SEARCHING FOR NEUTRINOS FROM BLAZAR FLARES WITH ICECUBE AND FERMI-LAT

CHRISTOPH RAAB

2021-09-26

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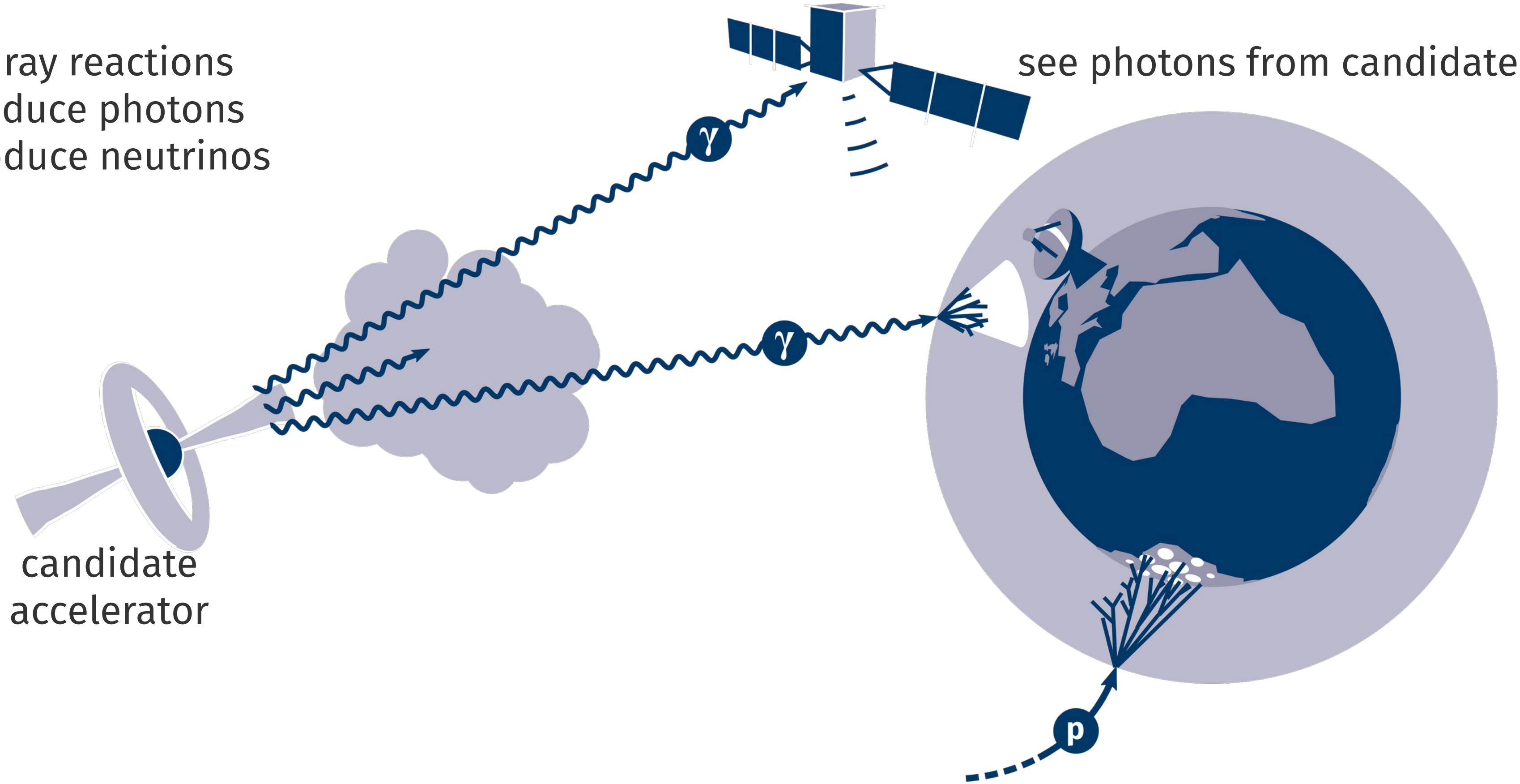
Introduction

Multi-messenger astronomy

Cosmic ray reactions
can produce photons
will produce neutrinos



see photons from candidate

candidate
accelerator

see cosmic rays from *somewhere*

Multi-messenger astronomy

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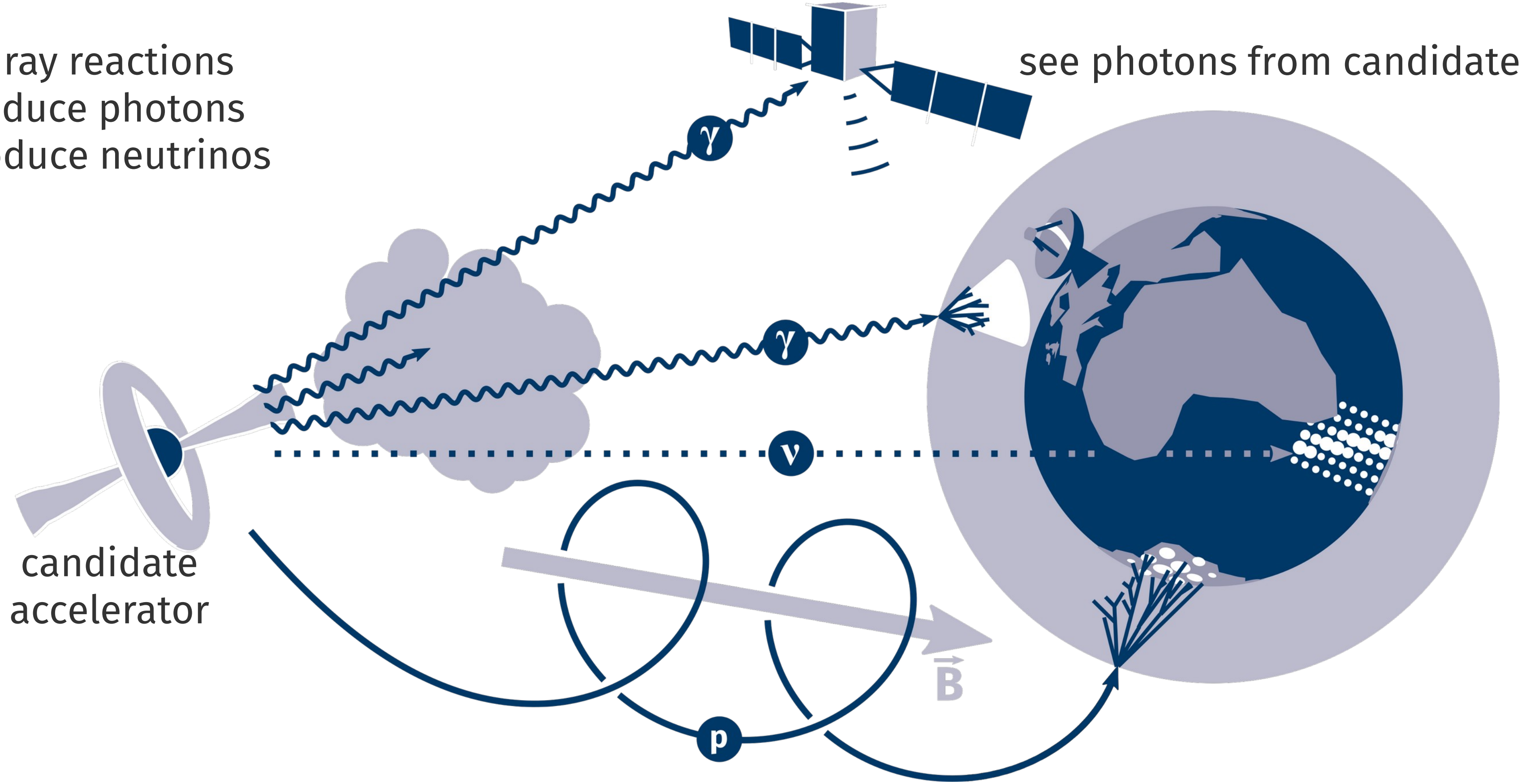
can produce photons
will produce neutrinos

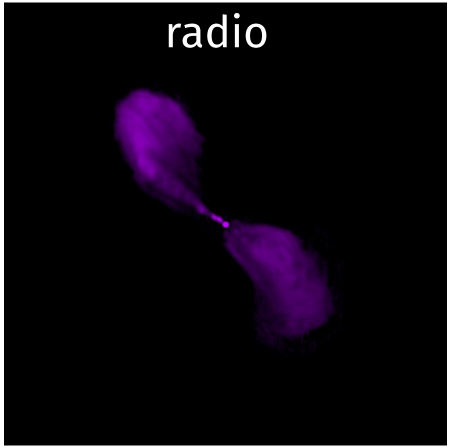
see photons from candidate

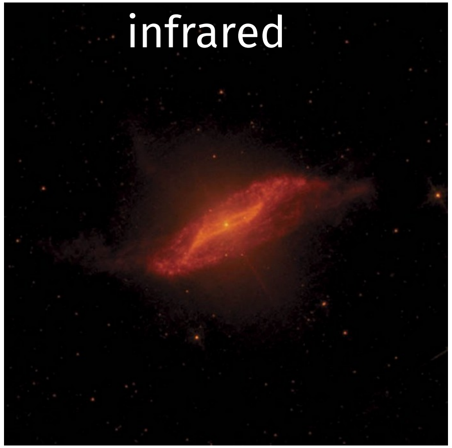


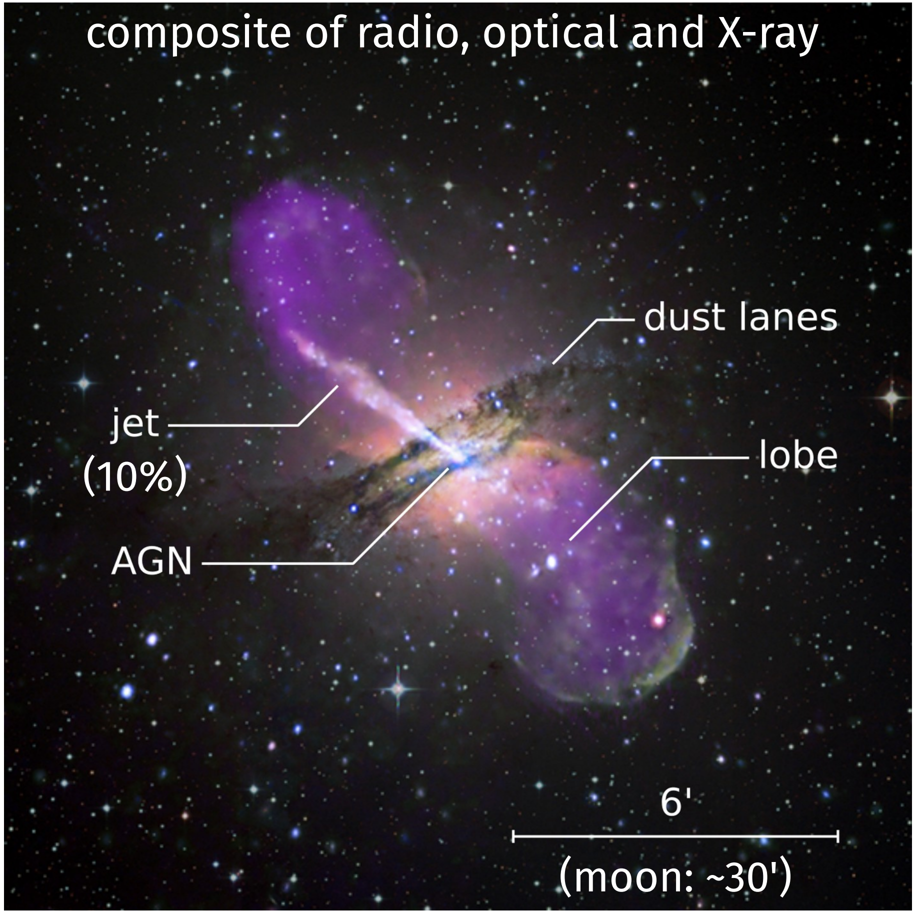
candidate
accelerator

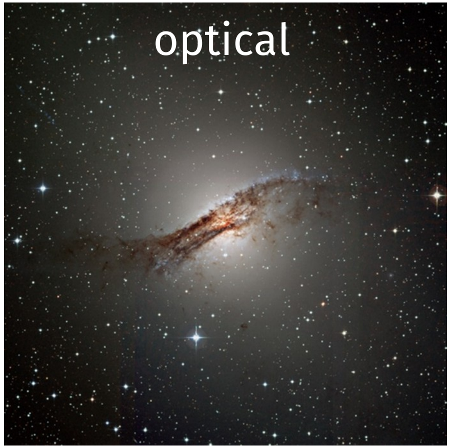
If we see neutrinos as well → cosmic ray reactions at work → see cosmic rays from candidate

