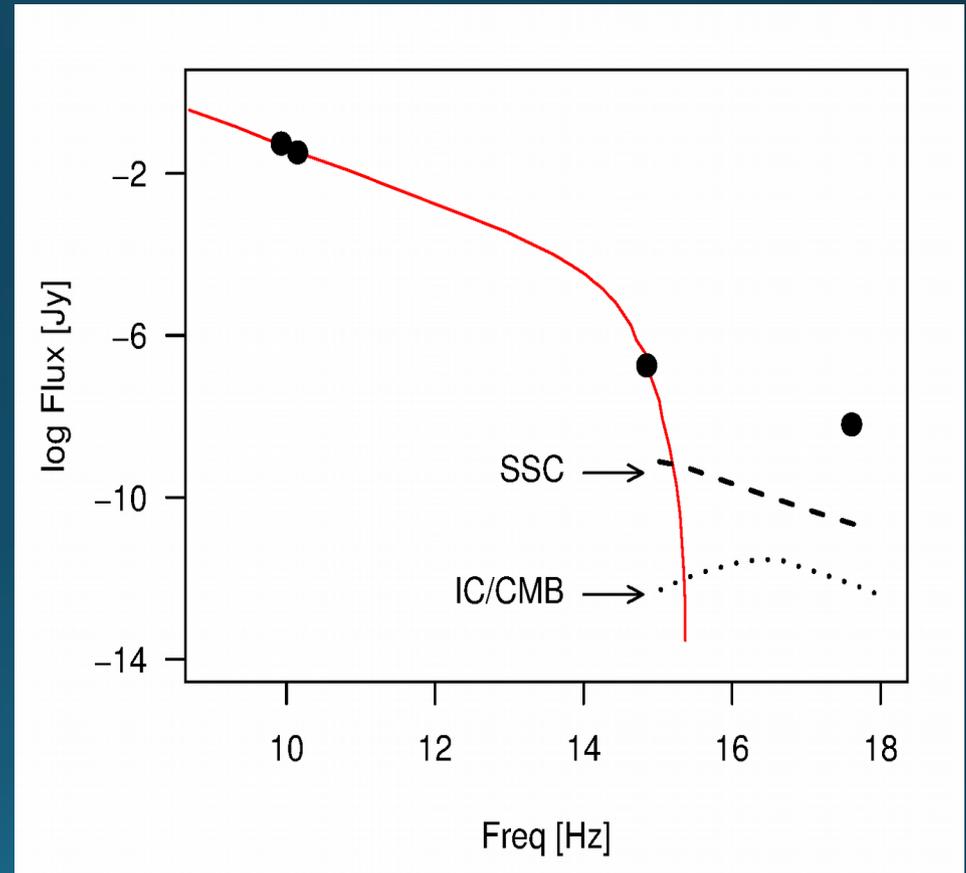
Fermi Limits on Large-Scale Quasar Jets

November 2000: Tavecchio et al. and **February 2001:** Celotti et al.:
is it IC/CMB after all?

Quasar Jets are frequently observed to be highly relativistic on sub-parsec scales probed by VLBI with Γ=10-50

But Radio surveys have long suggested that on kiloparsec scales the jet is only mildly relativistic withΓ=1.2-1.5

[e.g., Arshakian & Longair 2004, Mullin & Hardcastle 2009]

However, if you assume that powerful quasar jets remain highly relativistic on kpc scales, then IC/CMB works.

# Fermi Limits on Large-Scale Quasar Jets

If you simply take Γ~15, the increased beaming allows the IC/CMB to match the observed X-rays without any other majorly contrived assumptions.
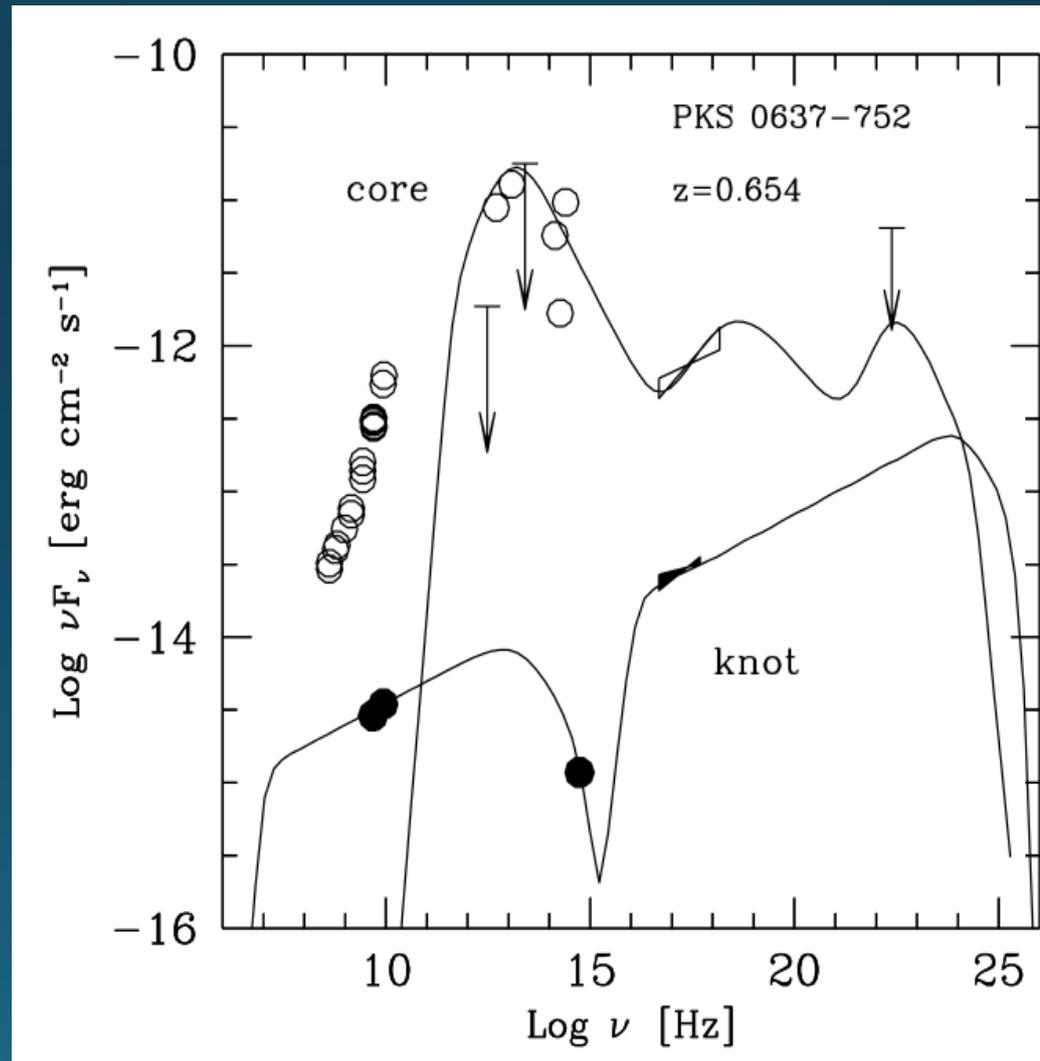
Working IC/CMB model for the knots of PKS 0637-752

Fermi Limits on Large-Scale Quasar Jets

- Over the past 15 years, the IC/CMB model is the most popular, though technically unconfirmed explanation for the anomalous X-ray jets.

