Under-the-Threshold Populations with *Fermi*-LAT: the Case of Star-Forming Galaxies and Extreme BL Lacs

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Introduction

- In over a decade of sky patrolling, *Fermi*-LAT has detected γ-ray emission from a variety of astrophysical objects, e.g. AGN, pulsars

- What about the sources/populations yet to be detected?

- Crucial for background related studies

- Also important for next generation missions, e.g. AMEGO, Cherenkov Telescope Array

Introduction

- To characterize the average γ-ray properties of undetected sources, we have developed a stacking analysis pipeline

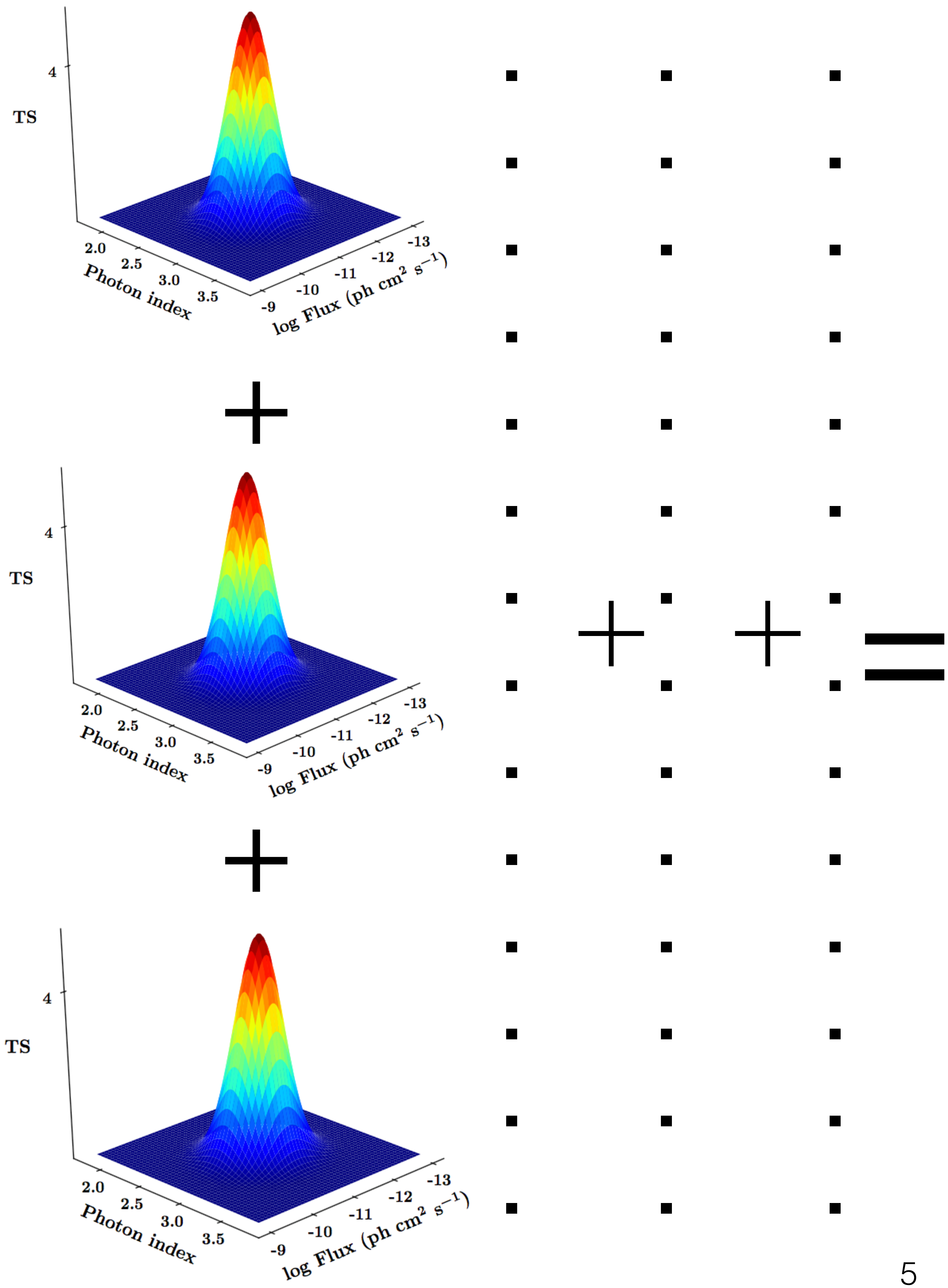
- Two steps:
  - Pre-processing (fermiPy)
  - Stacking (pyLikelihood)