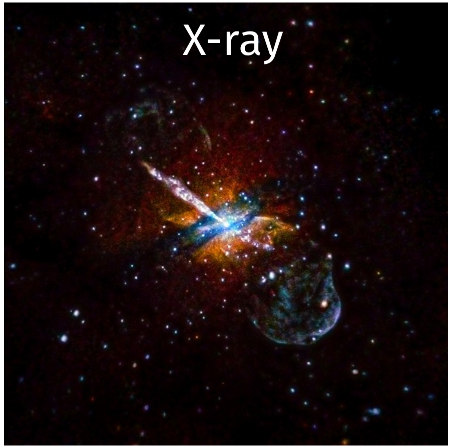
Active galactic nuclei (example Centaurus A)





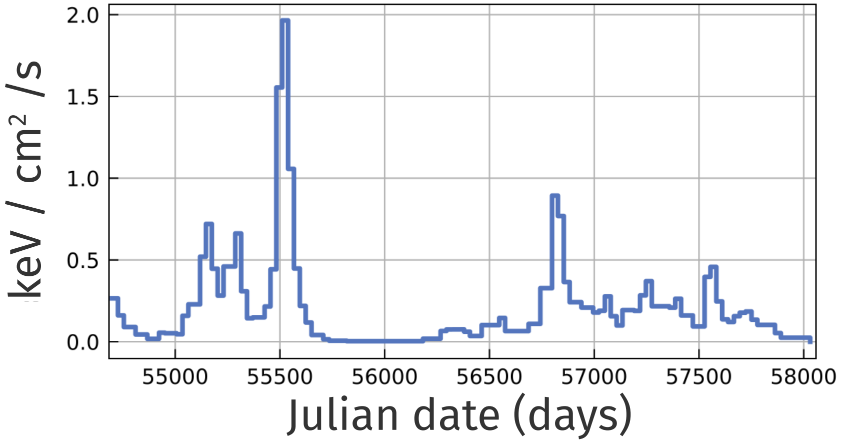


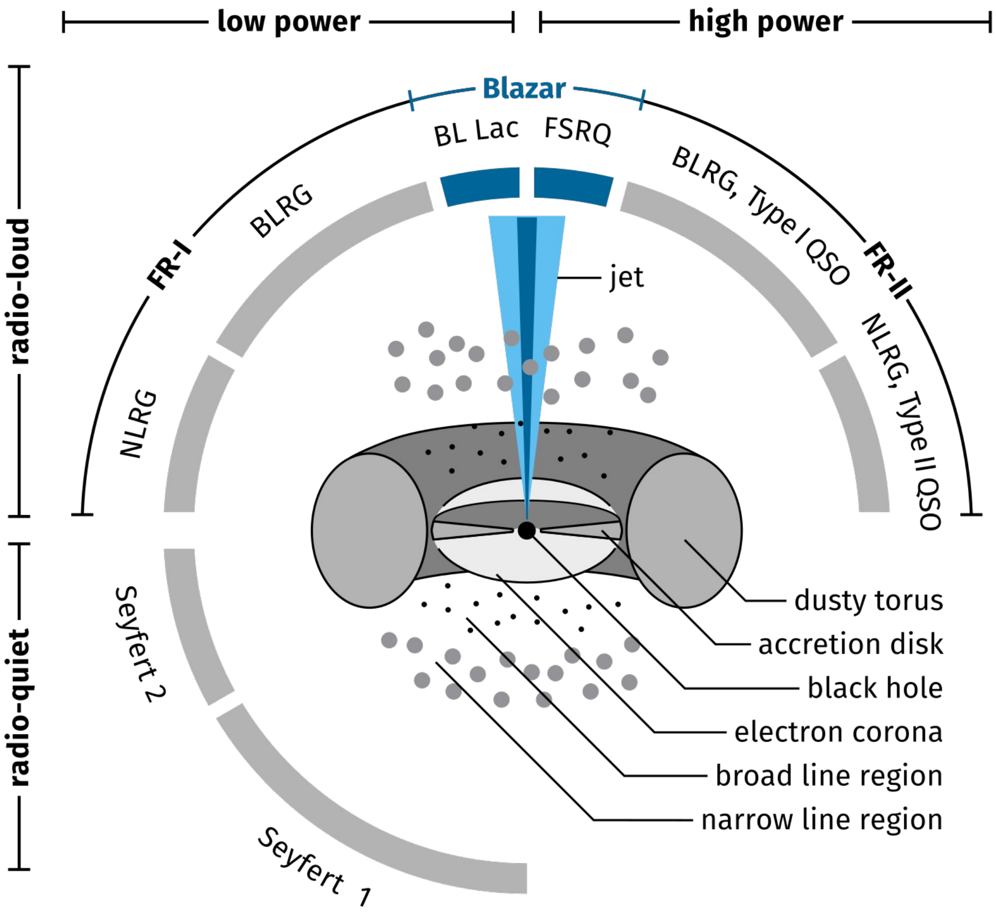




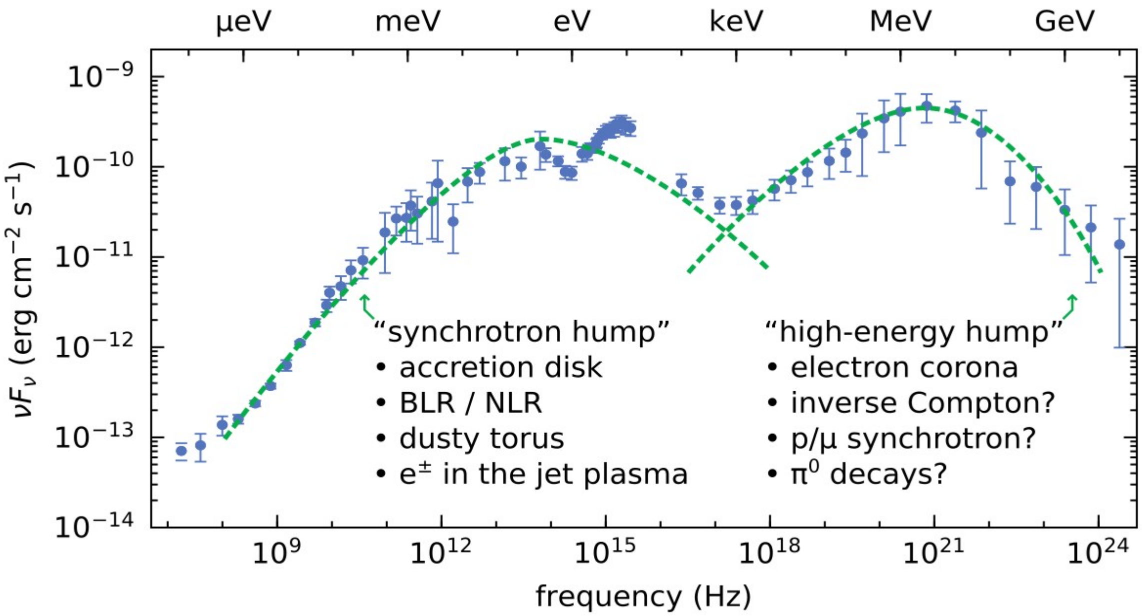
Blazars

- Radio-loud AGN, extended jet
- **Blazar:** looking into jet
- Jet power: BL Lacs and FSRQs
- Blazars have bright gamma-ray emission
- Quiescence & flares:





High-energy blazar emission



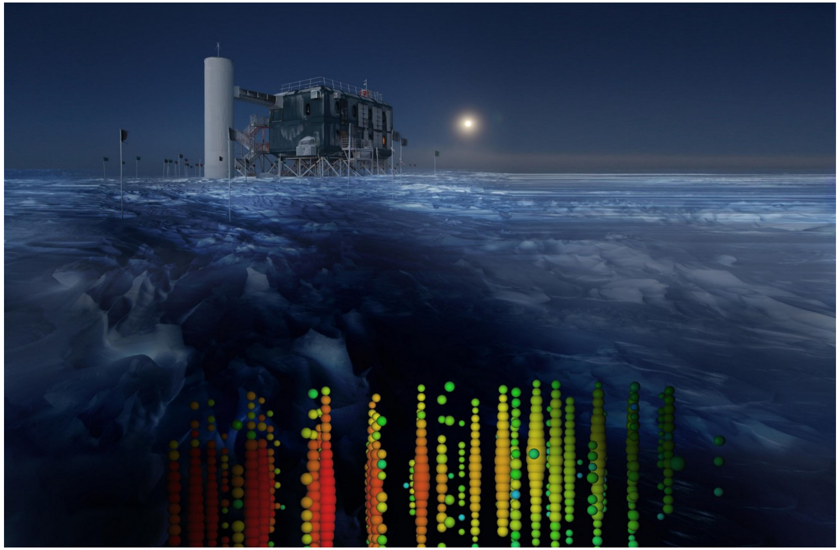
- Dominated by jet
  → Doppler beaming
  → energy, time scale, luminosity
- **Quiescent** emission vs.
- Month – minute **flares**

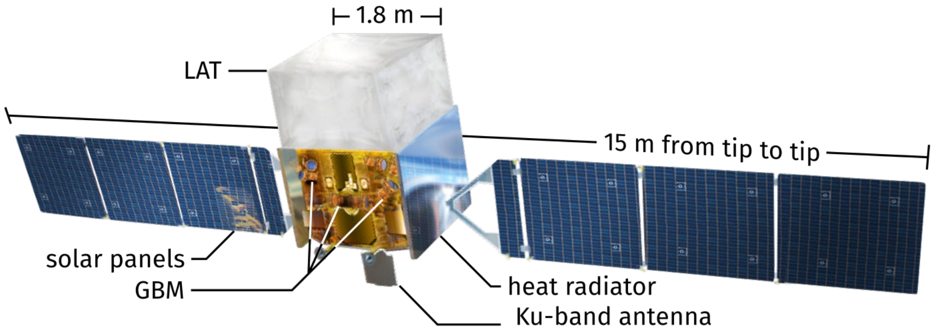
- Leptonic? e.g.
  $e + \gamma_{soft} \rightarrow$ (Compton) $\rightarrow \gamma$
- Hadronic? e.g.
  $p + \gamma_{soft} \rightarrow \ldots \rightarrow \pi^0 \rightarrow \gamma\gamma$
- Candidate shock sites exist
  → neutrino production?