PKS 0723+679

Sambruna+ 2002
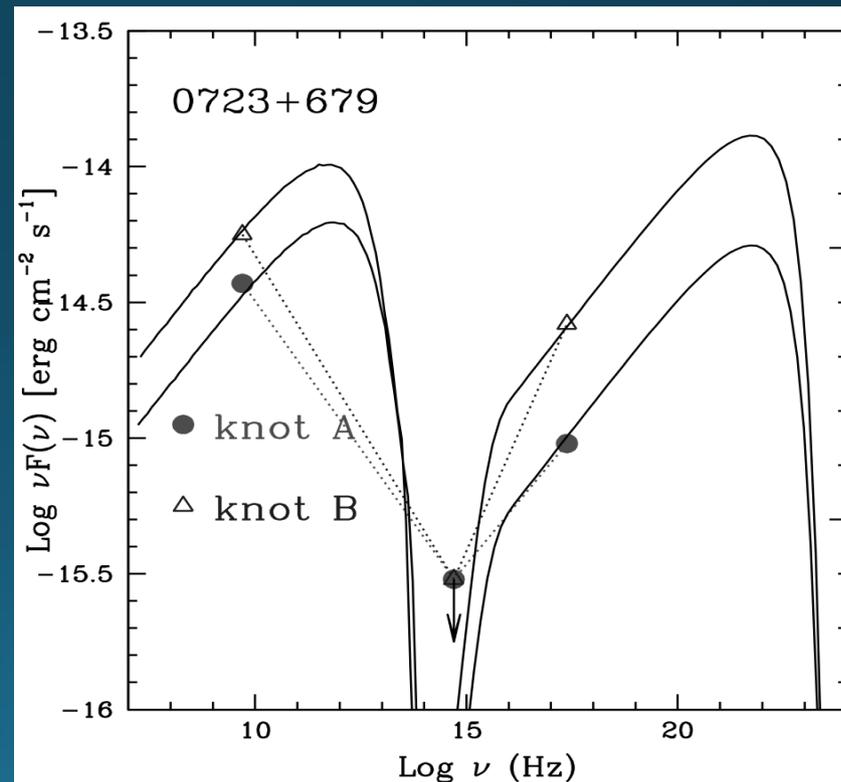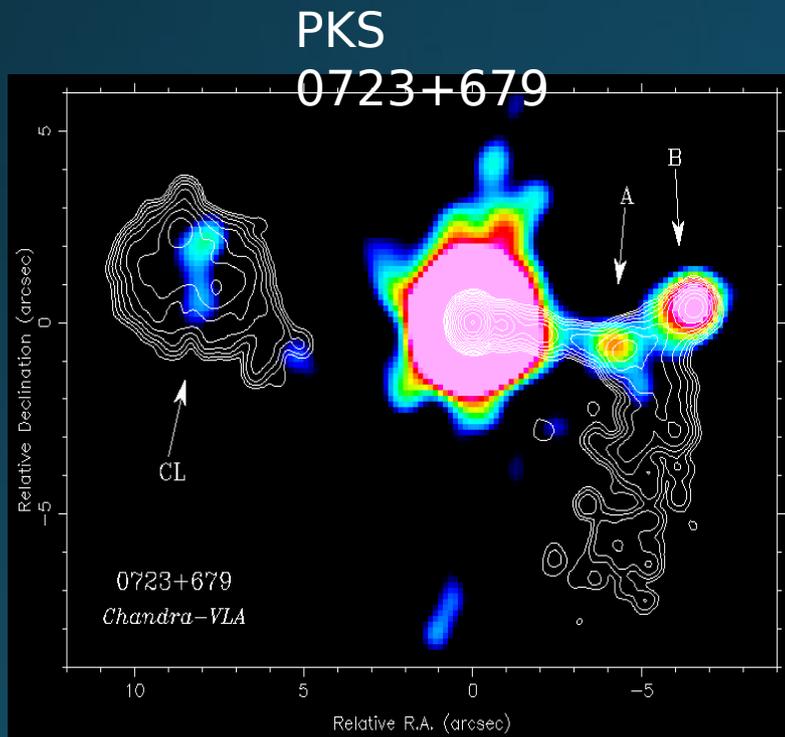
Anomalously Bright Quasar Jets: One of Chandra's major discoveries, and an ongoing puzzle
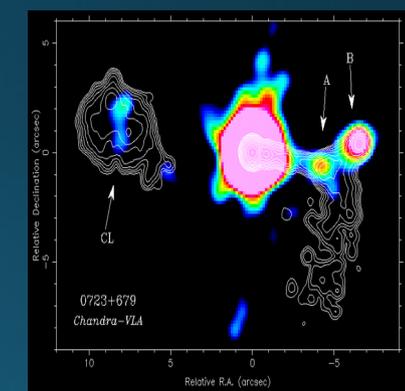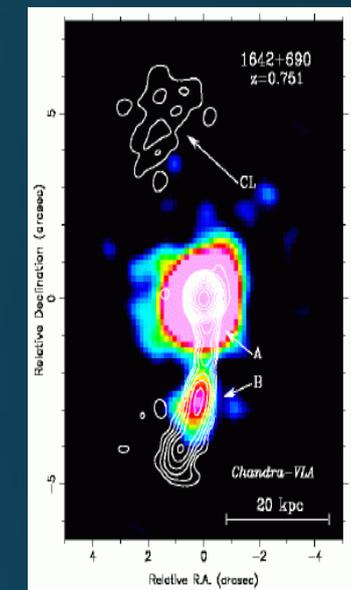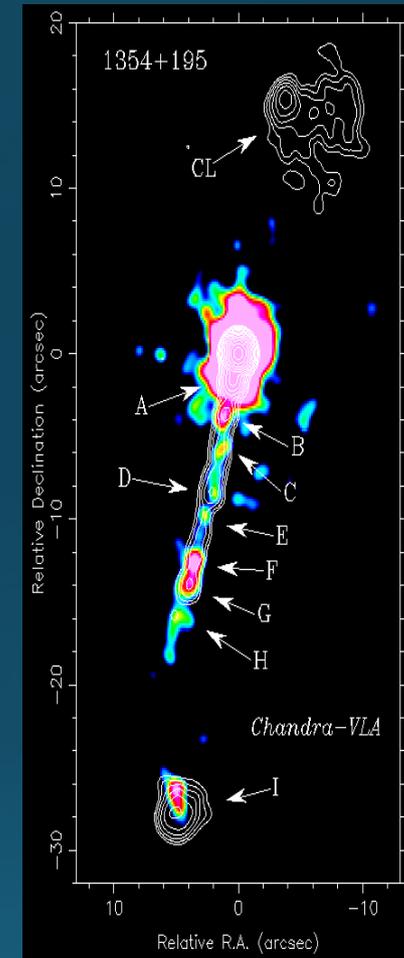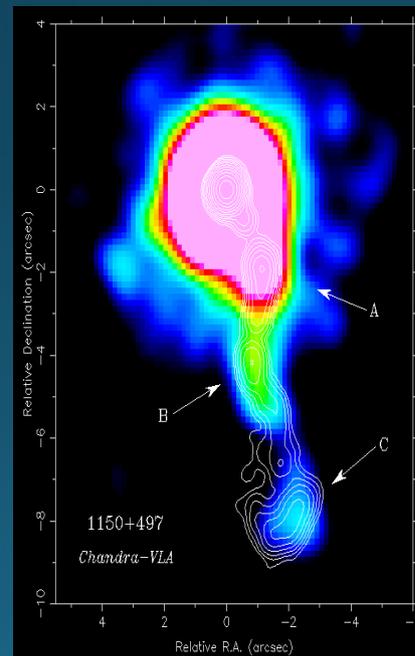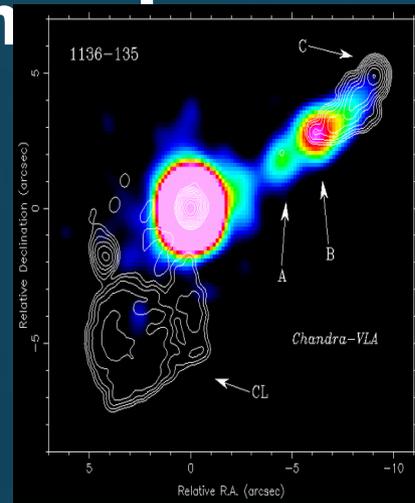
Several dozen now discovered (see review by Harris & Krawczynski 2006, Also papers by Marshall, Sambruna, Jorstad & Marscher, Kharb, Godfrey, Siemiginowska, and many more…

The Essential Problem

Second-synchrotron and IC/CMB fit radio-optical-Xray equally well.
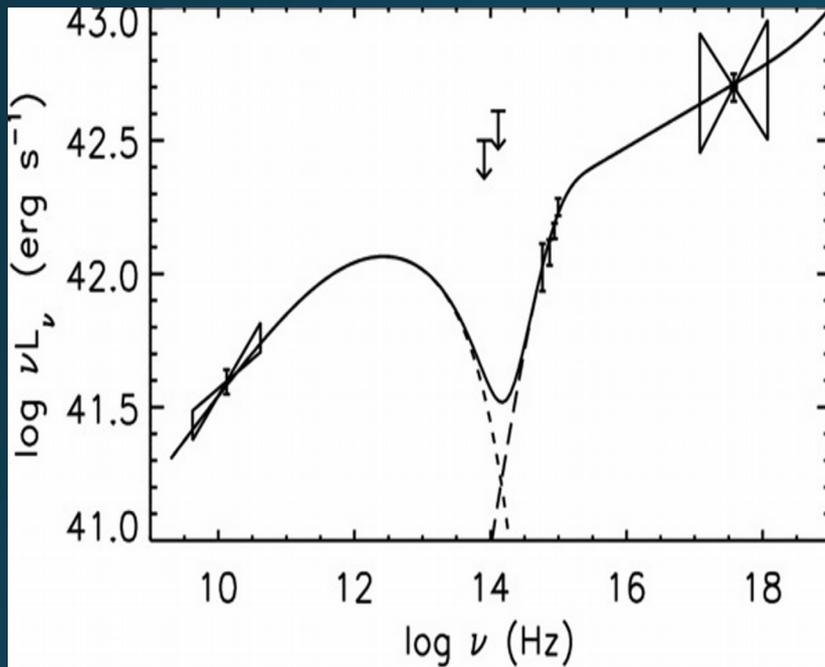
PKS 1136-135, IC/CMB Model
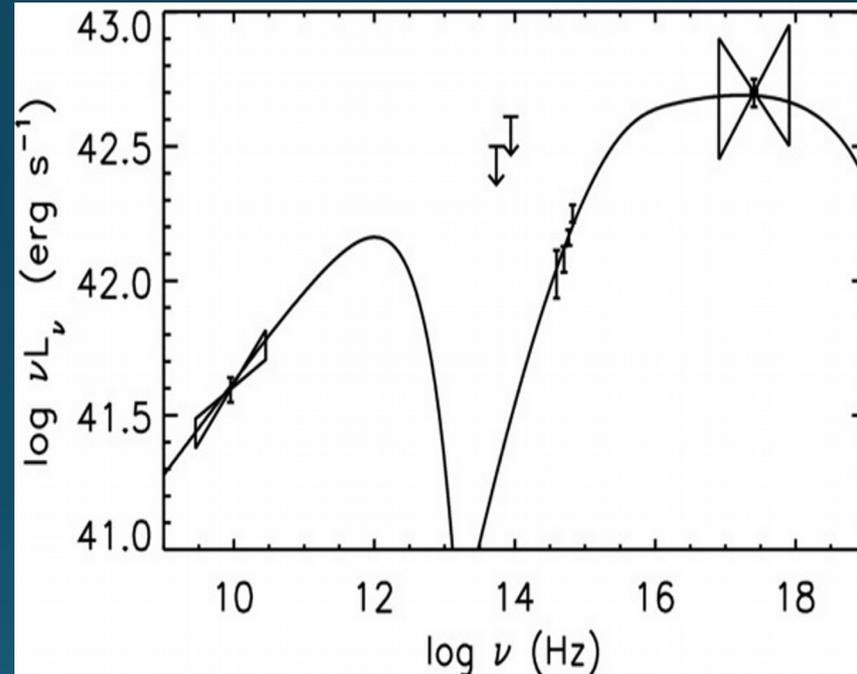
PKS 1136-135, synchrotron Model

Cara+ 2013 – Showing that X-rays of PKS 1136-135 are synchrotron due to high UV polarization

The Test: How to Rule out IC/CMB

The IC Component is a copy of the synchrotron, shifted in frequency and luminosity.