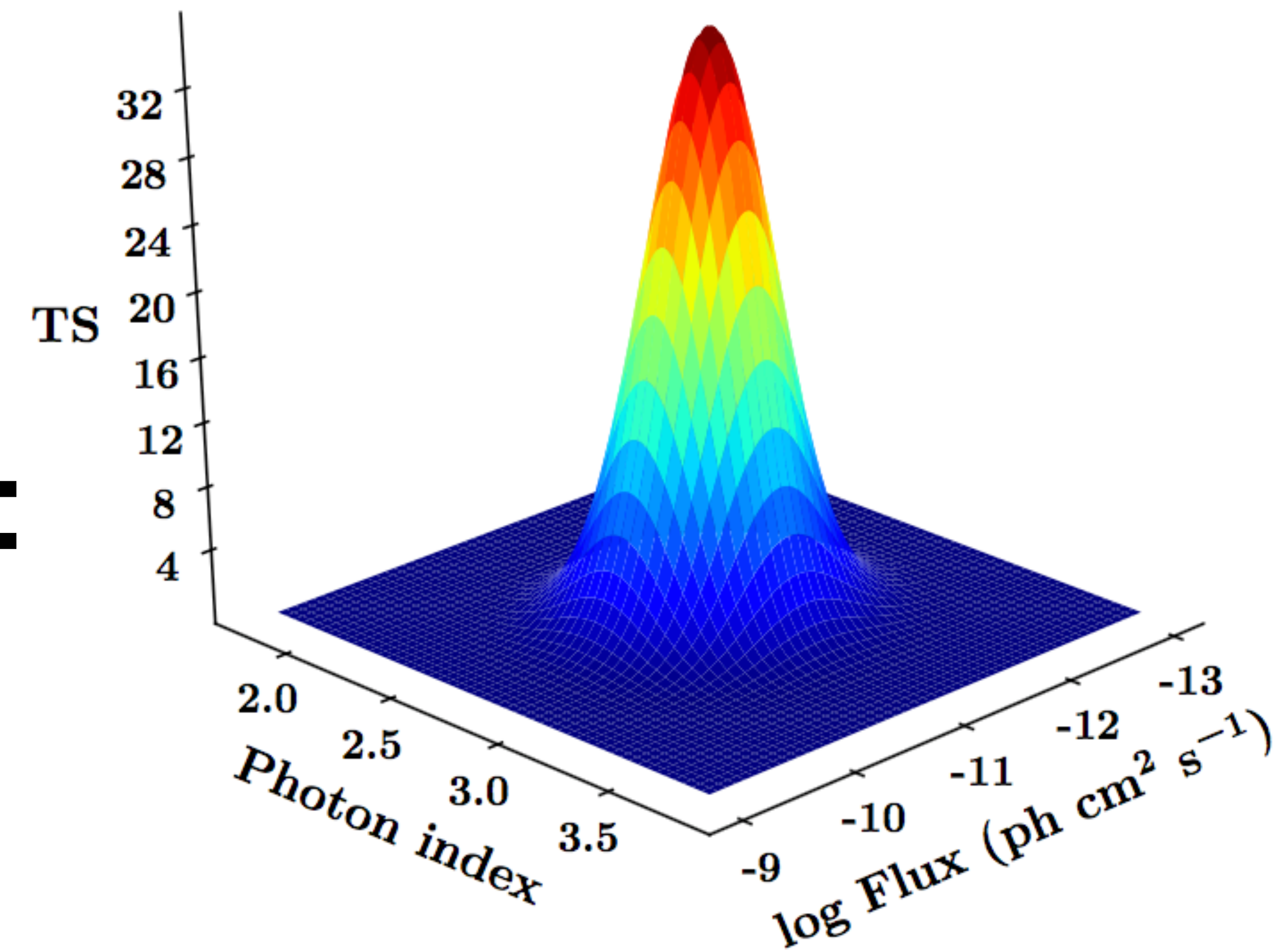
The Pipeline

- Perform an average analysis of the *Fermi*-LAT data
- Search for new γ-ray emitters and ensure the final sample to consist only γ-ray undetected objects

- We make a grid of photon flux (e.g. 10^{-15} to 10^{-8} ph/cm^2/s, in 50 logarithmic steps) and photon index (e.g. 1.5:3.5:0.1)
- The pipeline determines the likelihood value at every grid point. This is repeated for all sources in the sample
- Then, it combines the likelihood profiles of the whole sample and determines the overall peak position, i.e. peak flux, photon index and TS_peak

Pictorial representation





Star-forming galaxies

- Star-forming galaxies (SFG) enables us to study the connection between the star-forming activities and the γ-ray radiation

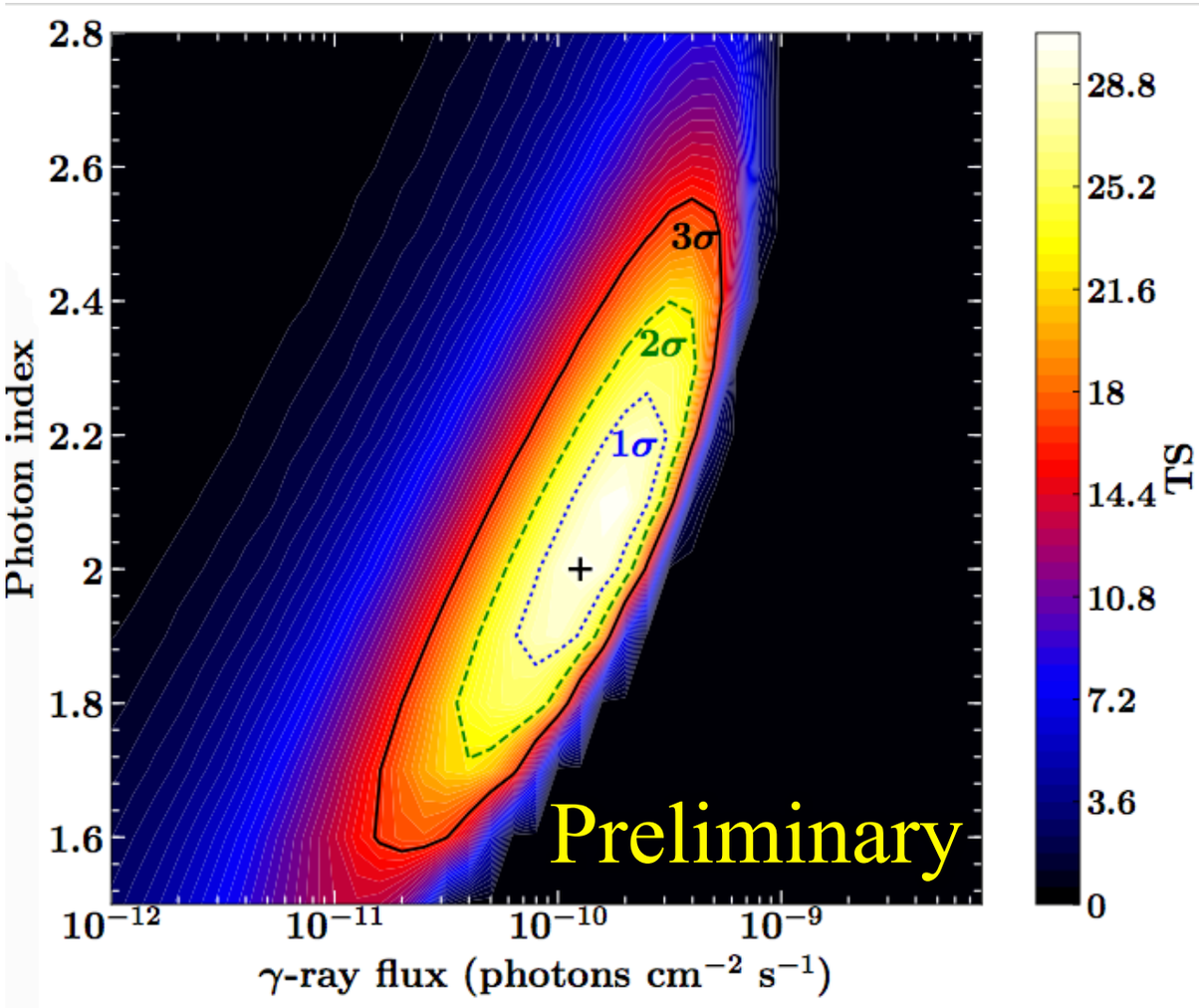
- Ideal sources to study the cosmic-ray induced diffuse γ-ray emission

- May contribute significantly to the extragalactic γ-ray background

- We built a sample of SFG considering 64 objects reported in Ackermann+ (2012, ApJ, 755, 164) and ~550 sources from IRAS catalog (Sanders+ 2003, AJ, 126, 1607)