IceCube and Fermi-LAT

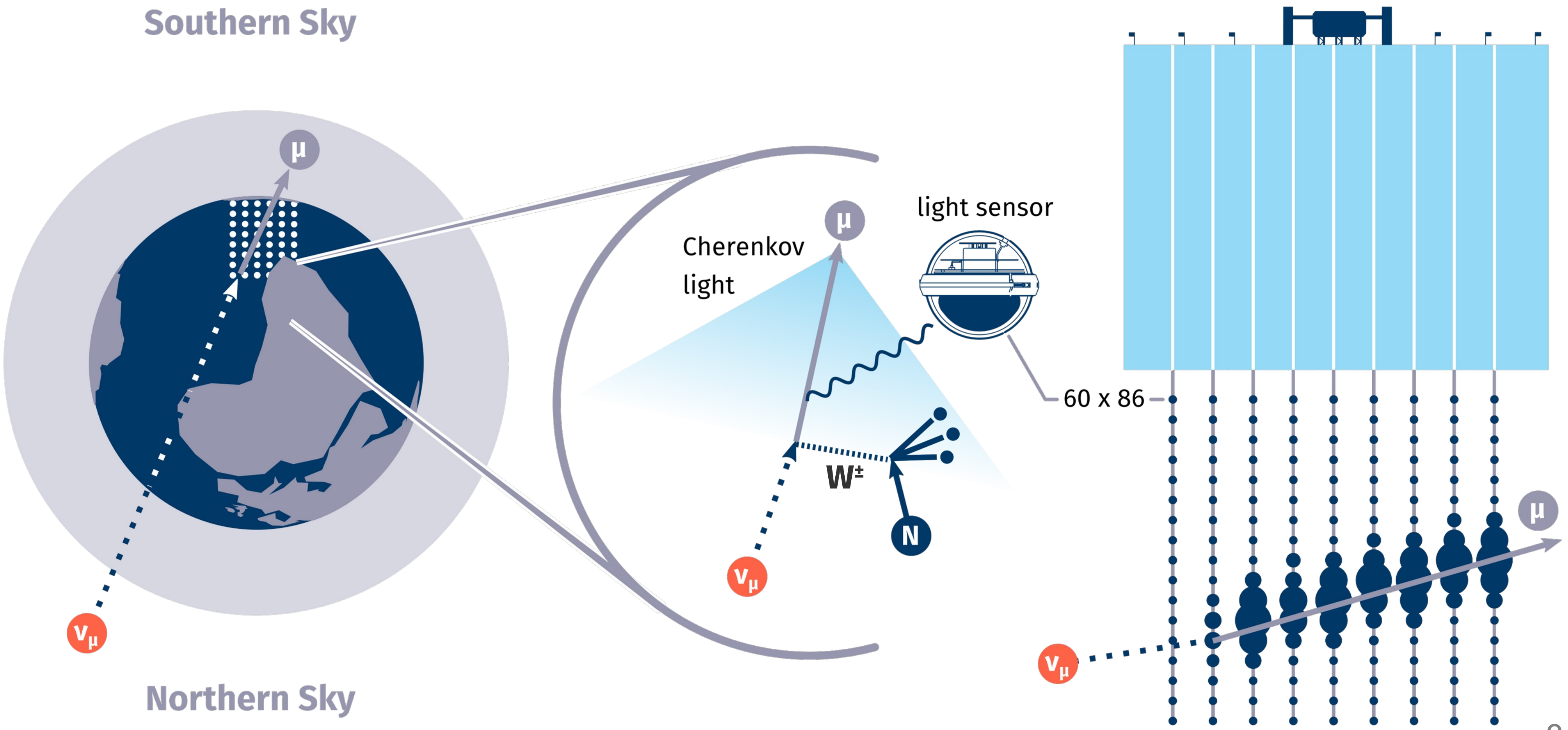
- Neutrino telescope in 1 km^3 of South Pole ice
- Construction 2004 – 2011
- Discovered astrophysical neutrinos
- 100 GeV – 10 PeV

- Gamma-ray space telescope
- Launched 2008
- Monitors O(1000) blazars every 3 hours
- 100 MeV – 300 GeV

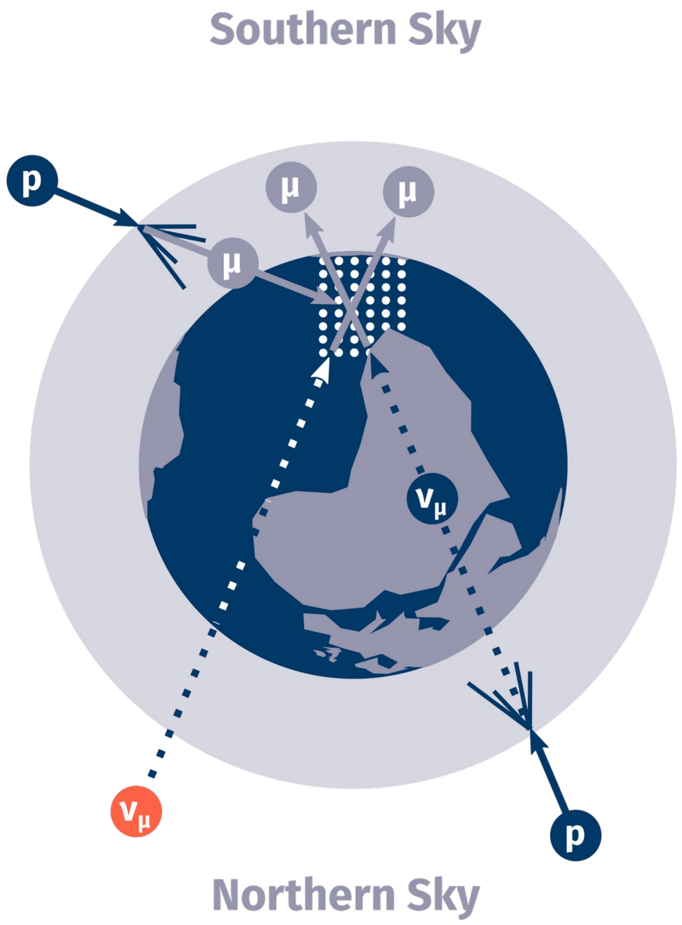




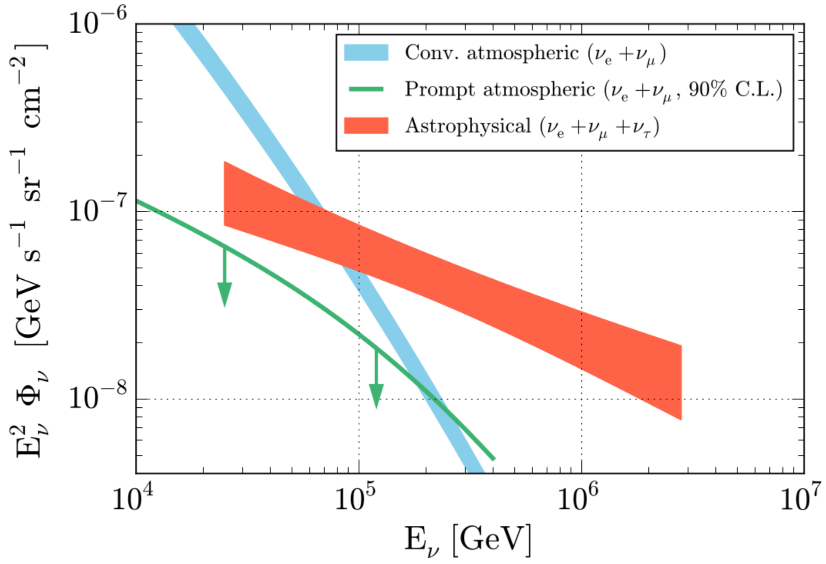
Detection principle for muon neutrino “tracks”



Neutrino detection backgrounds



- High energies: astrophysical
- Low energies: atmospheric
  - South: muons
  - North: neutrinos (muons blocked)



IceCube neutrino sky

- Any sources in an all-sky search?
- High energies: only single astrophysical events (most **not** ν_μ tracks → worse resolution)
- Low-energy tracks: mostly background

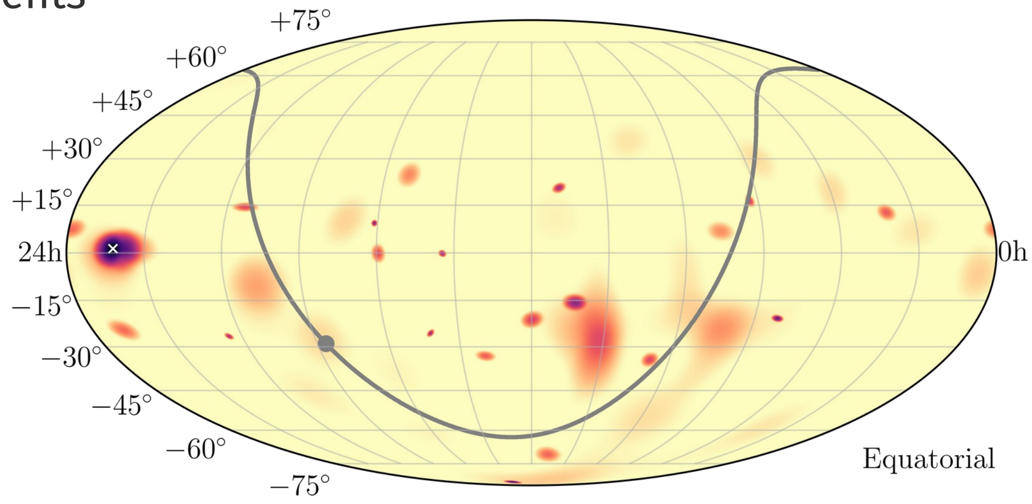
  → No **significant** (5σ) source

  (most: NGC 1068, 4.2σ)