That shift is parameterized ONLY by B/δ, <u>no other free parameters.</u>

[Georganopoulos+ 2006]
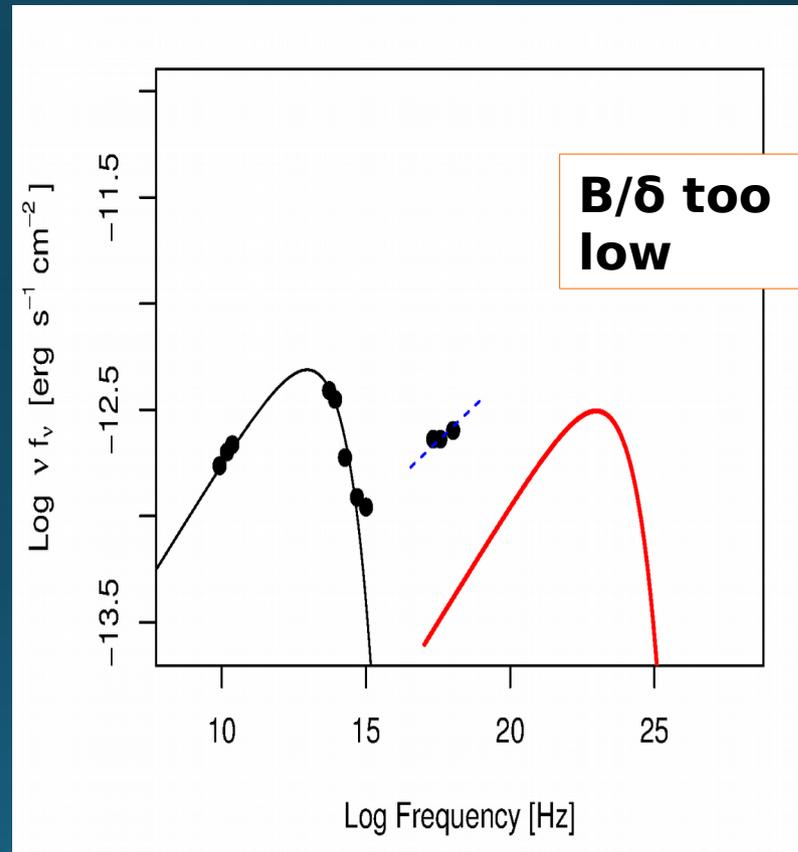
The Test: How to Rule out IC/CMB

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The Test: How to Rule out IC/CMB

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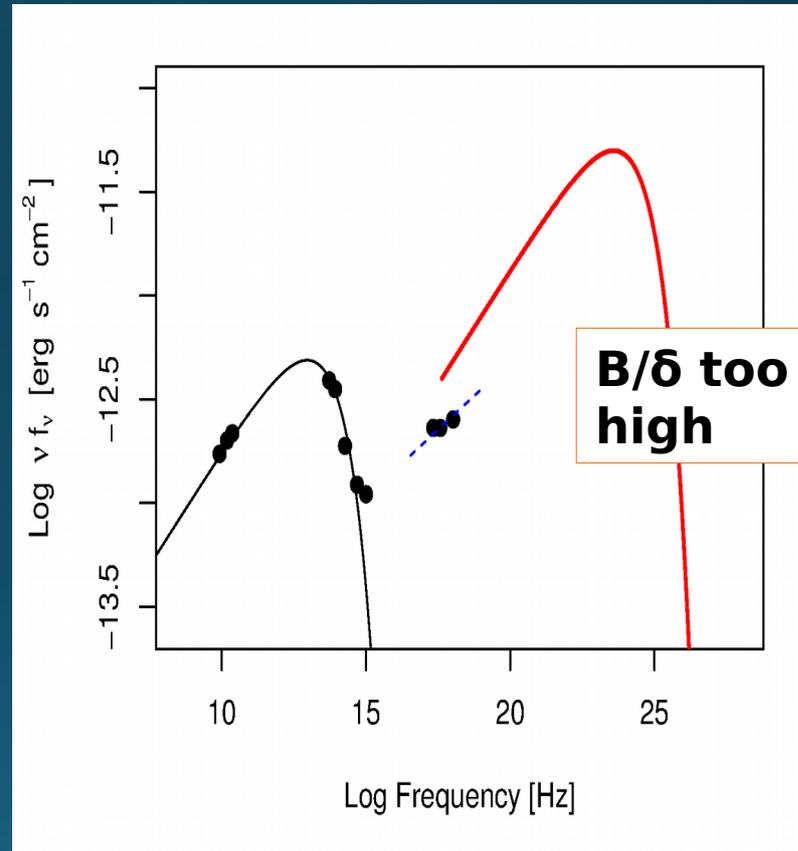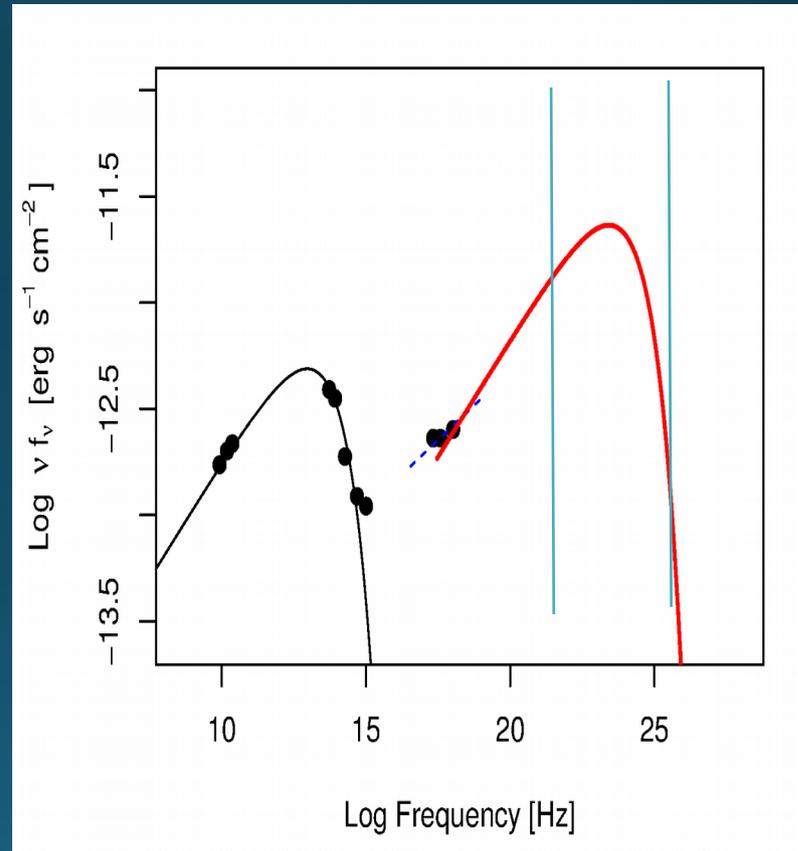Getting the X-rays just right means fixing B/**δ and consequently implies a high level of gamma-ray emission which should be detectable with Fermi**

The case of 3C 273
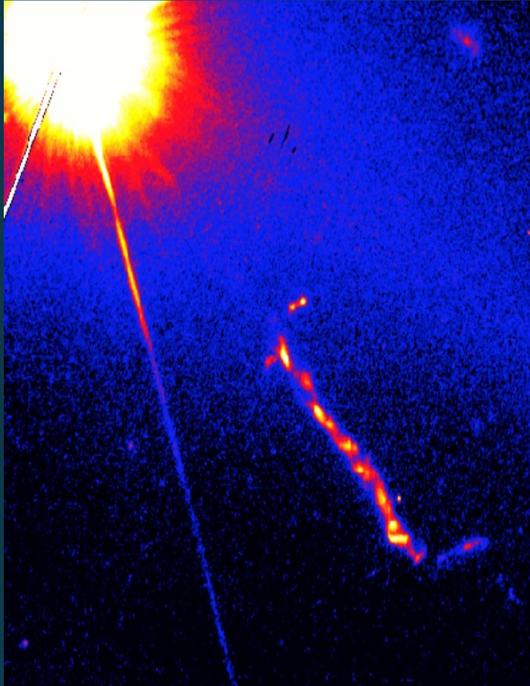
Resolution Issue: From core to end of the jet is ~ 24" - even the 68% PSF at 3 GeV is >10x this scale (few tenths of a degree)