SFG: Stacking

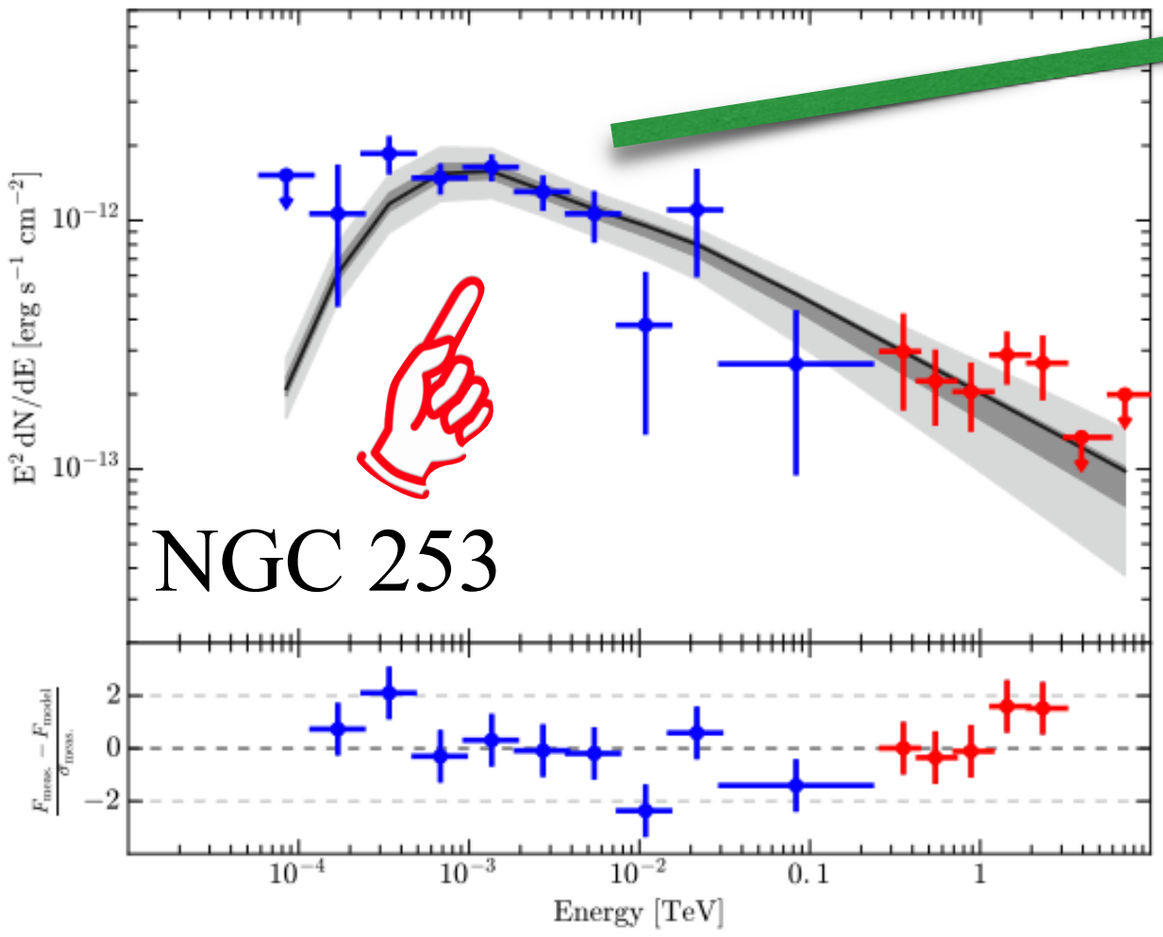
- Star-forming galaxies, as a population, are γ-ray emitters