- Look for multi-messenger connection

  → source location from astronomy

  → restrict hypothesis space



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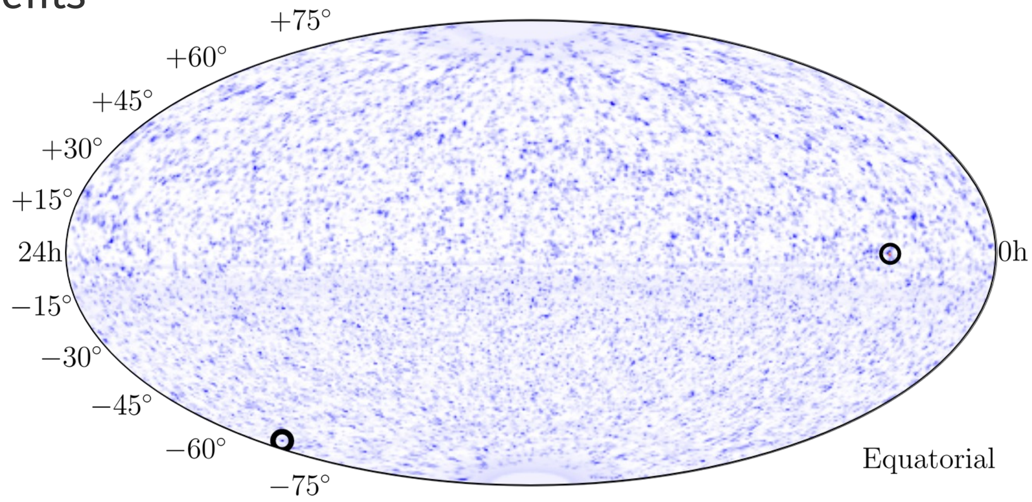
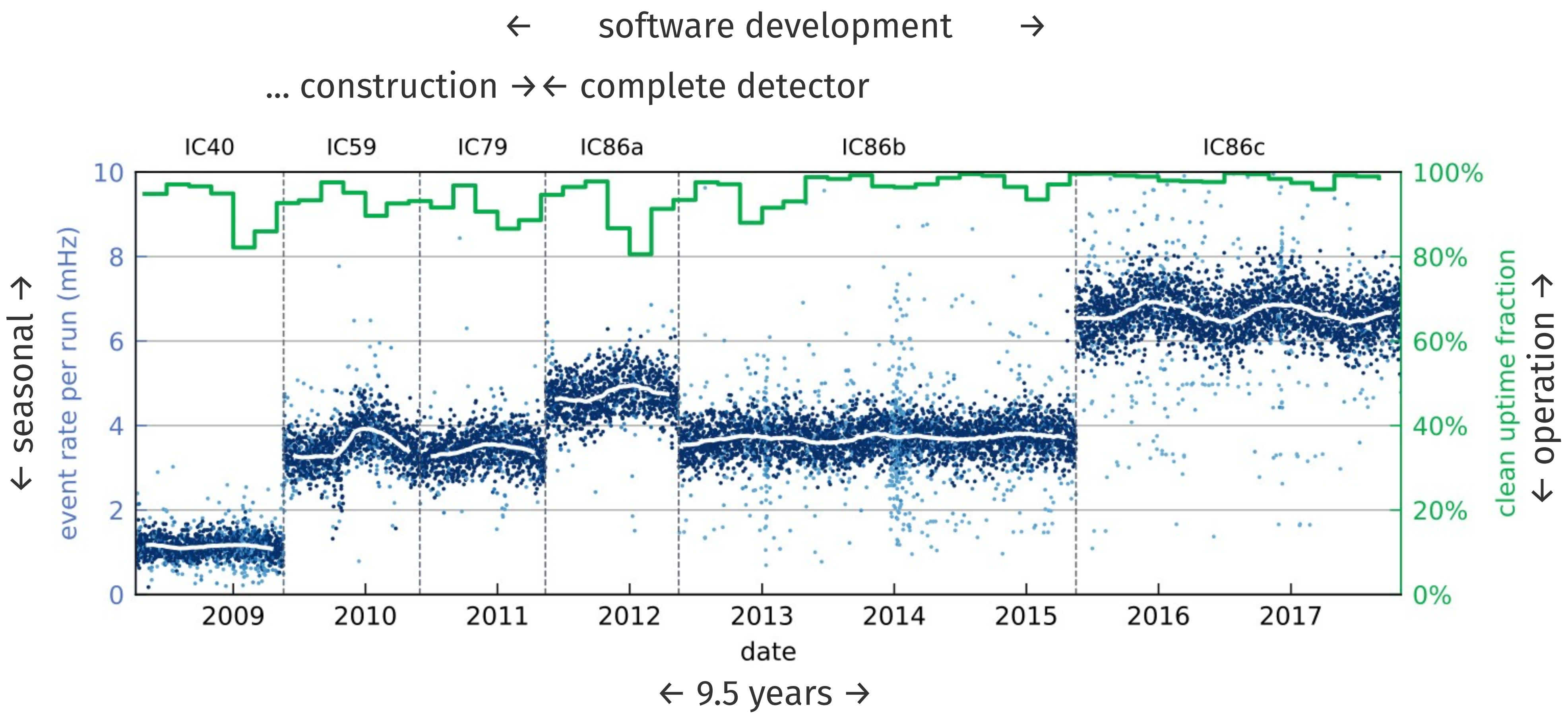


- Look for multi-messenger connection

→ source location from astronomy

→ restrict hypothesis space

Data set

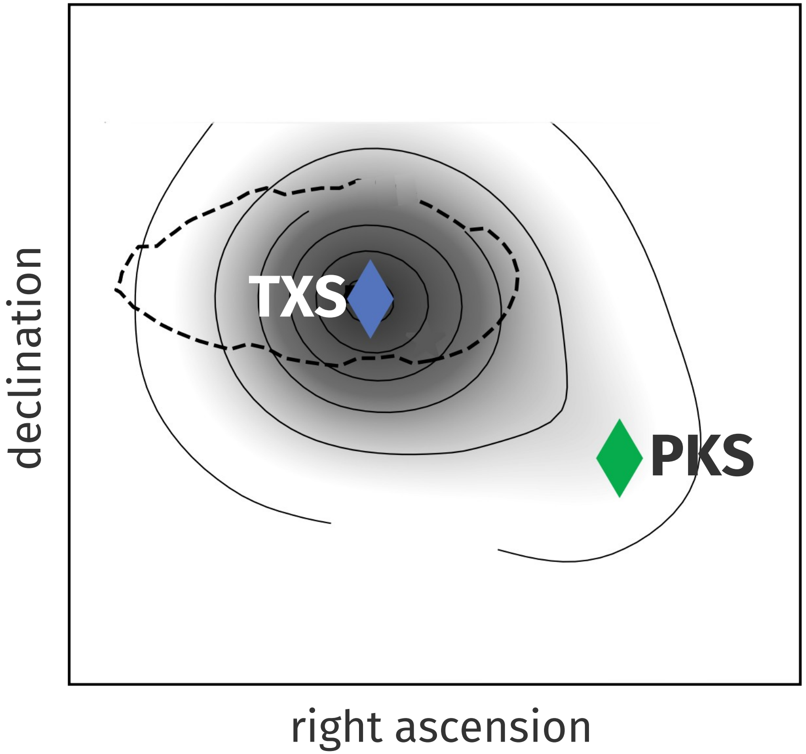

← software development →
... construction →← complete detector
IC40
IC59
IC79
IC86a
IC86b
IC86c
← seasonal →
event rate per run (mHz)
10
8
6
4
2
0
100%
80%
60%
40%
20%
0%
clean uptime fraction
← operation →
2009
2010
2011
2012
2013
2014
2015
2016
2017
date
← 9.5 years →

2

Gamma-ray Lightcurves

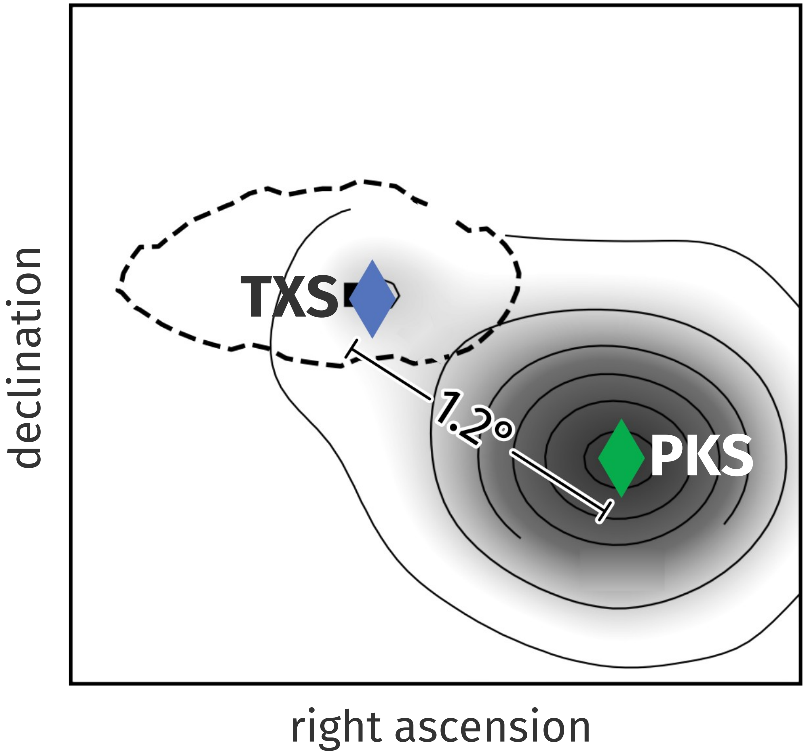
Two blazars, two flares

2017



Flare of TXS 0506+056 dominates field

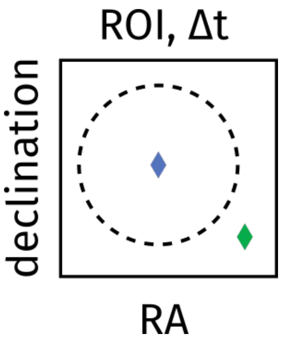
2014/2015



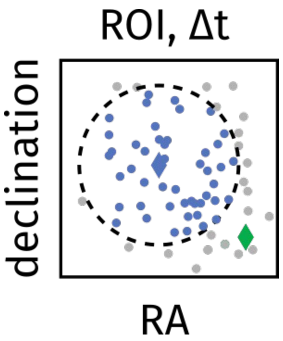
Flare of PKS 0502+049 dominates
Only 1.2° away! → example for method