However:
- IC/CMB emission of the 3C273 should be quite **hard and completely non-variable**.
- The core is known to be soft ($\Gamma\sim2.7$), and **variable**.
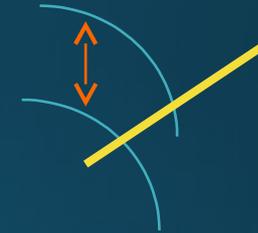
We can thus stack the parts of the 3C 273 lightcurve when the blazar is low to get the lowest upper limit, which applies to both the core + the jet.
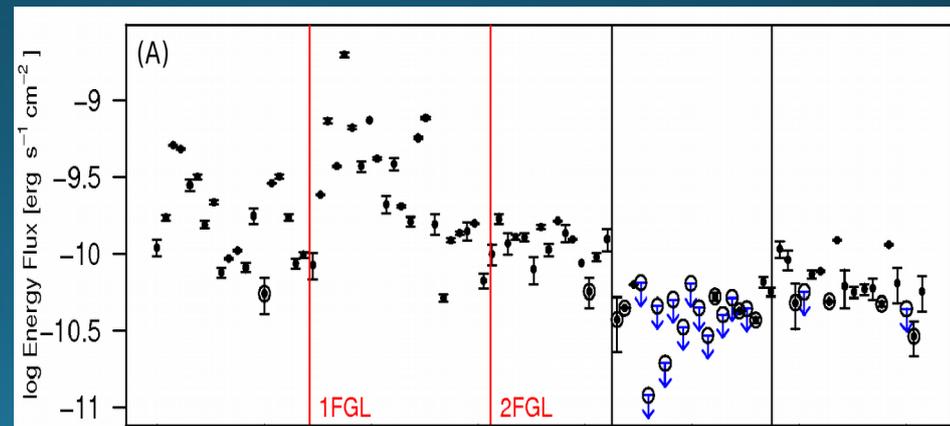
The case of 3C 273
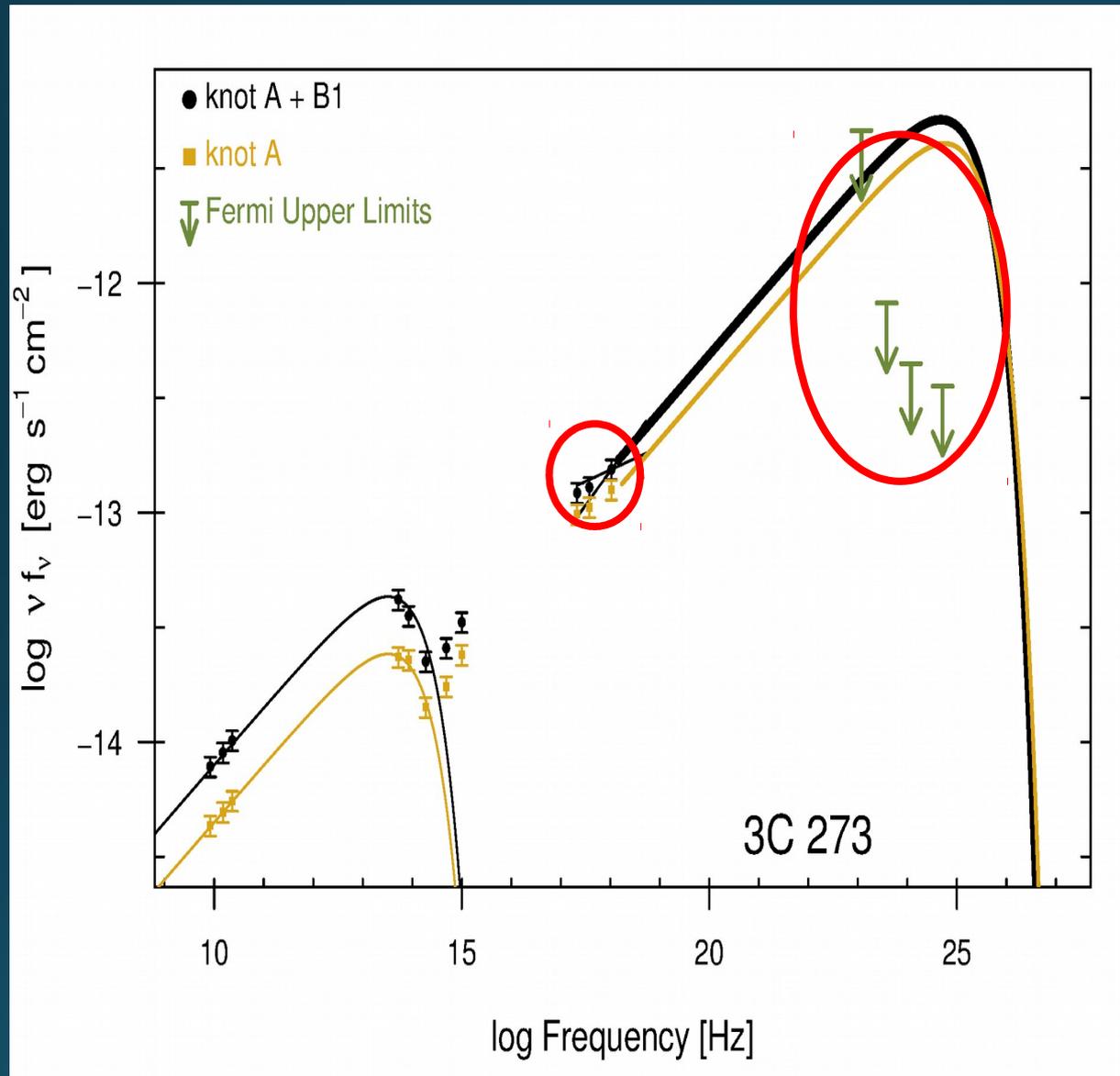
IC/CMB clearly ruled out at the > 99.99% level

You cannot satisfy producing the X-rays and the gamma-ray limits.

The case of PKS 0637-752
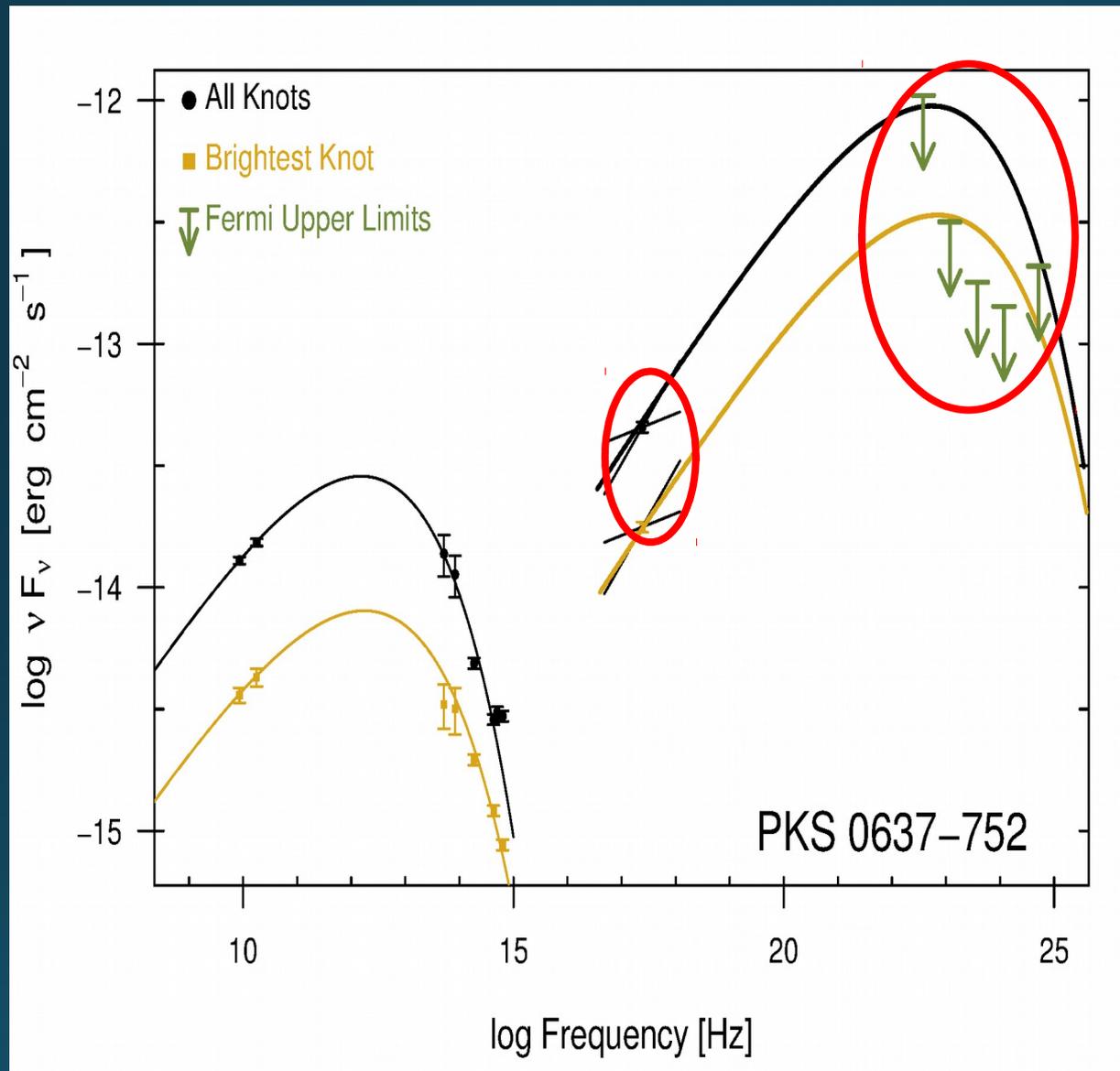
IC/CMB is now ruled out at the > 99.99% level for the original jet for which the model was first proposed!

The "Progressive Binning" Method

Purpose: Any case where you have a bright, variable known "nuisance" source very close (<u>unresolved from</u>) a **second source of interest** which is expected to be **steady and totally unconnected with the flaring source.**
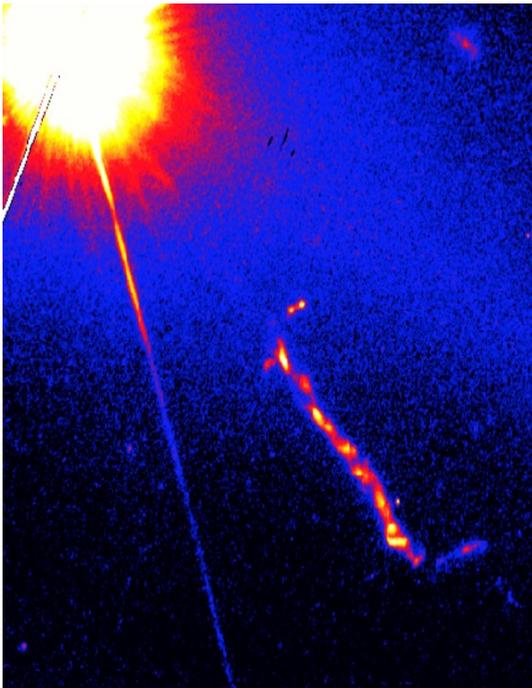
Step 0: Using the full time range, do an initial likelihood fit with catalog sources.