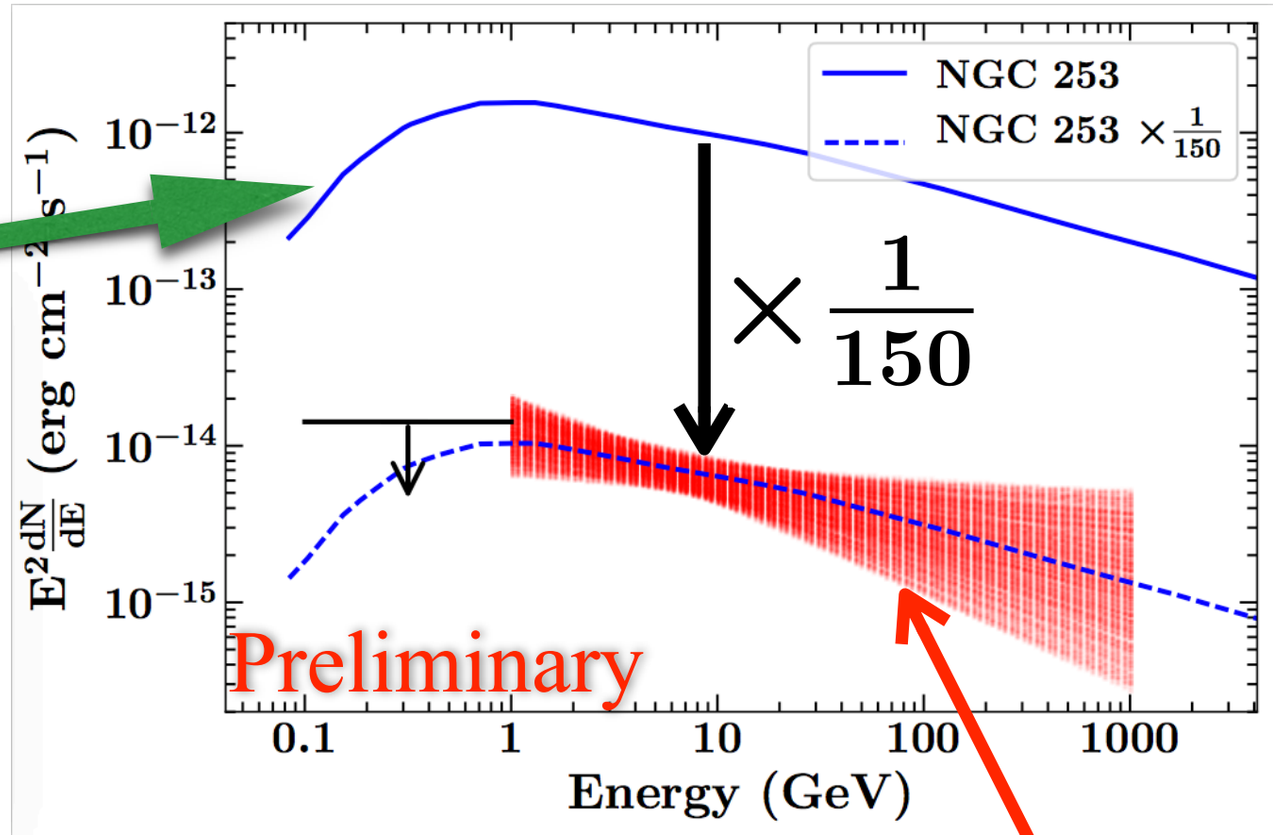
Ackermann+ 2012 sample:
59 objects

SFG: Stacking

- Star-forming galaxies, as a population, are γ-ray emitters



H.E.S.S. collaboration, 2018, A&A, 617, 73

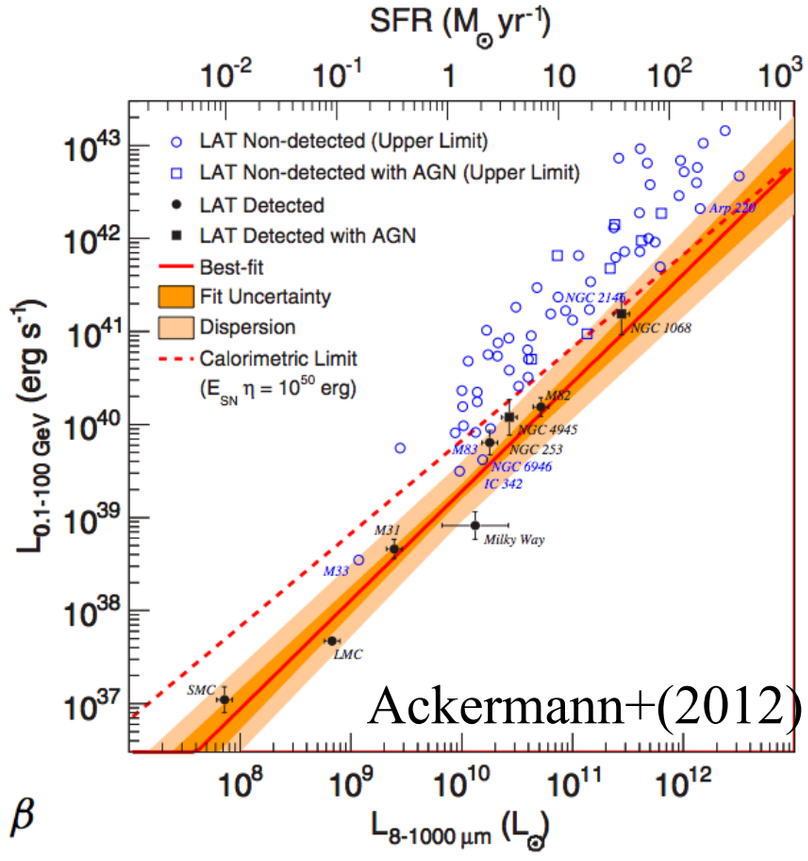


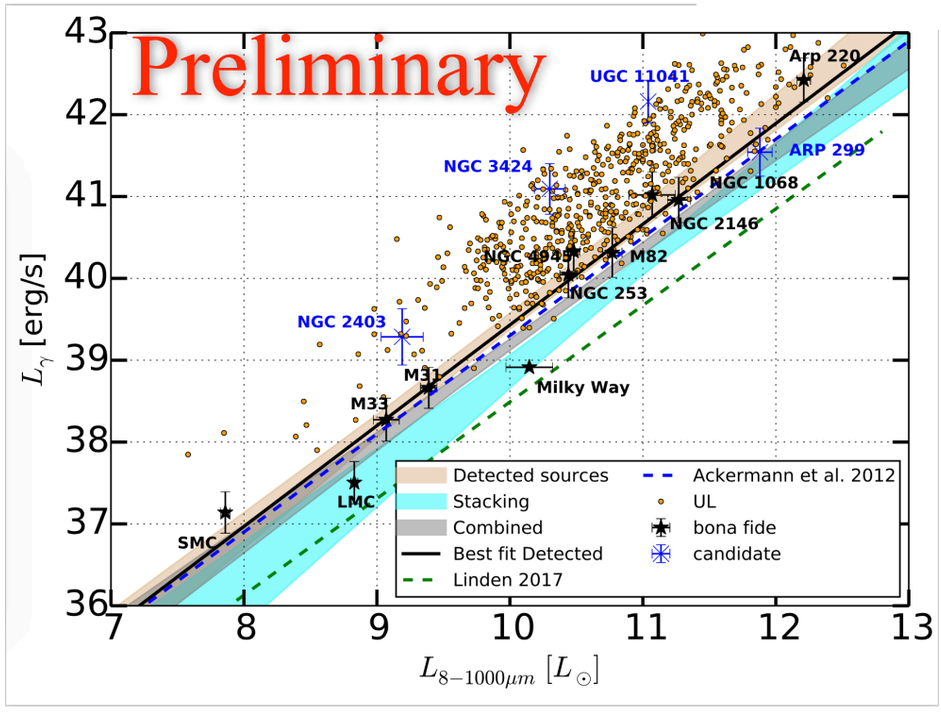
We are able to extract the spectrum of SFG which is 150 times fainter than NGC 253

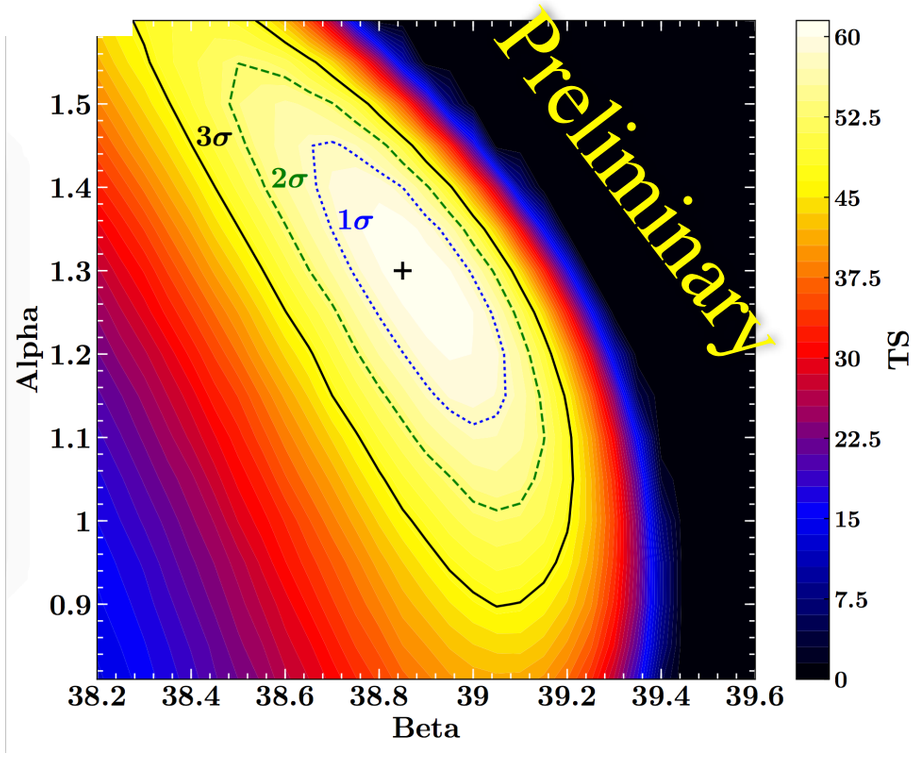
SFG: L_{IR} vs L_γ Correlation

- Stacking also enables us to determine the best-fit correlation parameters
- The best TS was found for the photon index = 2.1±0.1
- Corresponding peak alpha & beta values are consistent with Ackermann+ (2012)

$$\log\left(\frac{L_{0.1-100\,\mathrm{GeV}}}{\mathrm{erg\,s^{-1}}}\right) = \alpha \log\left(\frac{L_{8-1000\,\mu\mathrm{m}}}{10^{10} L_\odot}\right) + \beta$$