Old method: aperture photometry

source,
aperture →
time bin

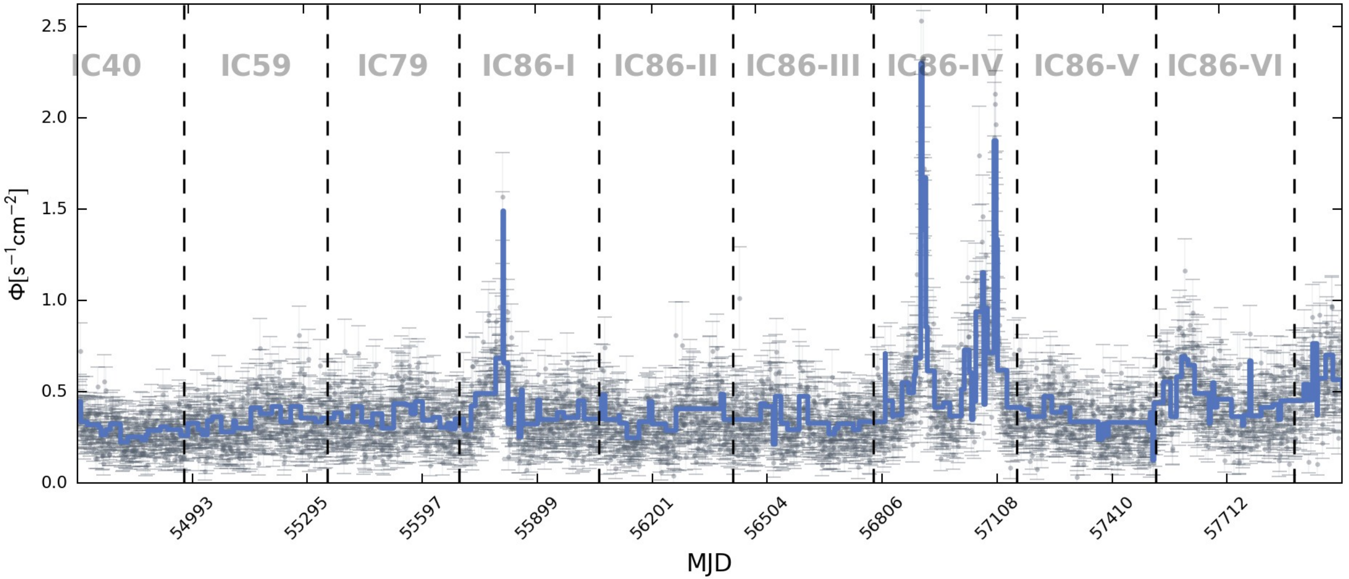


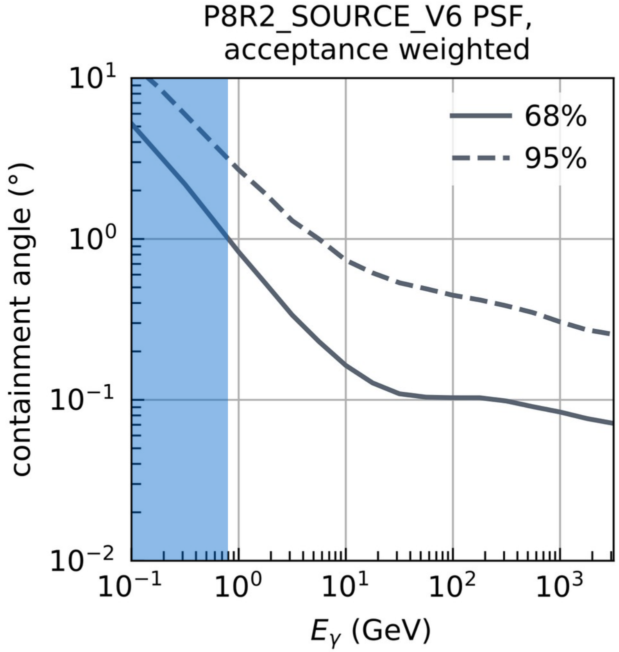
→ photons →



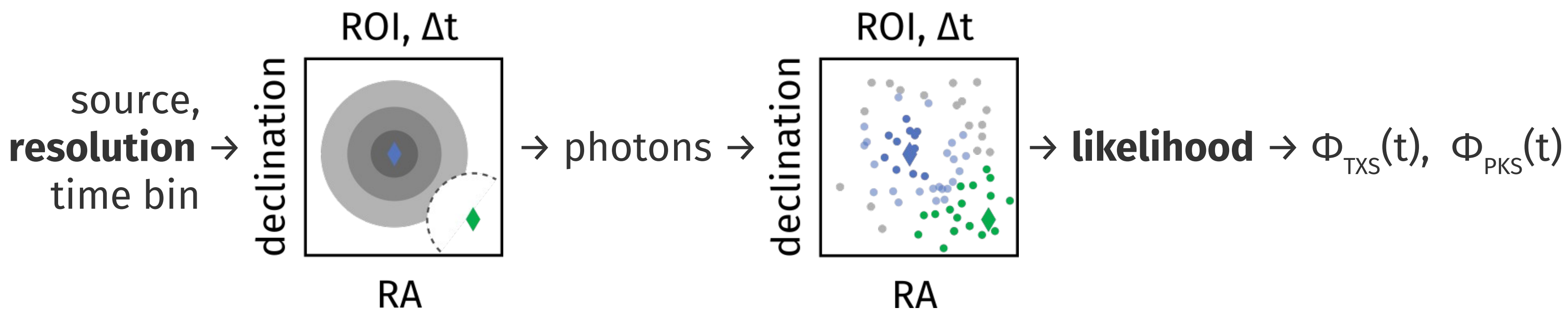
→ exposure → Φ(t)

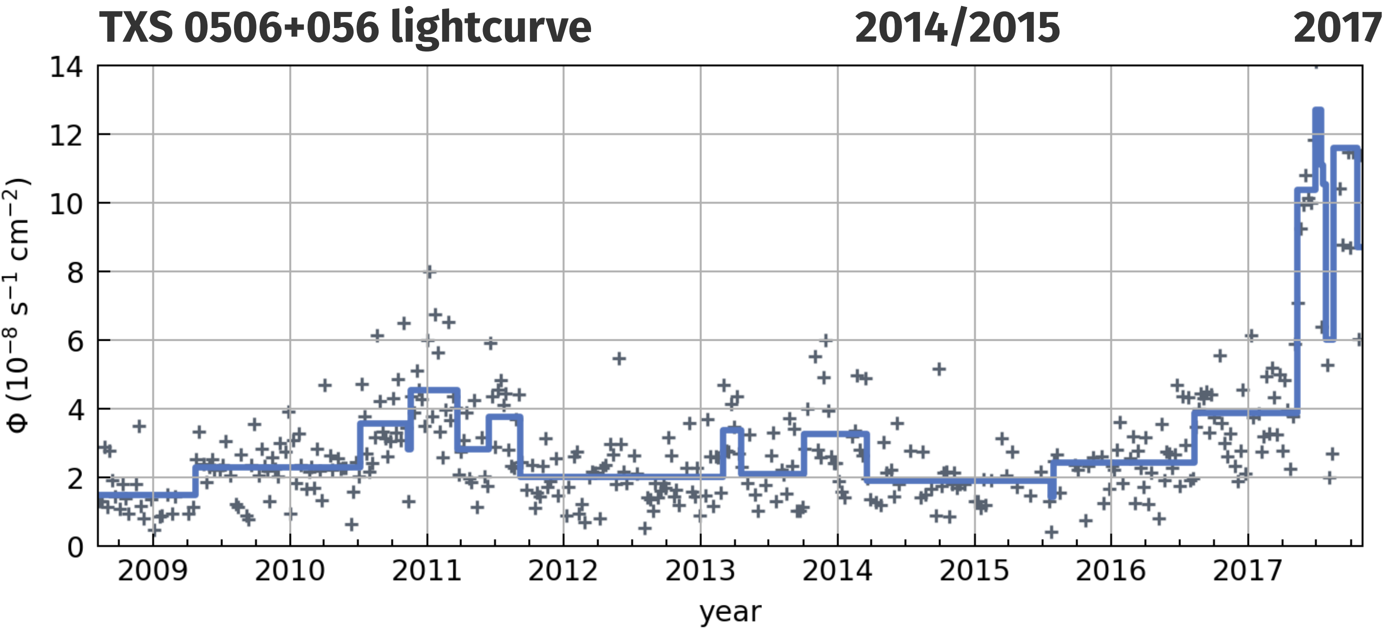
TXS 0506+056 lightcurve **2014/2015** **2017**

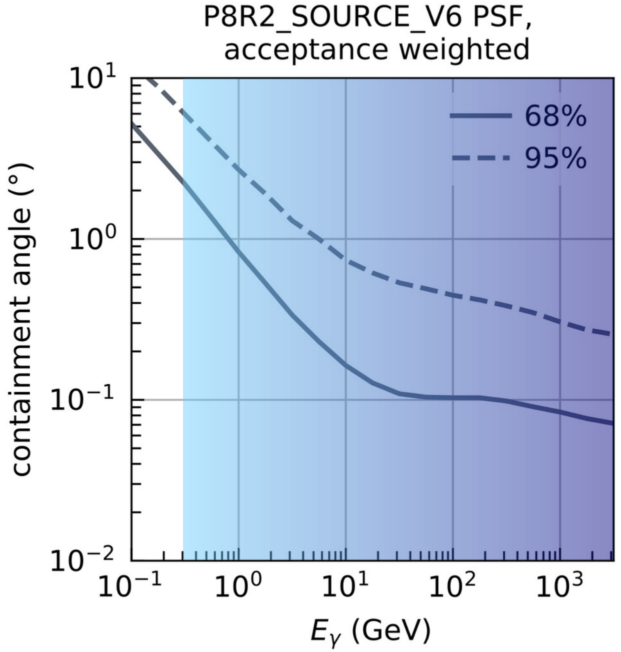




New method: PSF photometry



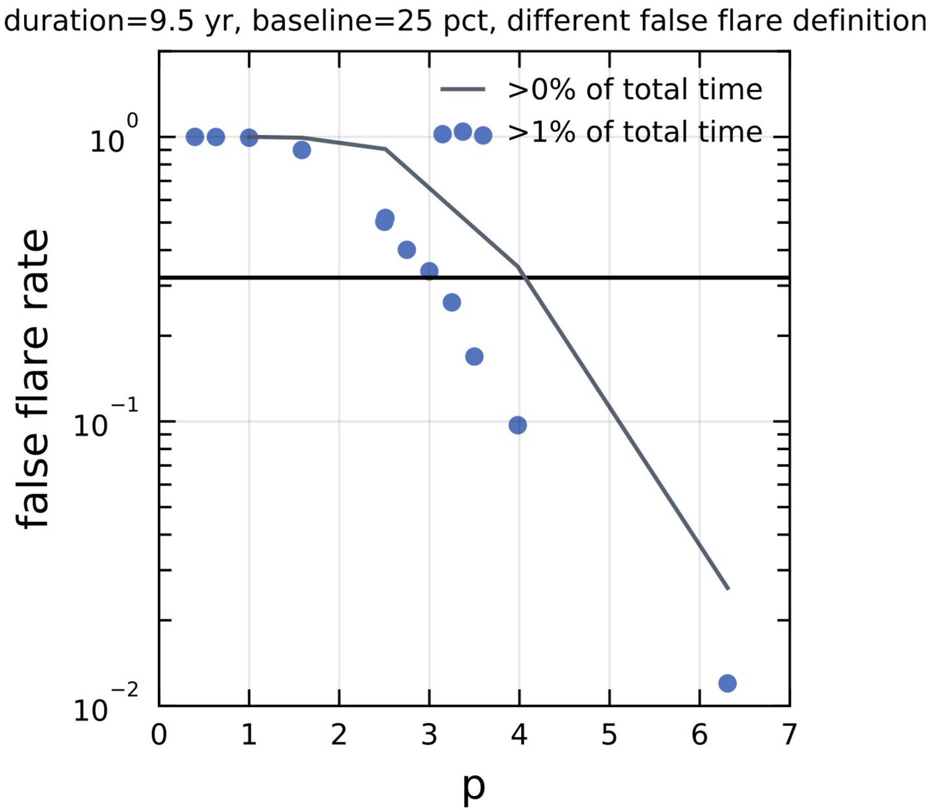




Bayesian blocks optimization

- Statistical fluctuations → Bayesian blocks
- Smoothing strength **p** → optimize
- Simulate steady lightcurves with toy MC
- “False flare” criterium