Generate a TS map and locate any new sources.

Add these to the model (see later demo).

Do a final likelihood fit and updated TS map to ensure there is no "unaccounted TS" in the ROI.

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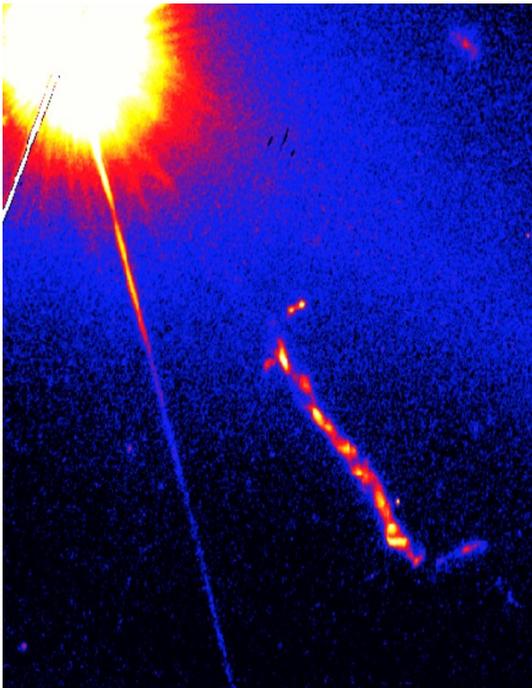
Step 1: Make a Lightcurve.

Size of the time bins important: They should be small enough to effectively isolate flares from the competing bright source. They should not be so small that you are on the order of photon arrival times.

We generally choose time bins such that the mean # of photons expected is large enough (100 is a good number).

The "Progressive Binning" Method
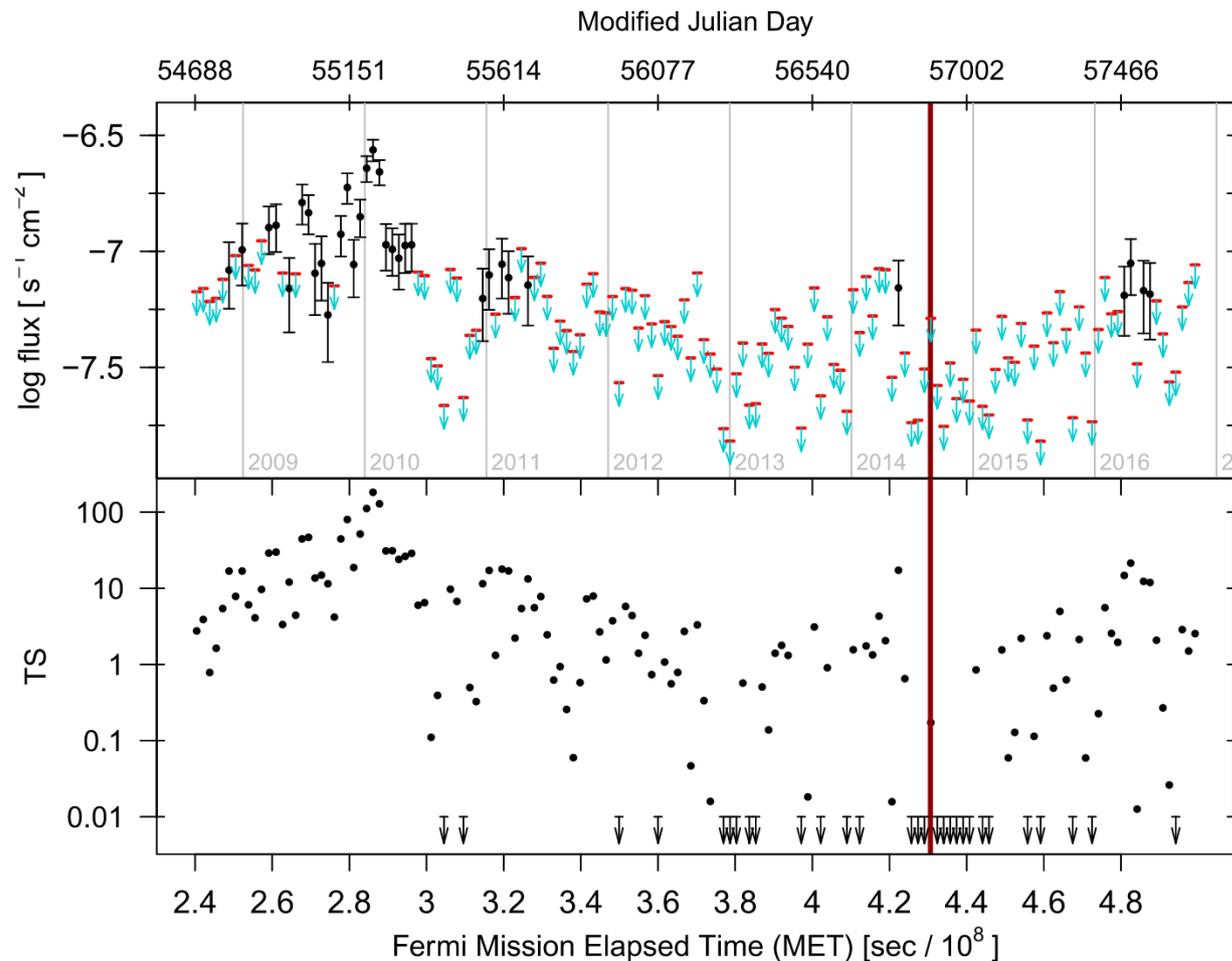
Step 2: Plot the Lightcurve & Order Bins from Lowest to Highest TS.

The idea is that the ordering of the bins is entirely driven by variability in the competing source. We are now chopping up the timeline and re-arranging it from times of lowest flux to highest.

This allows us to accumulate time on our steady, fainter source while minimizing interference from the bright source.

The "Progressive Binning" Method
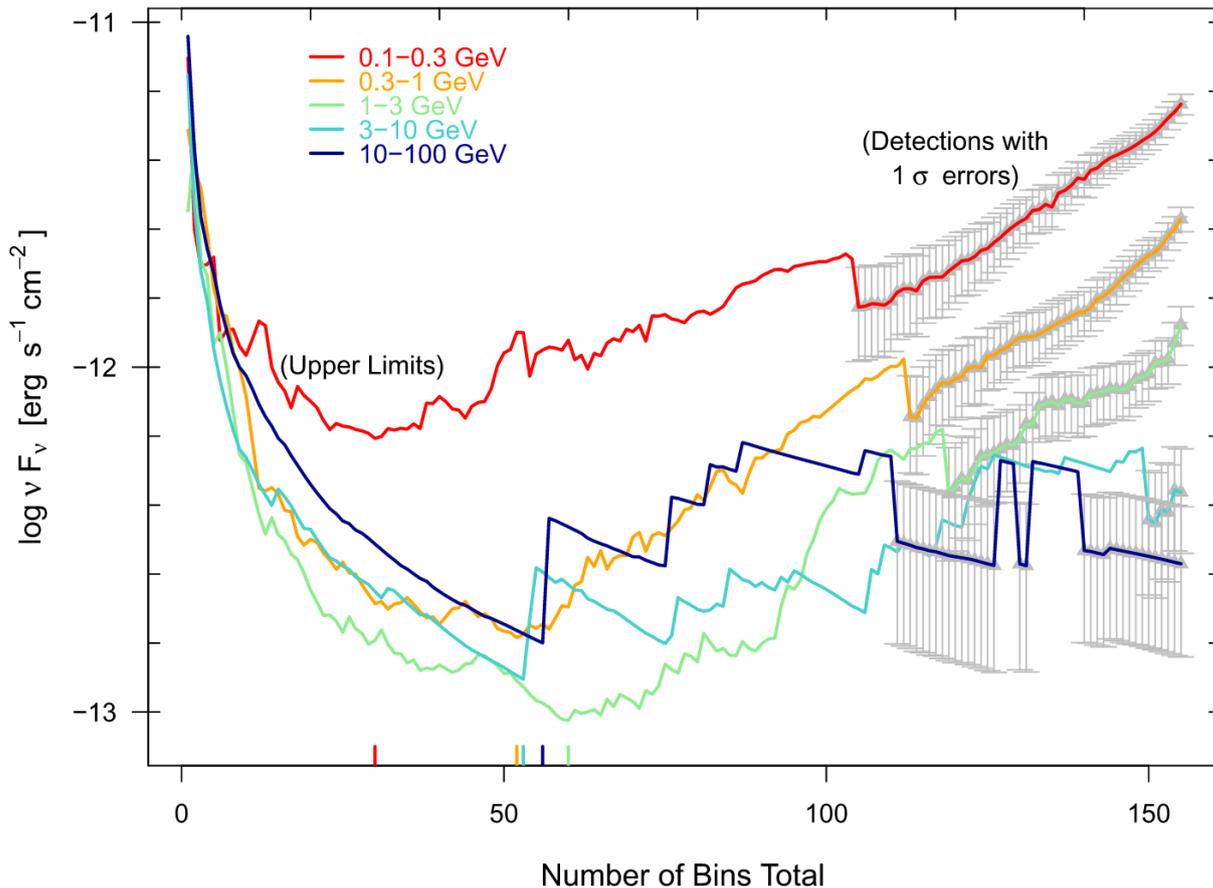
Step 3: Progressively Bin

Analyze the two lowest time bins, then three lowest, then four lowest, etc.