Extreme BL Lacs

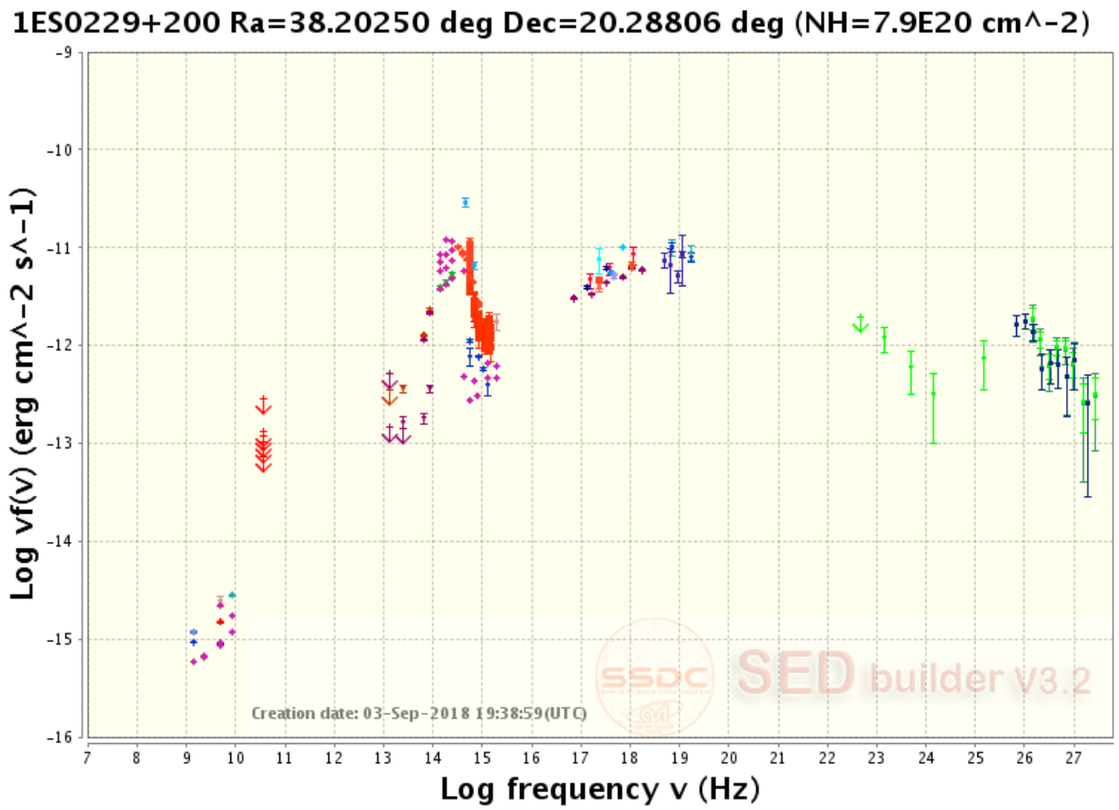
- High synchrotron peak ($\nu_{peak}>10^{15}$ Hz) BL Lacs that are yet to be detected with *Fermi*-LAT in large numbers

- Sample is made from 1WHSP + 2WHSP BL Lac catalogs (Arsioli+, 2015, A&A, 579, 34, Chang+ 2017, A&A, 598, 17)

- The energy range is 10-800 GeV

- After pre-processing, removed all γ-ray detected ones

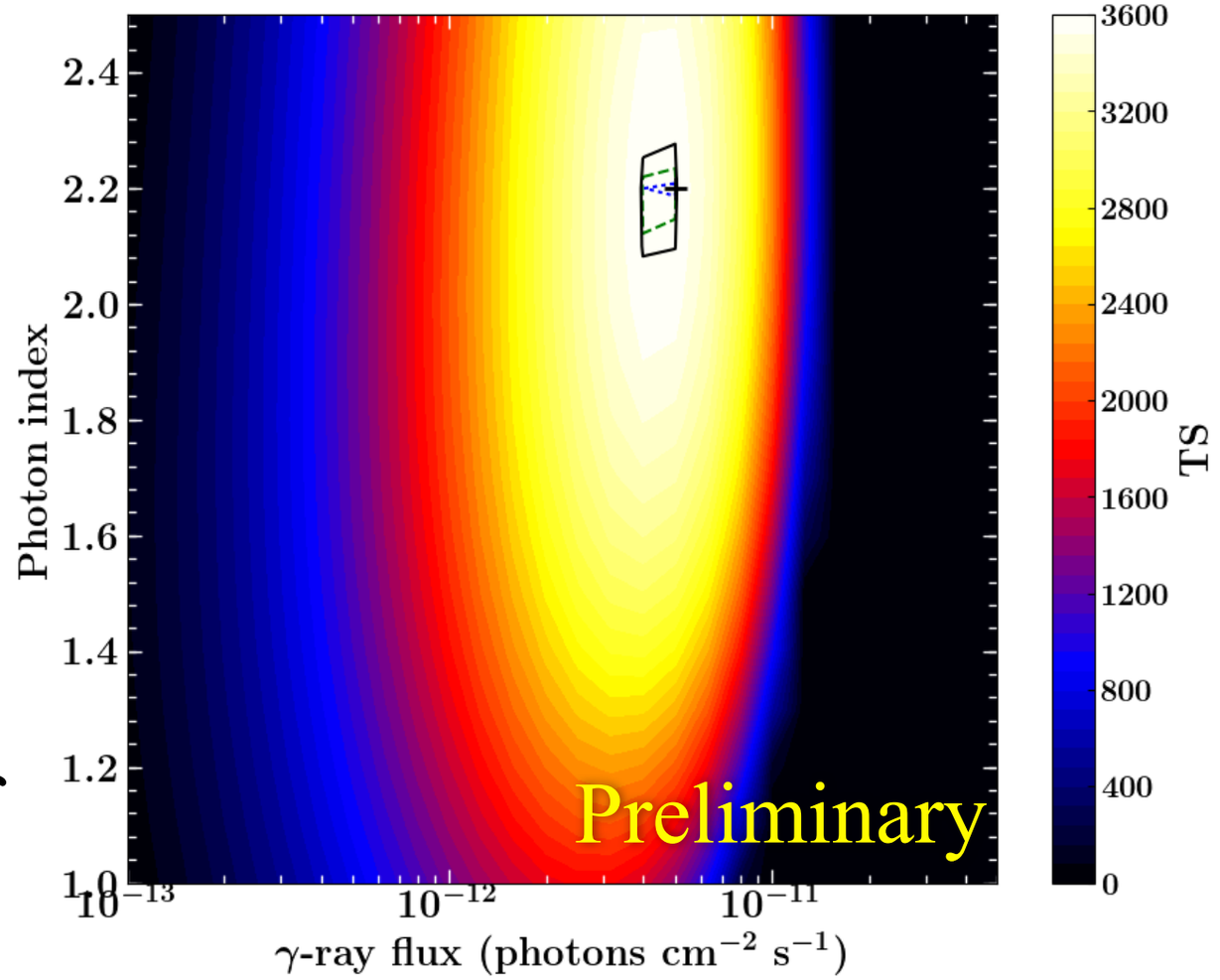
- About ~1000 extreme BL Lacs are then stacked



(Credit: ASDC)