→ false flare rate (p_{opt} = 3.05) = 32%



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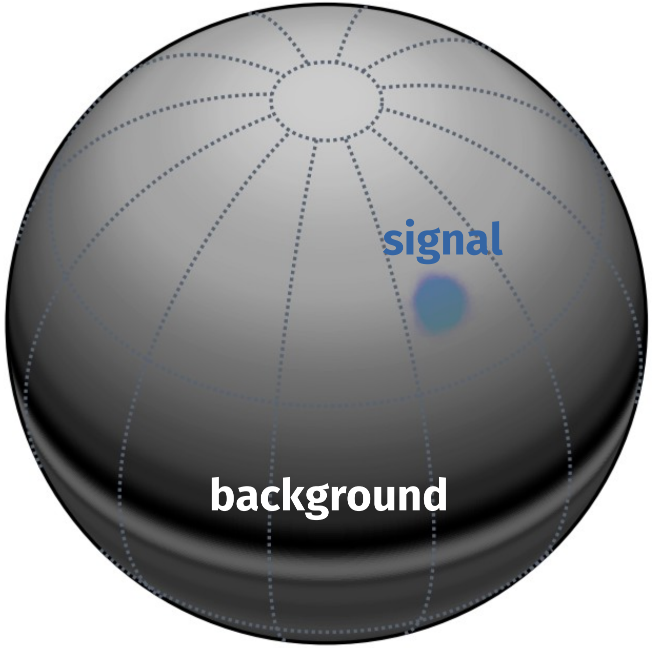
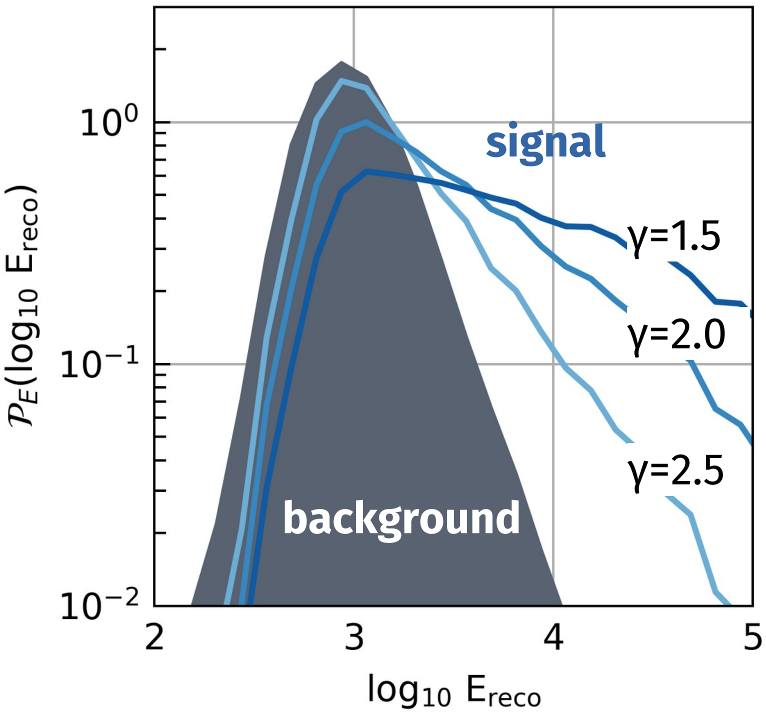
Likelihood Method

Typical time-integrated search

n_s events from a source → spatial PDF



with a spectral index **γ** → energy PDF



→ combine into likelihood L → define test statistic

TS = $2\,\mathrm{sgn}(n_s)\, L(n_s, \gamma) / L(n_s{=}0)$

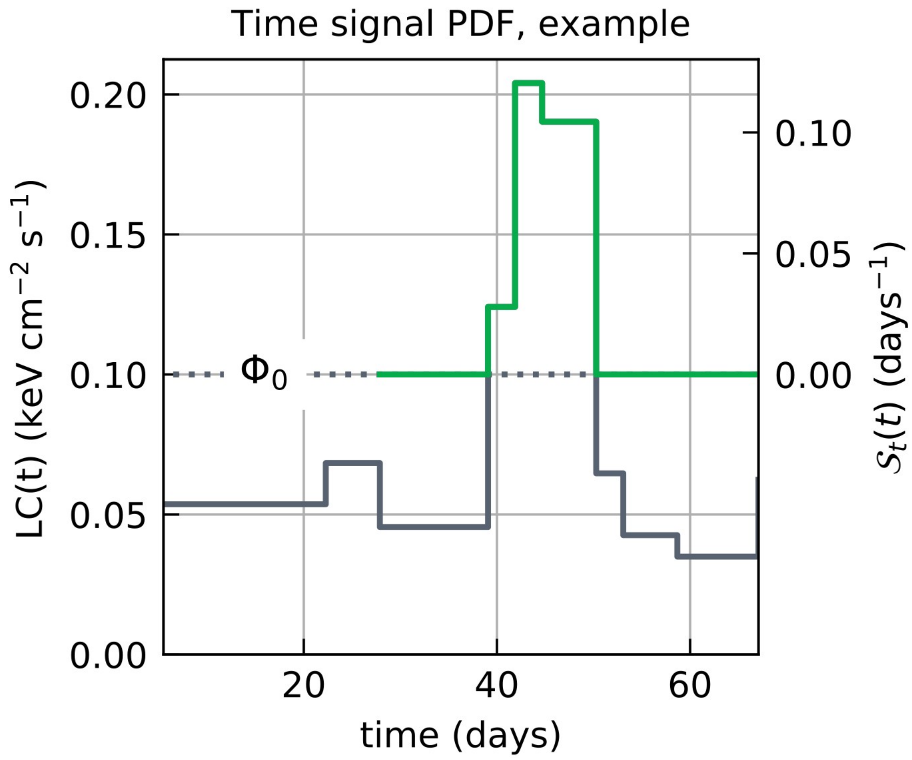
→ maximize **TS** to free parameters of hypothesis **n_s, γ**

Time PDF

- E.g. p-γ in blazar jets → ν∝γ
- Hypothesis: only flares?
- Quiescent flux: free parameter $\mathbf{\Phi_0}$

→ Truncate lightcurve at threshold $\mathbf{\Phi_0}$

→ Extend likelihood with S(t)



Stacking motivation

- Previous time-dependent on **single** blazars
  → need single bright source for discovery

- **Stacking:** signal = $\Sigma_{k=sources}$ w_k $signal_k$
- Requires assumption on relative signal strength
  → "weighting scheme"

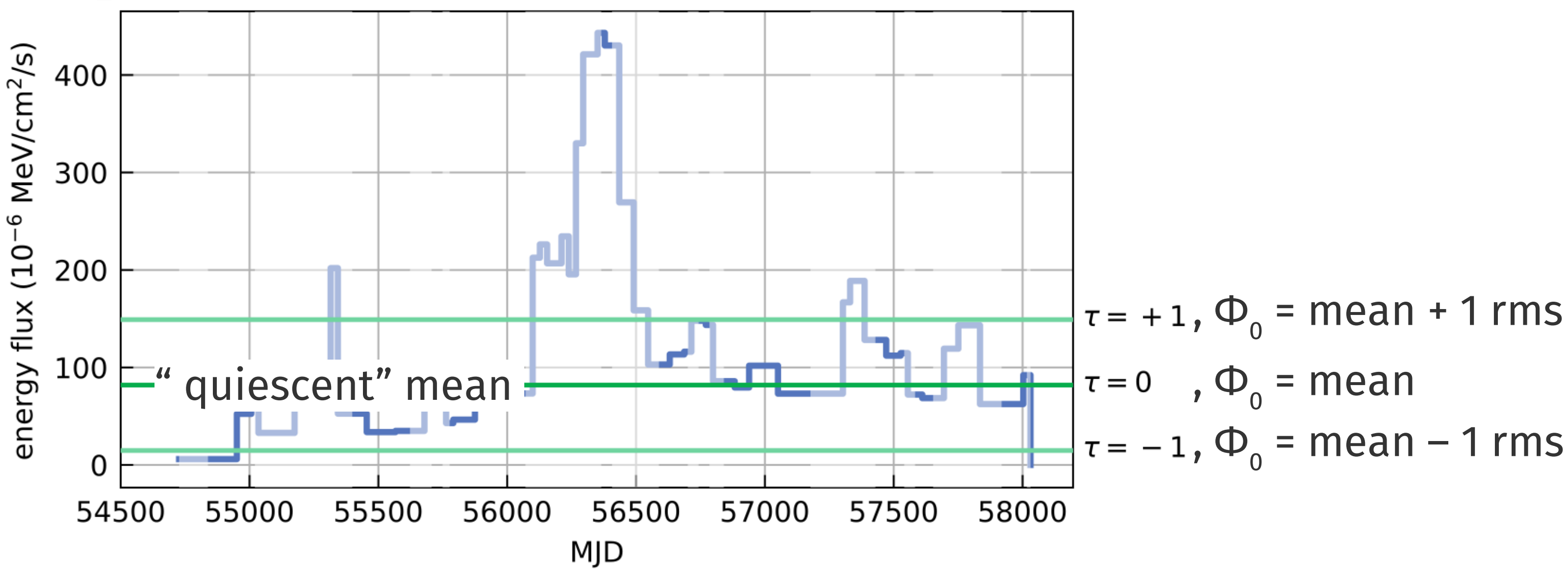
- **Time-integrated** IceCube stacking analyses set limits

  → Do not exploit blazar variability

- Discovery could come from a **stacking analysis** that is also **time-dependent**

Stacking method

- Problem: O(100) lightcurves, each a threshold
- Can not maximize w.r.t. O(100) free parameters
- → Retain one free parameter **τ**
  → determines $\mathbf{\Phi_{0,k}}$ via estimate of quiescent state



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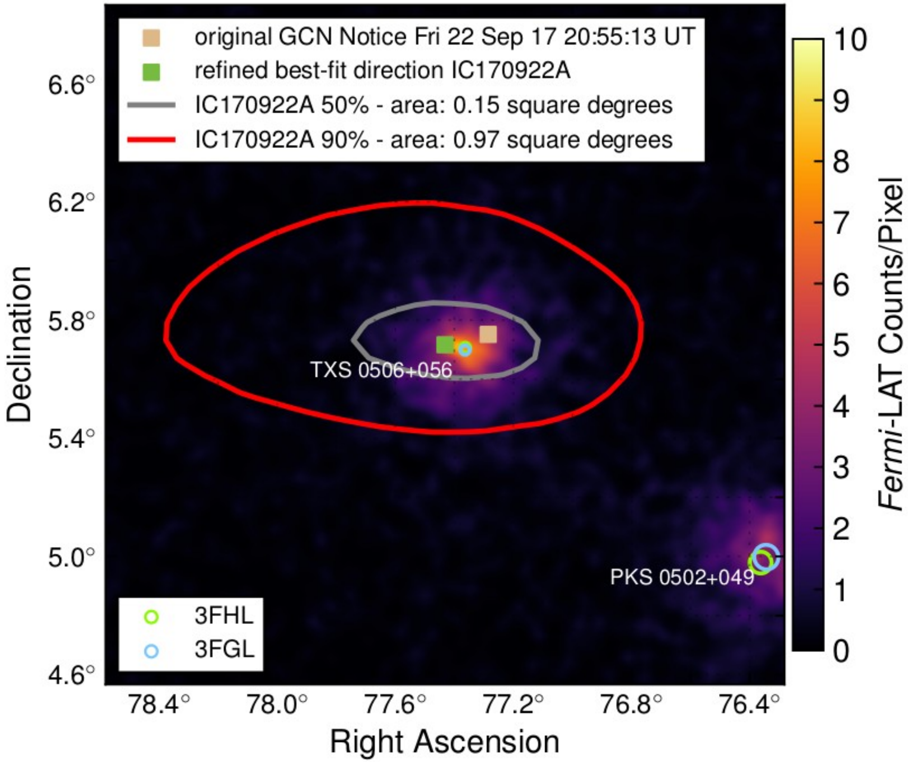
TXS 0506+056