Upper limits should go down as 1/sqrt(time) when there is significant background.

At high energies with the LAT, there is so little background that the limits to as 1/time

The deepest limits you get in each energy band correspond to the best upper limit for your faint source (and the bright source, combined).

Procedure for Upper Limits

- **First: Identify your Source (RA,Dec)**

- **Check if it is already associated with a Fermi source!**

https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilpsc.html

W3Browse table will resolve your source into RA/Dec Position

Note: you may want to put in a larger default search radius

Procedure for Upper Limits

Fermi LAT 4-Year Point Source Catalog (fermilpsc)   Bulletin   README
Search radius used: 10.00 '

Select All	Services	name	ra	dec	flux 1 100 gev [photon/cm^2/s]	flux 1 100 gev error [photon/cm^2/s]	spectral index	spectral index error	detection significance	assoc name 1	Search Offset ['] from (target)
O R N S D		3FGL J1229.1+0202	12 29 09.0	+02 02 28	9.42442e-09	2.53035e-10	2.51628	0.02065	149.0121002	3C 273	0.891 (3c 273)

1 row retrieved from fermilpsc

Data Product Retrieval   **Further Actions:**

^^ If you see this kind of result, your source is probably already in the catalog! (Caveat: these are generally associations, not confirmed detections, and if you know your source is not 3C 273 but is rather just near to it, then read on…)

No matches for

Fermi LAT 4-Year Point Source Catalog (fermilpsc)

Page maintainer: Browse Feedback

^^ Your source is not in the latest catalog. (This doesn't mean that Fermi hasn't detected it… yet.)

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Upper Limits: Setting Up

- **Decide on your ROI**
  - Typical recommendation is 30 degrees
  - For demo (or first-run) purposes, can go much less (7 or 10 degrees)
- **Get the data from the server**

Demo Source: PKS 1030-357
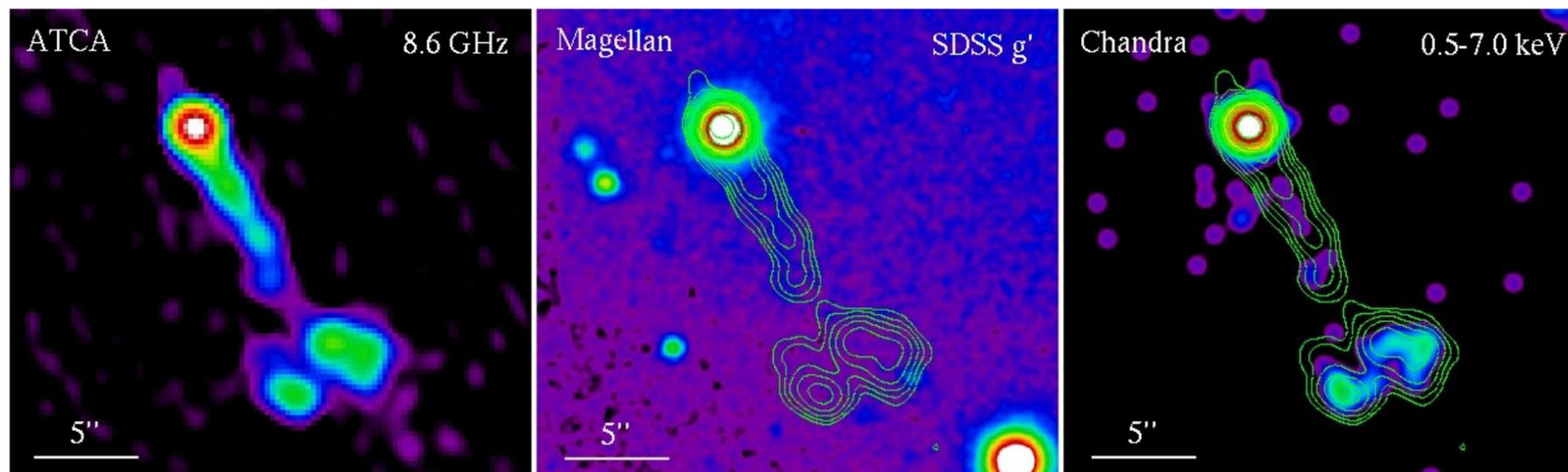
Basic data :

QSO B1030-357 -- Quasar

Other object types:	QSO (Ref,QSO,...), Rad (Ref,Cul,...), Bla (Ref,[MGL2009]), G (LEDA), cm (AT20G), IR (WISE), X (Ref)
ICRS coord. *(ep=J2000)* :	10 33 07.6656 -36 01 56.790 [387.5 287.6 90] C 2009A&A...505..385A
FK4 coord. *(ep=B1950 eq=1950)* :	10 30 52.04 -35 46 27.4 [387.5 287.6 90]
Gal coord. *(ep=J2000)* :	273.9079 +18.9267 [387.5 287.6 90]
Radial velocity / Redshift / cz :	V(km/s) 214467 [~] / z(~) 1.455000 [~] / cz 436198.03 [~] 　　D 1989ApJS...69....1H
Fluxes (3) :	B 20.6 [~] D ~ V 20.6 [~] E ~ R 18.4 [~] E 2009A&A...495..691M

Demo Source: PKS 1030-357
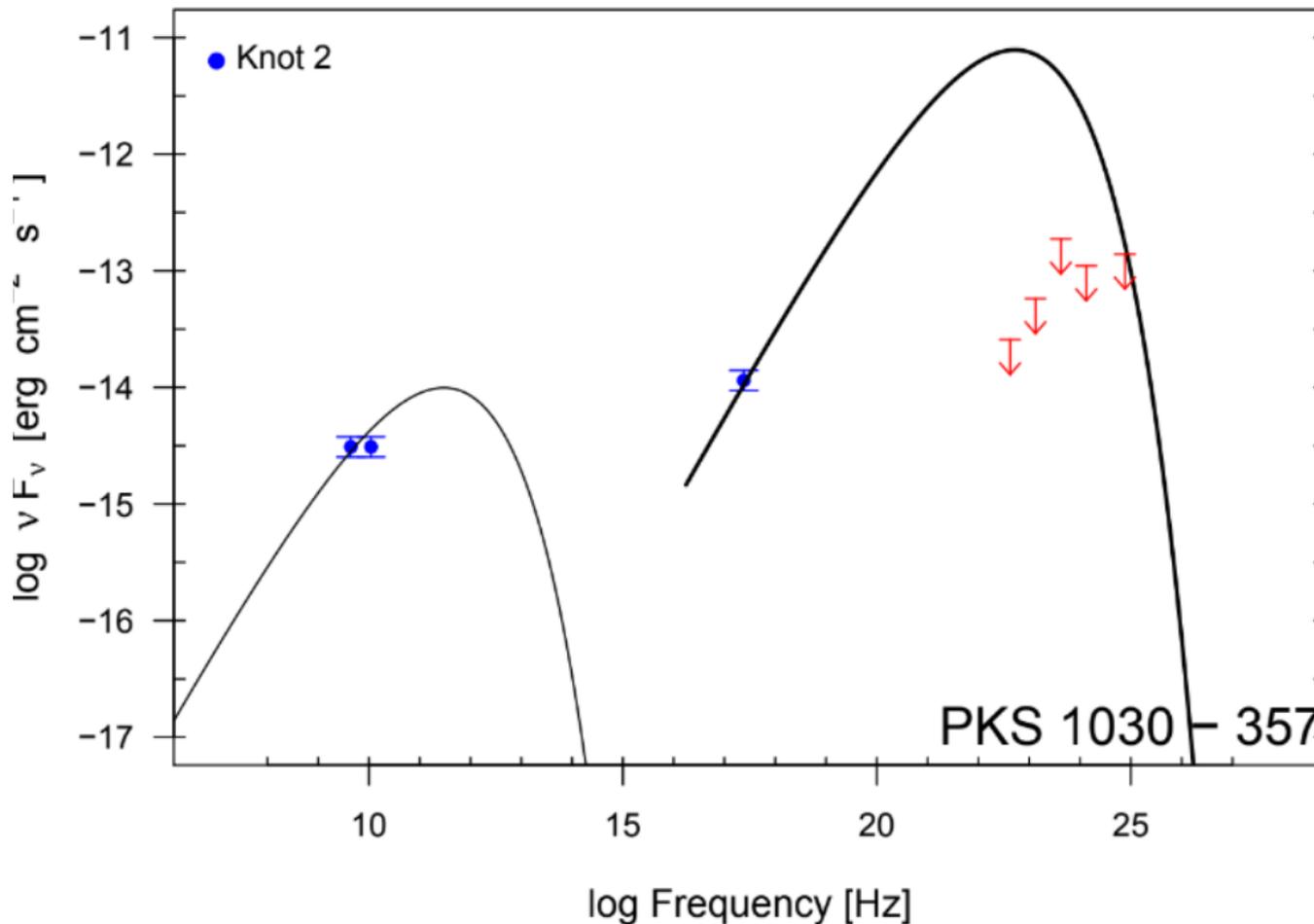
← Very high X-ray flux, so the predicted gamma-rays from IC/CMB are… crazy.

We don't need to use 9+ years of data (as here) to get good limits.

We'll do a 2-year fit to make it a little faster.