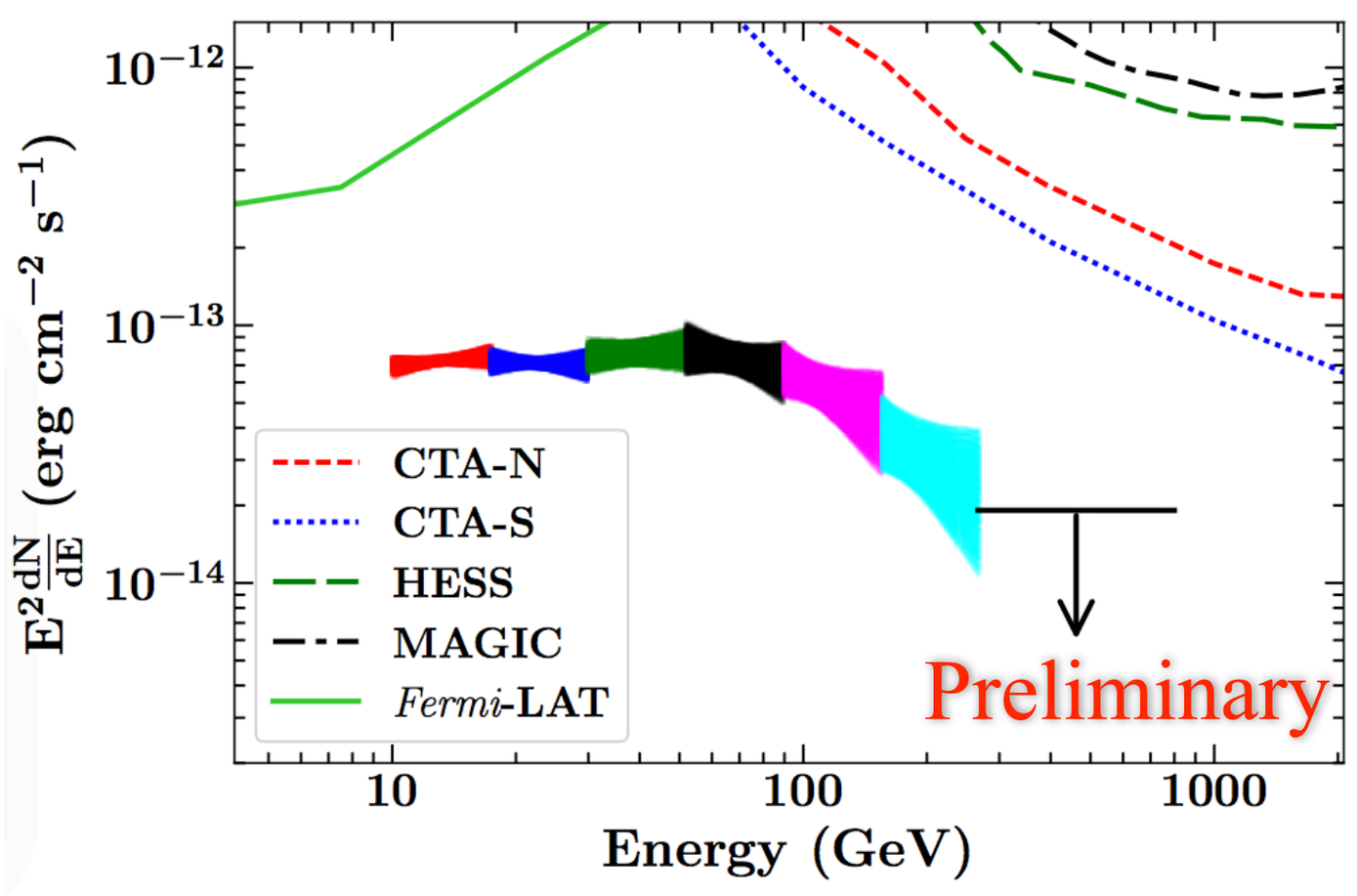
Extreme BL Lacs: Stacking

- These LAT undetected blazars are γ-ray emitters
- Note the low flux limit probed by the stacking
- Gamma-ray spectrum is not extremely hard (possible role of the EBL absorption)



Extreme BL Lacs: Stacked Spectrum

- The stacked γ-ray spectrum lies well below the sensitivity limits of the currently operating HE/ VHE facilities and also CTA
- A turnover around 100 GeV possibly due to EBL &/or peak of the inverse Compton mechanism