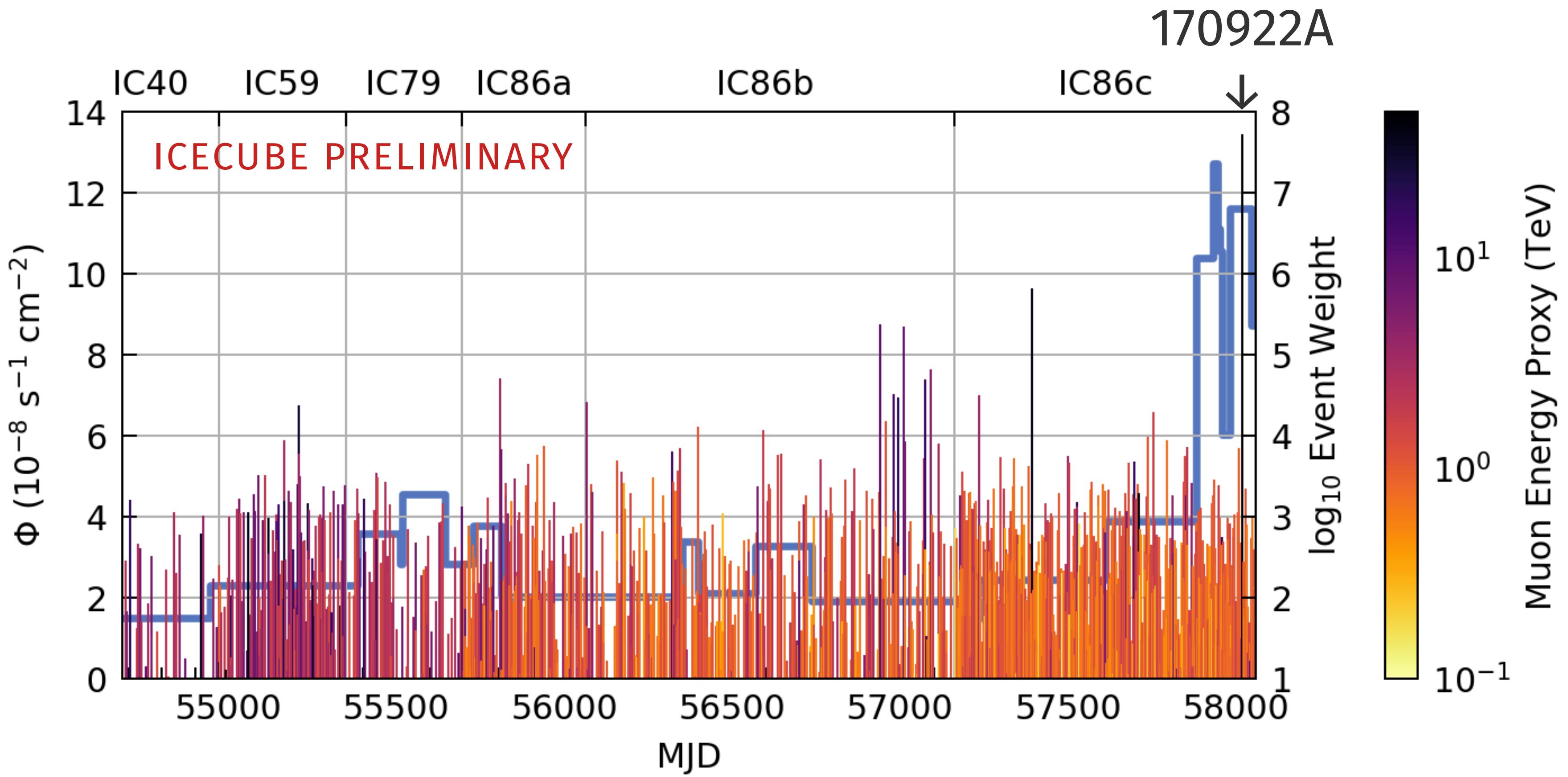
IceCube–170922A

- EHE neutrino alert in 2017
- Coincident with blazar flare of TXS 0506+056
  → large MWL/MMA campaign
- Additional neutrinos
    - at lower energies?
    - correlated to entire lightcurve?

→ develop blinded analysis



Unblinded neutrino times



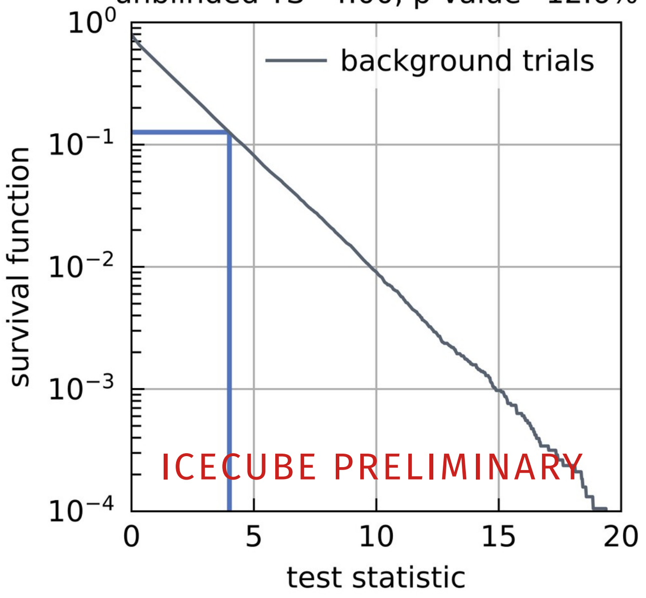
Only a selection shown:
- near TXS
- high energy

→ S/B > 1 (without time weight)

Unblinding results

- **without IceCube-170922A**
- maximize TS on unblinded data
- scramble times → background realization
  → background TS distribution → p-value

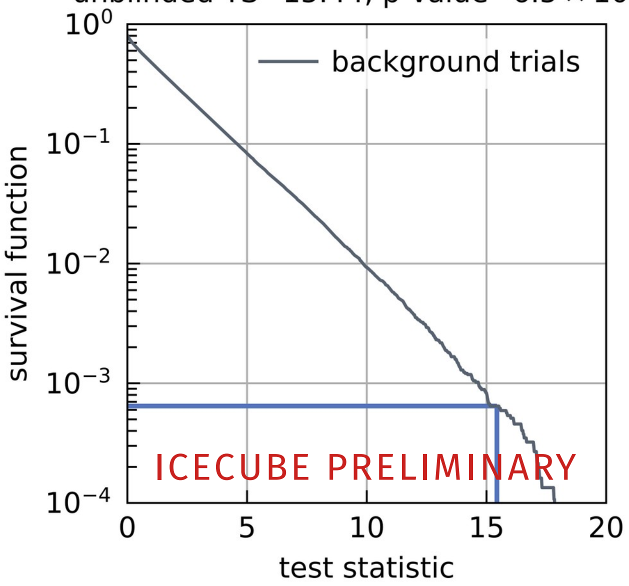
unblinded TS=4.00, p-value=12.6% **= 1.1 σ**



→ **no evidence** for other ν correlated to γ-rays

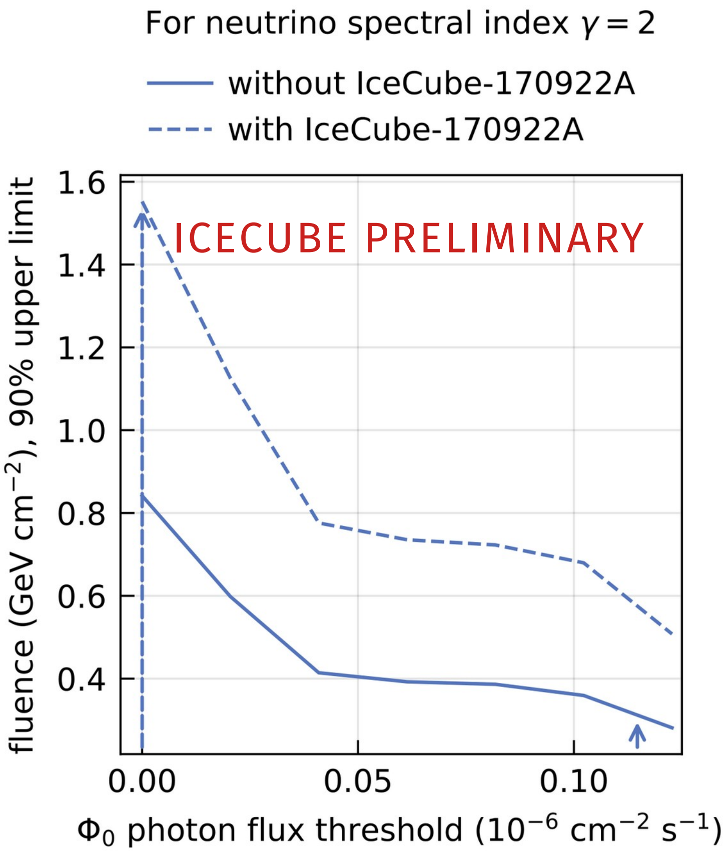
- **with IceCube-170922A**

unblinded TS=15.44, p-value=6.5×10^{-4} **= 3.2 σ**



→ **evidence** reflects the original trigger

Upper limits



high background low background

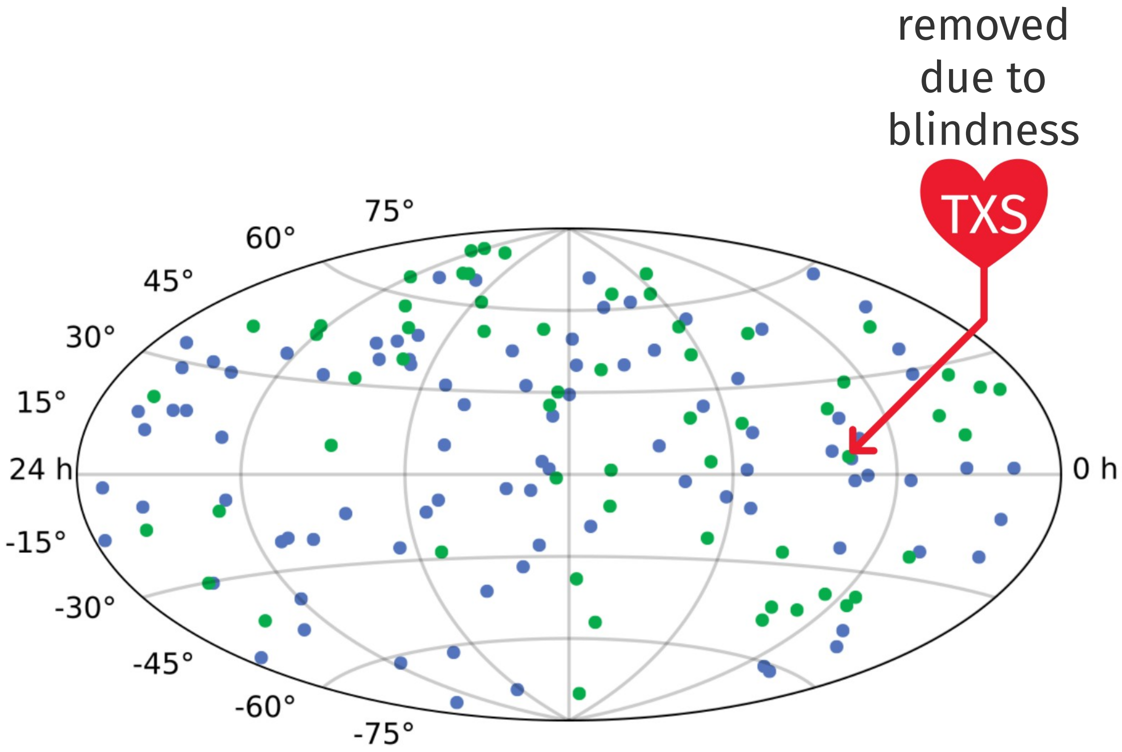
- To scrambled background:
- Add injected signal hypothesis like LLH
  - spectral index **γ = 2**
  - threshold $\boldsymbol{\Phi_0 \in [0,\max]}$
- Vary signal strength
  → limits at 90% CL
  → express as fluence
- Φ_0 ↔ lightcurve ↔ background ↔ limit
- These are not limits on possible neutrinos with other time distribution!