Methods

- **Standard Binned Analysis using 3FGL catalog sources**

- **Follow all the way through max likelihood to get initial fit.**

Data

Data

LAT Photon, Event, and Spacecraft Data Query

Object name or coordinates: PKS 1030-357

Coordinate system: J2000

Search radius (degrees): 10

Observation dates: 239557417,302313602

Beginning of Operations (Aug 2008) through Aug 1 2010

Time system: MET

Energy range (MeV): 100,1000000

LAT data type: Photon

Spacecraft data: ☑

Start Search   Reset

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Data

You can get the photon and spacecraft files for this demo here:

http://astro.umbc.edu/~meyer/upload
bin/fermi_summer_2018/

gtselect, gtmktime

```
[fermi@317a2d7ae456 pks1030-357]$ gtselect evclass=128 evtype=3
Input FT1 file[] @files.txt
Output FT1 file[] pks1030_binned_filtered.fits
RA for new search center (degrees) (0:360) [INDEF]
Dec for new search center (degrees) (-90:90) [INDEF]
radius of new search region (degrees) (0:180) [INDEF]
start time (MET in s) (0:) [INDEF]
end time (MET in s) (0:) [INDEF]
lower energy limit (MeV) (0:) [30] 100
upper energy limit (MeV) (0:) [300000] 100000
maximum zenith angle value (degrees) (0:180) [180] 90
Done.
```

```
[fermi@317a2d7ae456 pks1030-357]$ gtmktime
Spacecraft data file[] L180601151725268CC1D909_SC00.fits
Filter expression[DATA_QUAL>0 && LAT_CONFIG==1 && ABS(ROCK_ANGLE)<52] (DATA_QUAL>0)&&(LAT_CONFIG==1)
Apply ROI-based zenith angle cut[yes] no
Event data file[] pks1030_binned_filtered.fits
Output event file name[] pks1030_binned_gti.fits
[fermi@317a2d7ae456 pks1030-357]$
```

gtbin – counts map (optional)

Nothing obvious shows up at our source location – good (if you're not expecting a signal).
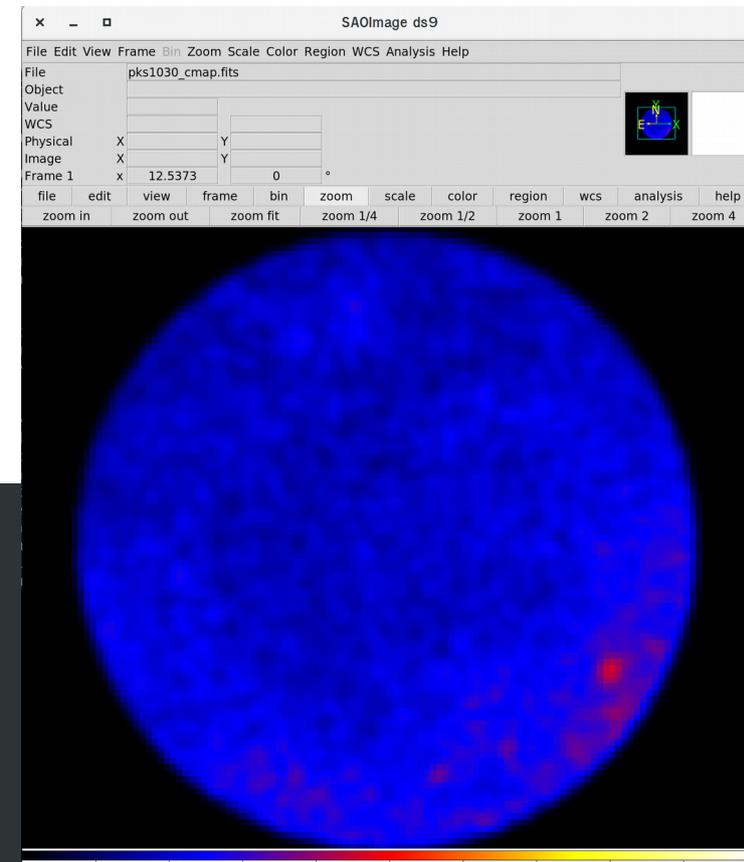

```
[fermi@317a2d7ae456 pks1030-357]$ gtbin
This is gtbin version ScienceTools-v11r5p3-fssc-20170716
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [PHA2] CMAP
Event data file name[] pks1030_binned_gti.fits
Output file name[] pks1030_cmap.fits
Spacecraft data file name[NONE]
Size of the X axis in pixels[] 200
Size of the Y axis in pixels[] 200
Image scale (in degrees/pixel)[] 0.2
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [CEL]
First coordinate of image center in degrees (RA or galactic l)[] 158.282
Second coordinate of image center in degrees (DEC or galactic b)[] -36.0324
Rotation angle of image axis, in degrees[0.]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[AIT]
gtbin: WARNING: No spacecraft file: EXPOSURE keyword will be set equal to ontime.
[fermi@317a2d7ae456 pks1030-357]$ ds9 pks1030_cmap.fits  &
```

3D Binned Counts Map

```
[fermi@317a2d7ae456 pks1030-357]$ gtbin
This is gtbin version ScienceTools-v11r5p3-fssc-20170716
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [CMAP] CCUBE
Event data file name[pks1030_binned_gti.fits] pks1030_binned_gti.fits
Output file name[pks1030_cmap.fits] pks1030_binned_ccube.fits
Spacecraft data file name[NONE]
Size of the X axis in pixels[200] 100
Size of the Y axis in pixels[200] 100
Image scale (in degrees/pixel)[0.2] 0.2
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [CEL]
First coordinate of image center in degrees (RA or galactic l)[158.282]
Second coordinate of image center in degrees (DEC or galactic b)[-36.0324]
Rotation angle of image axis, in degrees[0]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[AIT]
Algorithm for defining energy bins (FILE|LIN|LOG) [LOG]
Start value for first energy bin in MeV[30] 100
Stop value for last energy bin in MeV[200000] 100000
Number of logarithmically uniform energy bins[0] 20
gtbin: WARNING: No spacecraft file: EXPOSURE keyword will be set equal to ontime.
[fermi@317a2d7ae456 pks1030-357]$
```

Preparing for Livetime/Exposure

- **Download (or locate) diffuse emission file, make3FGLxml.py, etc**

- **Make an initial model XML file from 3FGL catalog:**

```
[fermi@317a2d7ae456 pks1030-357]$ python make3FGLxml.py gll_psc_v16.fit pks1030_binned_gti.fits -o pks1030_init_model.xml -G gll_iem_v06.fits -g gll_iem_
v06 -I iso_P8R2_SOURCE_V6_v06.txt -i iso_P8R2_SOURCE_V6_v06 -s 100 -p TRUE -v TRUE
/home/fermi/astrosoft/sciencetools/x86_64-unknown-linux-gnu-libc2.12/lib/python2.7/site-packages/pyfits/__init__.py:22: PyFITSDeprecationWarning: PyFITS
is deprecated, please use astropy.io.fits
  PyFITSDeprecationWarning)  # noqa
This is make3FGLxml version 01r01.
The default diffuse model files and names are for pass 8 and assume you have v10rxxpxx of the Fermi Science Tools or higher.
Creating file and adding sources from 3FGL
Added 87 point sources, note that any extended sources in ROI were modeled as point sources becaue psForce option was set to True
[fermi@317a2d7ae456 pks1030-357]$
```

Livetime

```
[fermi@317a2d7ae456 pks1030-357]$ gtltcube
Event data file[] pks1030_binned_gti.fits
Spacecraft data file[] L180601151725268CC1D909_SC00.fits
Output file[expCube.fits] pks1030_binned_ltcube.fits
Step size in cos(theta) (0.:1.) [0.025]
Pixel size (degrees)[1]
Working on file L180601151725268CC1D909_SC00.fits
.....................!
[fermi@317a2d7ae456 pks1030-357]$ 
```

Takes 2-3 hours to run depending on your system... get the file here:
astro.umbc.edu/~meyer/uploadbin/fermi_summer_2018

Binned Exp Map

```
[fermi@317a2d7ae456 pks1030-357]$ gtexpcube2
Livetime cube file[] pks1030_binned_ltcube.fits
Counts map file[] none
Output file name[] pks1030_binned_excube.fits
Response functions to use[CALDB] P8R2_SOURCE_V6
Size of the X axis in pixels[INDEF] 200
Size of the Y axis in pixels[INDEF] 200
Image scale (in degrees/pixel)[INDEF] 0.2
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [GAL] CEL
First coordinate of image center in degrees (RA or galactic l)[INDEF] 158.282
Second coordinate of image center in degrees (DEC or galactic b)[INDEF] -36.0324
Rotation angle of image axis, in degrees[0.]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN[CAR] AIT
Start energy (MeV) of first bin[INDEF] 100
Stop energy (MeV) of last bin[INDEF] 100000
Number of logarithmically-spaced energy bins[INDEF] 20
Computing binned exposure map....................!
[fermi@317a2d7ae456 pks1030-357]$
```

SrcMap

```
[fermi@317a2d7ae456 pks1030-357]$ gtsrcmaps
Exposure hypercube file[pks1030_binned_ltcube.fits]
Counts map file[pks1030_init_model.xml] pks1030_binned_ccube.fits
Source model file[pks1030_binned_excube.fits] pks1030_init_model.xml
Binned exposure map[pks1030_binned_srcmaps.fits] pks1030_binned_excube.fits
Source maps output file[CALDB] pks1030_binned_srcmaps.fits
Response functions[CALDB] CALDB
```

Likelihood fit

- **Do a standard coarse/fine likelihood fit (see Jeremy's basic intro to analysis)**

- **Save the final xml file**

- **Fix all the free parameters (!!)**

  – By hand or write/borrow a perl script:

  – astro.umbc.edu/~meyer/uploadbin/fermi_summer_2018/set_xml_fixed.pl

- **Feed this into gttsmap**

Initial TS Map

```
[fermi@317a2d7ae456 pks1030-357]$ gttsmap
Statistic to use (BINNED|UNBINNED) [BINNED]
Counts map file[pks1030_binned_ccube.fits]
Binned exposure map[pks1030_binned_excube.fits]
Exposure hypercube file[pks1030_binned_ltcube.fits]
Source model file[pks1030_fine.xml] pks1030_fine_fixed.xml
Response functions to use[CALDB]
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [MINUIT]
TS map file name[pks1030_init_tsmap.fits]
Number of X axis pixels[40]
Number of Y axis pixels[40]
Image scale (in degrees/pixel)[0.5]
Coordinate system (CEL|GAL) [CEL]
X-coordinate of image center in degrees (RA or l)[158.282]
Y-coordinate of image center in degrees (Dec or b)[-36.0324]
Projection method (AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN) [AIT]
```

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Initial TS Map
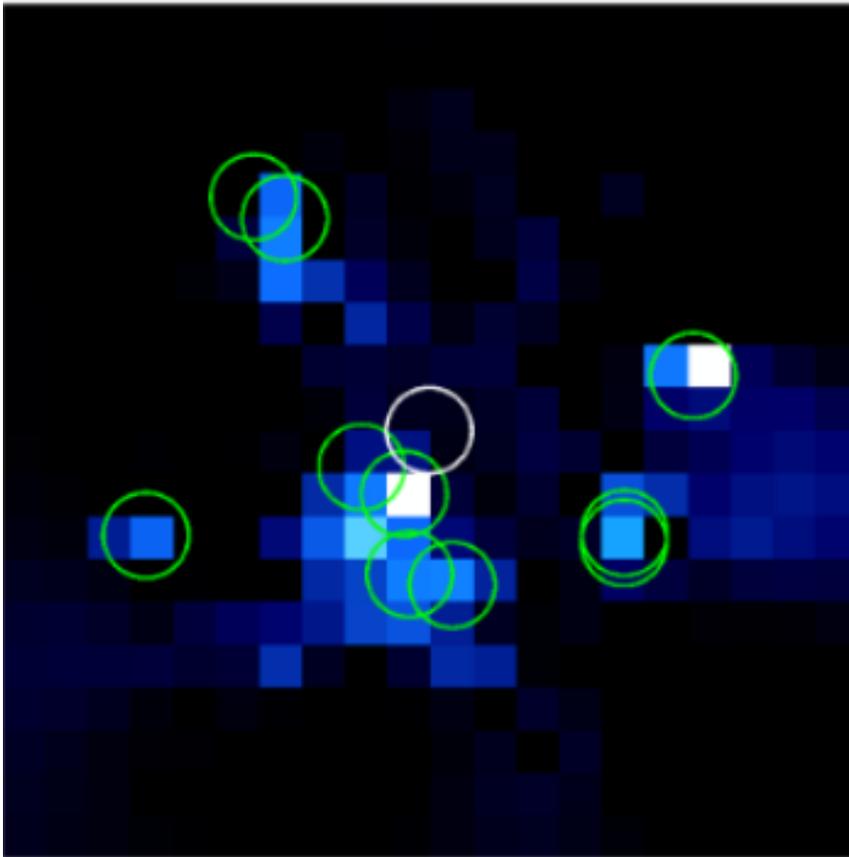
← Green Circles show where new sources were added to the model.

(Note: some were added after a first iteration when there was still some remaining TS residuals).

It is very important especially to account for flux near the source location.

Secondly, always make sure that excess TS is not because you maxed out the normalization of one of your catalog sources!

New Sources

The next step is extremely important: you MUST add any obvious new sources in your ROI to your XML model file.

Here is how our group does this:

1) Starting with the most significant peak (anything over TS ~ 20), use ds9 to find roughly the RA/Dec. Add a power-law source at this location to your XML file.
2) Do a new likelihood fit to initially constrain the normalization/index
3) fix all spectral parameters and optimize on the source location, alone.
4) Final likelihood fit to get the final normalization/index.

^ The main idea is that location and spectral parameters are not fit at the same time. We have found that a single round of iteration is accurate enough.

You continue adding sources in this way until you have no more to add.

Our group has an automated script for this which I can share on request.

Updated TS Maps

- **Fix all sources in your new XML model file and re-run gttsmap**

Breiding et al 2017

White circle is source location

Pixels are 1 deg.
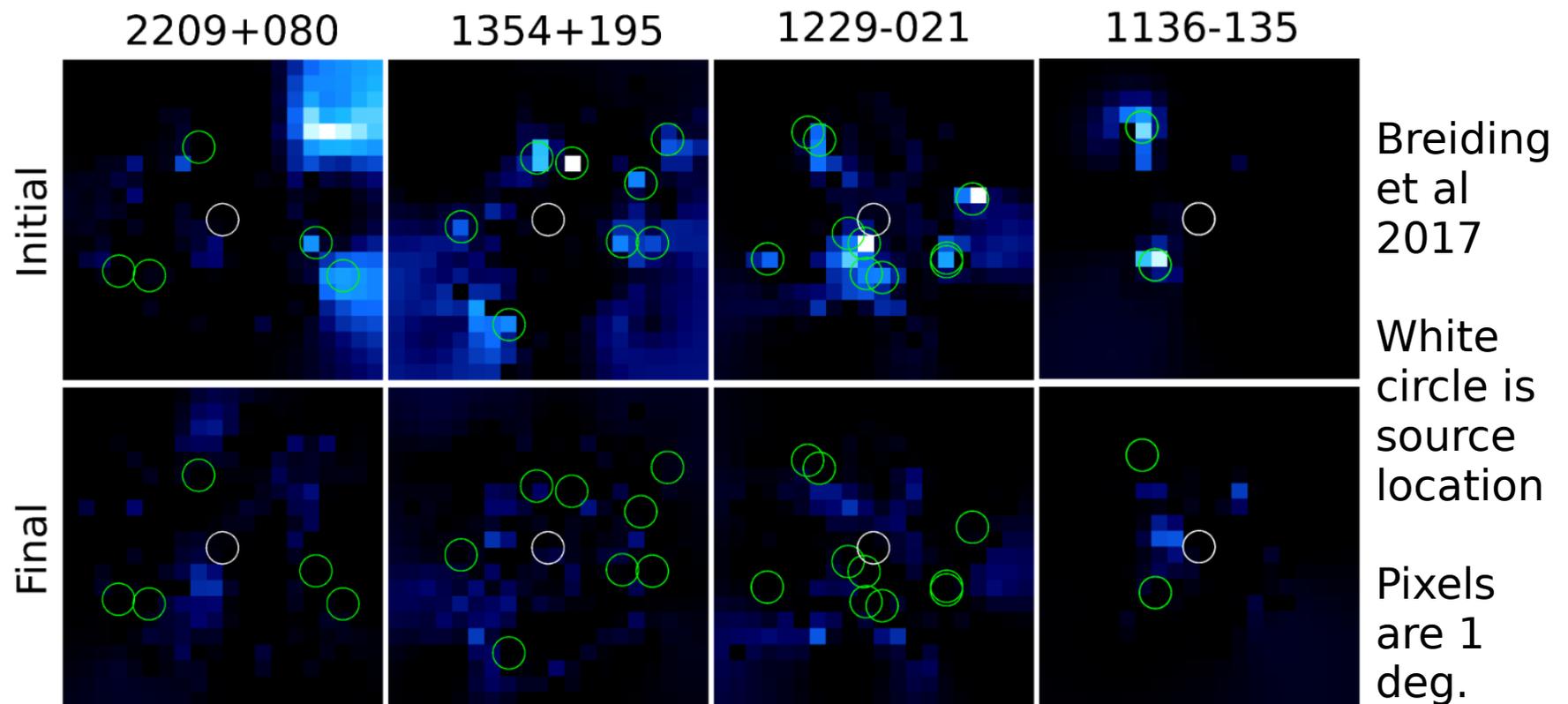
Warnings

- **You MUST do the previous step of finding and fitting new sources. The 3FGL (or whatever latest catalog) cannot be guaranteed to have all the sources in your ROI if you are using more data than the catalog was based on! (I would still do this even if it were a subset of the catalog data, for safety).**

- **If you have "unaccounted for TS" floating around in your ROI and you attempt to do an upper limit or detection experiment at the location of your source, the likelihood fitting may erroneously assign TS to your source! This is especially a concern if there are any new sources very near to your location and no other catalog sources nearby to "absorb" the TS.**

- **Not getting an accurate model file can lead to**

    - (1) False claims of a detection

    - (2) Much higher upper limits than are actually representative.

Calculate Upper Limits!

- **Add a new source to your (frozen) XML file at the RA/Dec. For most faint sources/upper limits a power-law is fine. Your source normalization should be the only thing free (choose a "reasonable" Photon index, or try a range of values if it is important).**

- **Initially similar to likelihood fit, but with extra upper limit calculation at end:**

```
>>> from UpperLimits import UpperLimit
>>> from BinnedAnalysis import *
>>> obs=BinnedObs(srcMaps='pks1030_binned_srcmaps.fits',binnedExpMap='pks1030_binned_excube.fits',expCube='pks1030_binned_ltcube.fits',irfs='CALDB')
>>> like=BinnedAnalysis(obs,'pks1030_for_UL.xml')
Generating SourceMap for newsource...................!
>>> like.optimizer='NewMinuit'
>>> like.tol=1e-3
```

```
>>> likeobj=pyLike.NewMinuit(like.logLike)
>>> like.fit(optObject=likeobj,covar=True)

Minuit did successfully converge.
# of function calls: 19
minimum function Value: 63194.40878689
```

```
ul = UpperLimits(like)
```

```
>>> UL = ul['newsource'].compute()
```

Practical Tips

- **You will probably want an upper limit over several energy bins**

- **This does require you to redo all the 'setup' steps with different energy ranges**

- **Very good idea to script all this!**