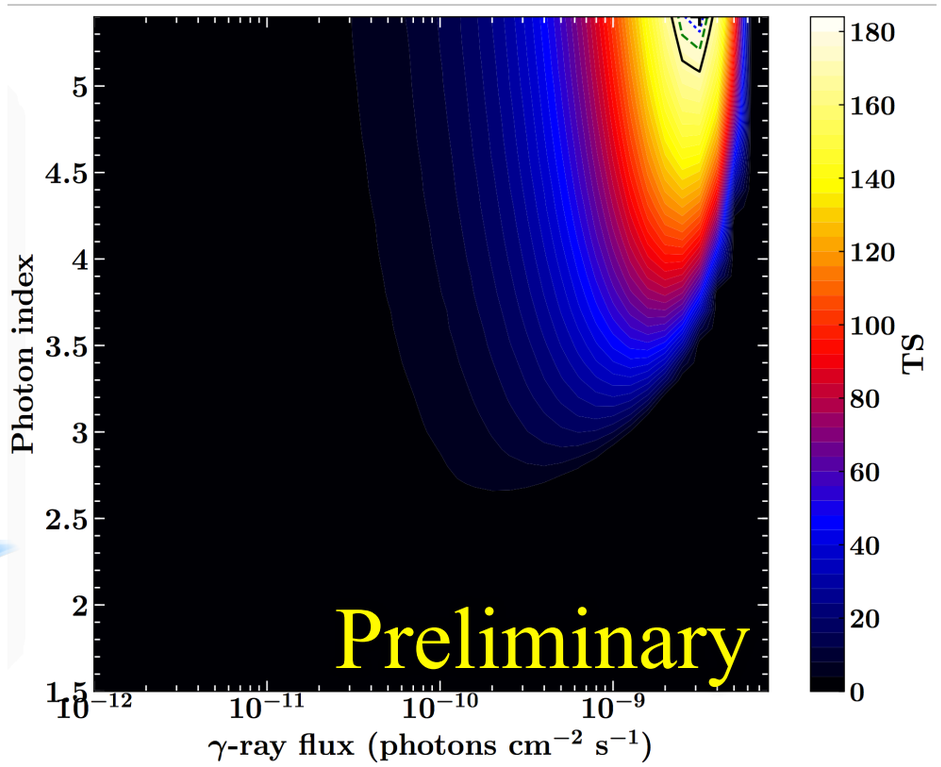


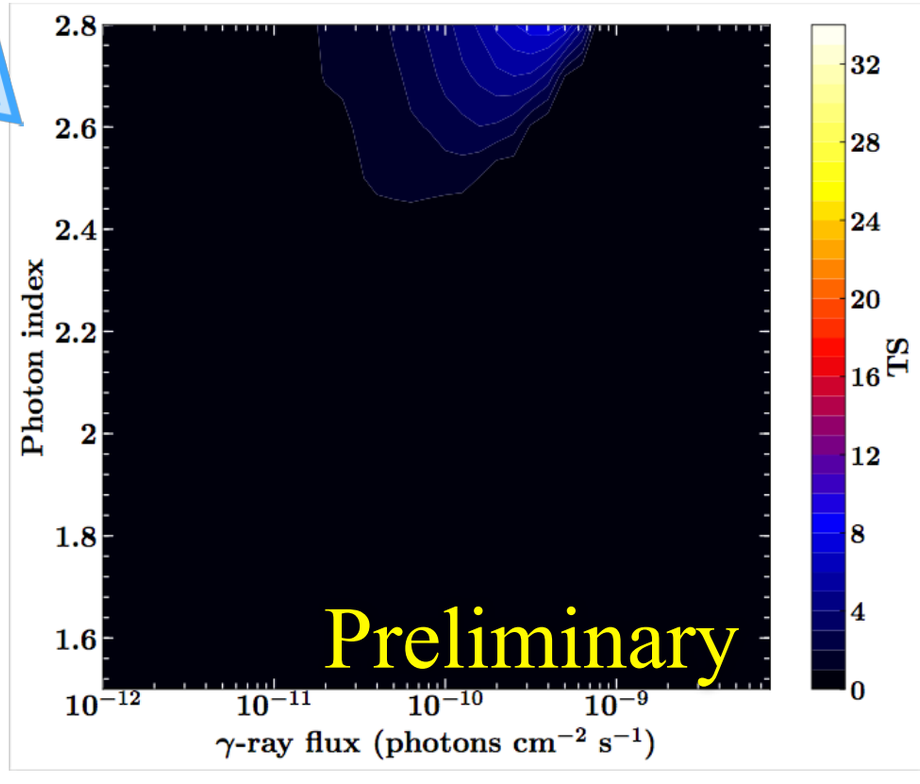
stacking pipeline is powerful 😎

Background Stacking

- The idea is to stack the pure background emission
- Randomly selected 600 sky positions not associated with any known γ-ray source
- Repeated the entire analysis
- There is some excess emission, however, it is very soft (index > 5.4) and hence our source analysis remains unaffected

Zoomed



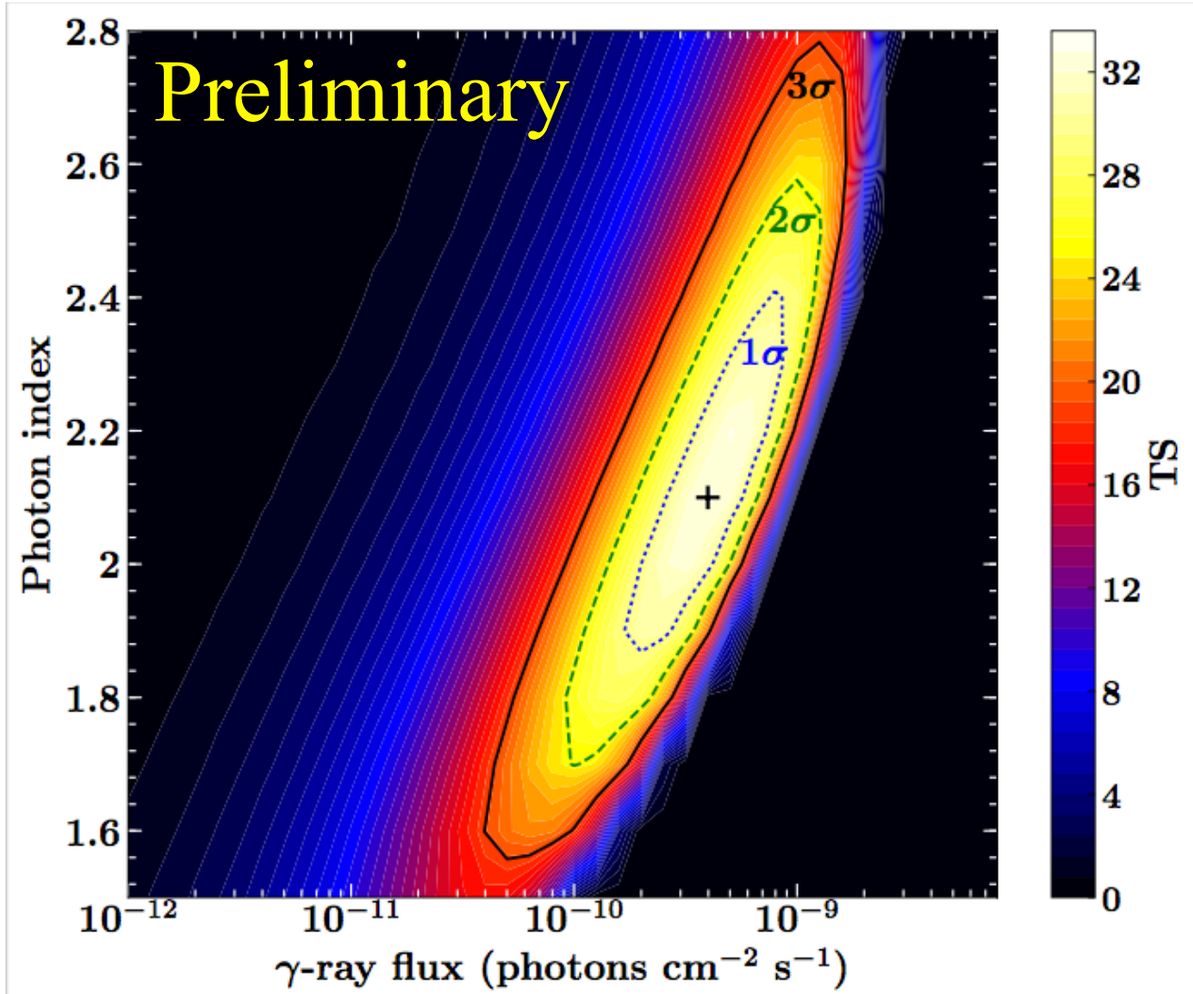


Simulation

- Input average flux & index (6.4±0.6) e-10 ph/cm^2/s & 2.21±0.23 for a sample of 50 sources

- Simulated stacked population gives
  - photon flux: (6.1±1.8) e-10 ph/cm^2/s
  - photon index: 2.08±0.12