5

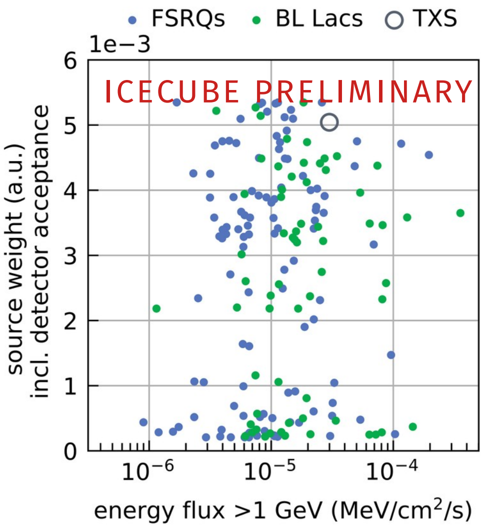
Blazar Flare Stacking

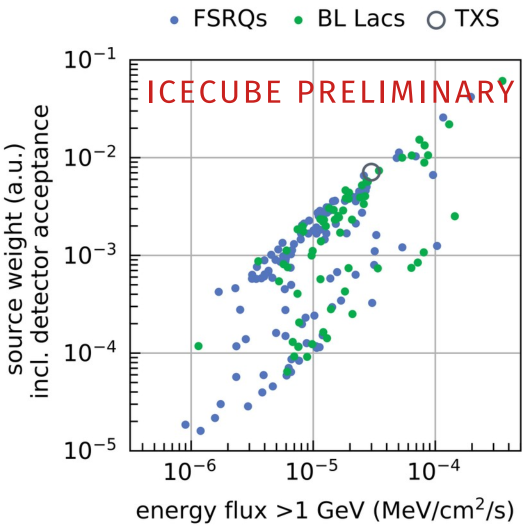
Source list

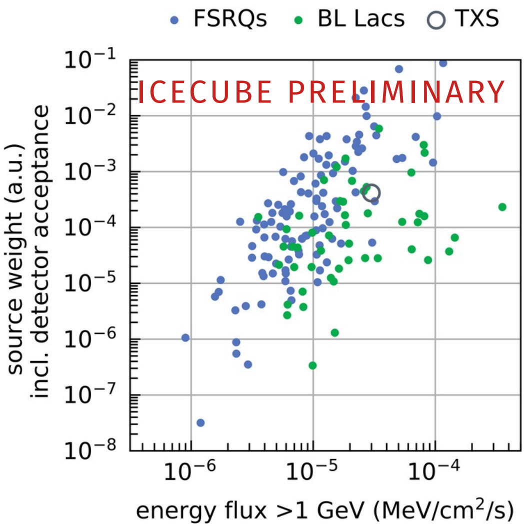
- Start: 2254 extragalactic Fermi sources
- “Associated” to known blazar
- Monthly lightcurves provided by Fermi
  → develop cuts (more detail in thesis)
  → select bright and variable sources
- 179 blazars: • BL Lac (65), • FSRQ (114)
- Separated:
  - different physics
  - different intrinsic luminosity



Weighting scheme







- **equal**
- catch-all
- need detector acceptance...

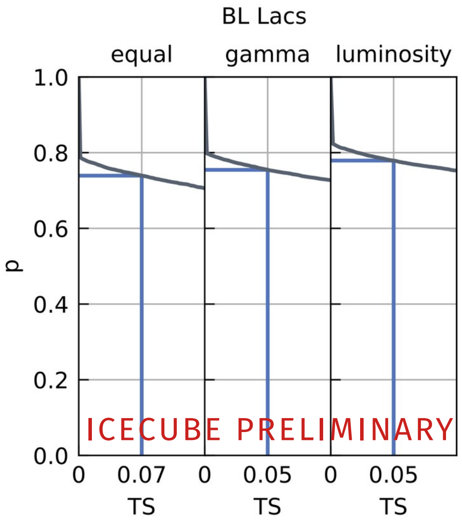
- **gamma**-ray energy flux
- same as likelihood
- ...and integrated Fermi data

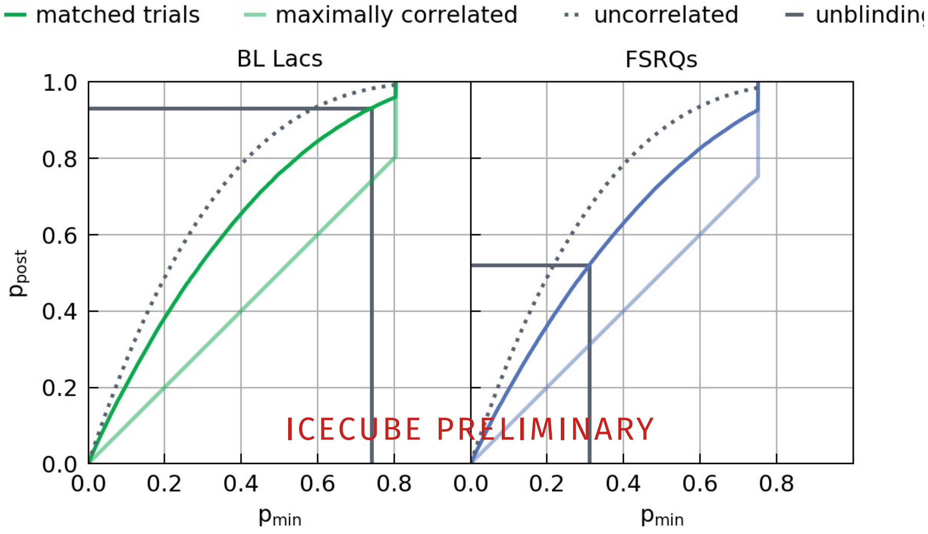
- **luminosity**-squared
- neutrino production model
- ...and redshift

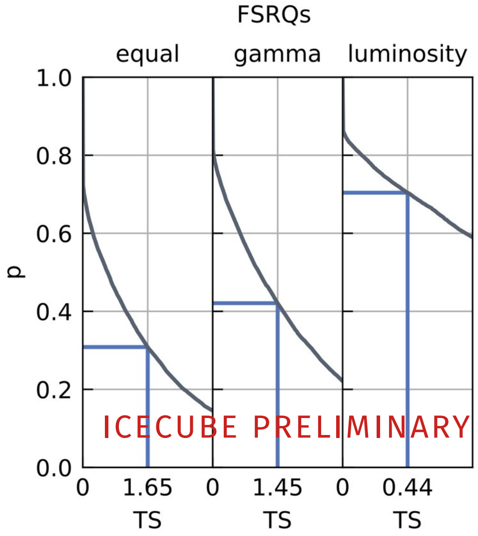
Unblinding

- Combine p_{equal}, p_{gamma}, $p_{luminosity}$ → smallest $\mathbf{p_{min}}$
- Repeat under background hypothesis → $\mathbf{p_{min}}$ distribution

→ compare → trial-corrected $\mathbf{p_{post}}$



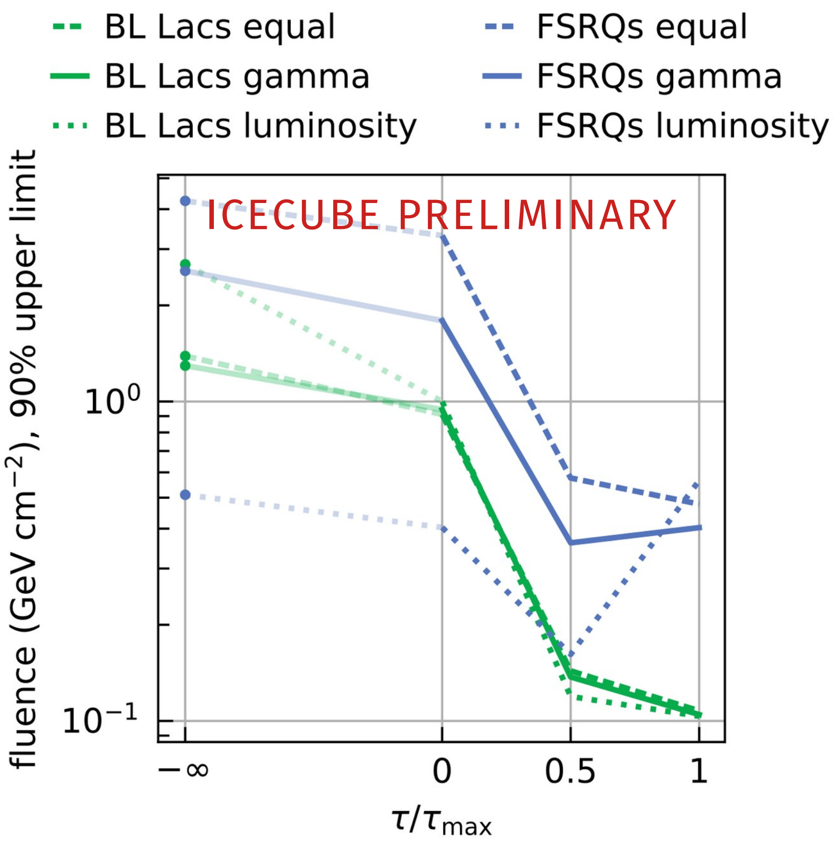




93% – 54%

→ 79%

Limits



- Analogous to single-source limits
- spectral index **γ = 2**
- threshold **$\tau \in$ [min,max]**
- fluence → $\Sigma_{sources}$ fluence

6

Final remarks

Conclusions

- IceCube searches for neutrino emission from blazars
- Correlated to their smoothed Fermi-LAT lightcurves

- TXS 0506+056
  → limits 0.05 GeV/cm^2 to 0.17 GeV/cm^2

- Novel blazar flare stacking analysis with 64 + 114 sources

  → p = 79.1%

Outlook

Other targets

- Markarian 421
  - nearby blazar
  - TeV variability

- Antiflares
  - dust/gas obscures gamma
    $\leftrightarrow$
  - neutrino production

Other data

- X-ray lightcurves
  - also blazar flares
  - models predict neutrinos

- IceCube-Gen2
  - high-energy extension
  - point sources expected

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Thanks!