- Confirms the robustness of the developed procedure



Summary & Outlook

- A stacking pipeline is developed to probe the γ-ray undetected populations

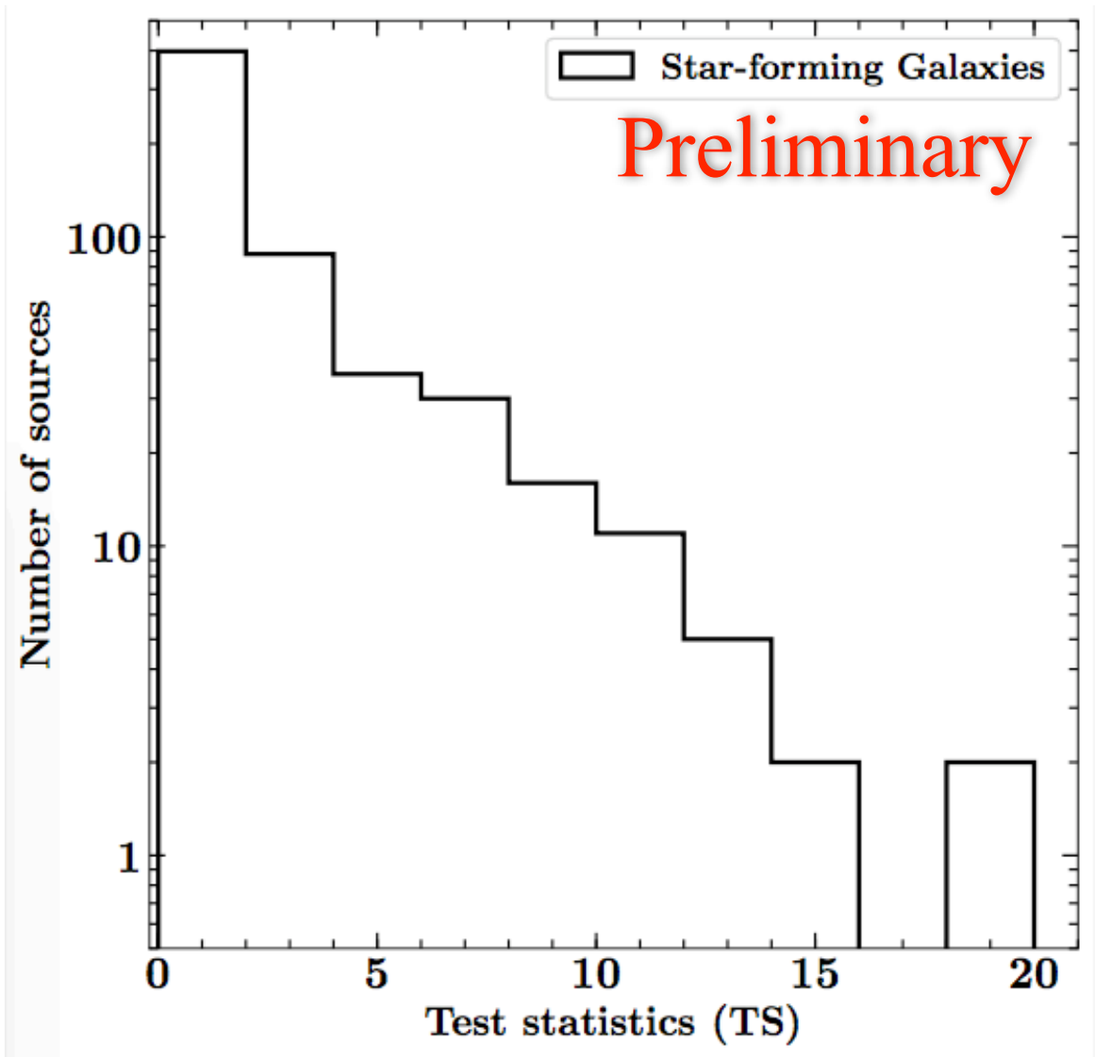
- Star-forming galaxies, as a population, are γ-ray emitters and so Extreme BL Lac sources

- Final goal: determine contributions of these populations to the extragalactic and isotropic γ-ray backgrounds

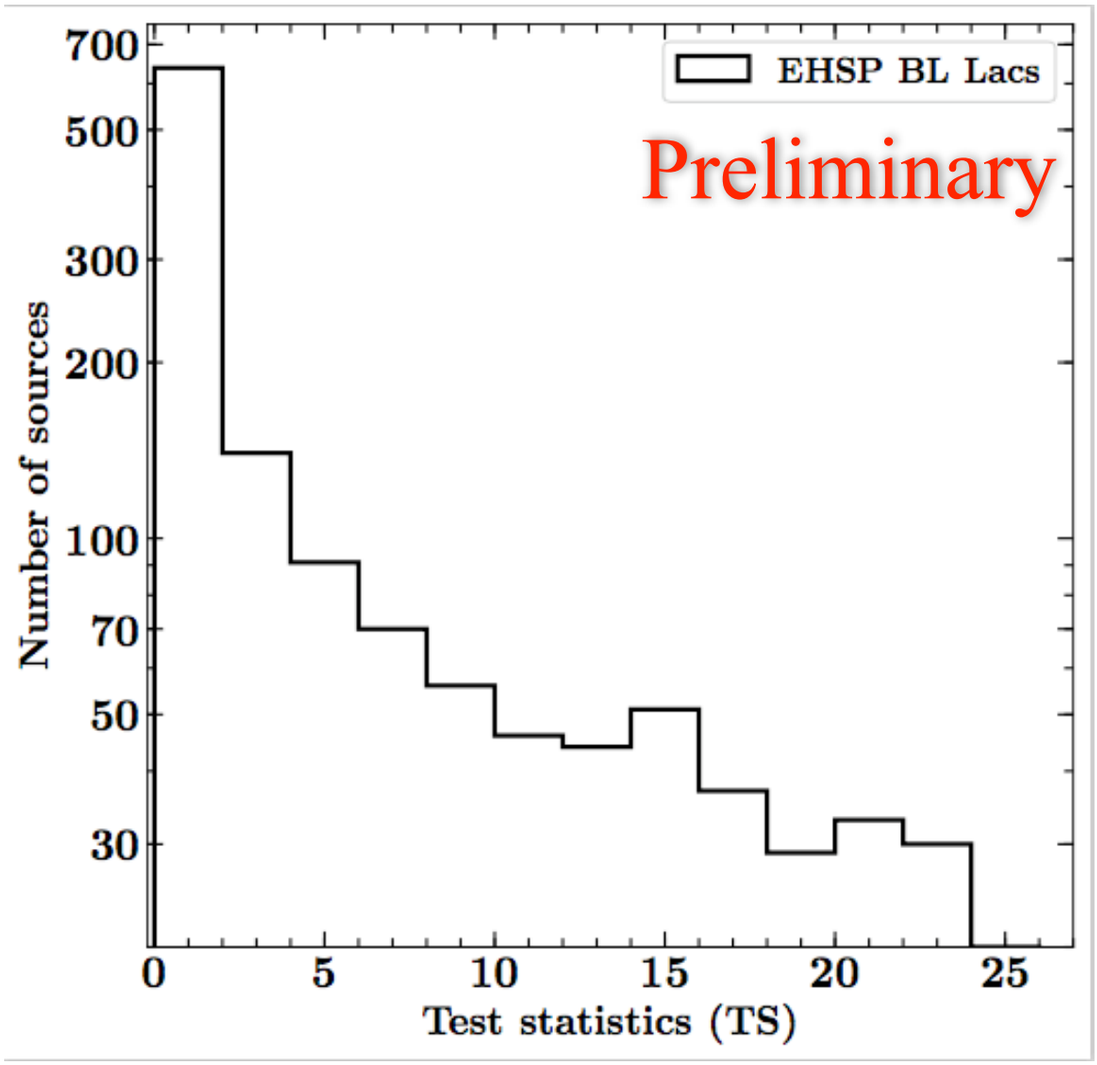
- Future: test various other types of source populations: high-redshift blazars, narrow line Seyfert 1 galaxies, High mass X-ray binaries, clusters, etc.

!!Thanks!!

TS Histograms



Star-forming galaxies



Extreme BL Lac objects