Can Fermi-LAT unassociated sources be mismodeled interstellar gas?

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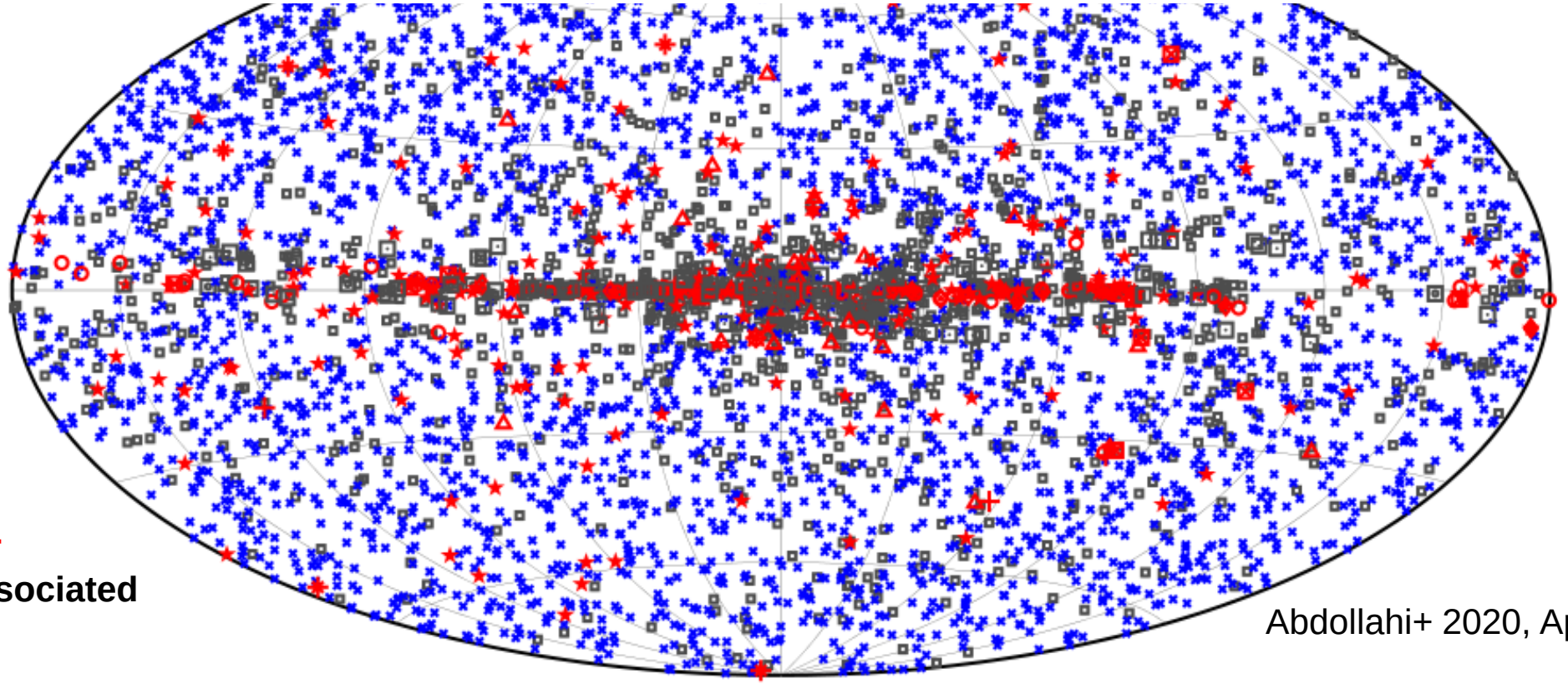
Fermi-LAT unassociated sources



- **AGN**
- **Other**
- **Unassociated**

4FGL
Abdollahi+ 2020, ApJS 247, 33

In 4FGL-DR4, 2423 sources (1/3) remain unassociated

At high latitudes, 1/4 are unassociated, and they look similar to associated ones

Within 10° of the Galactic plane, 1140 sources (54%) remain unassociated (48% in DR1)

Galactic unassociated sources (GUs)

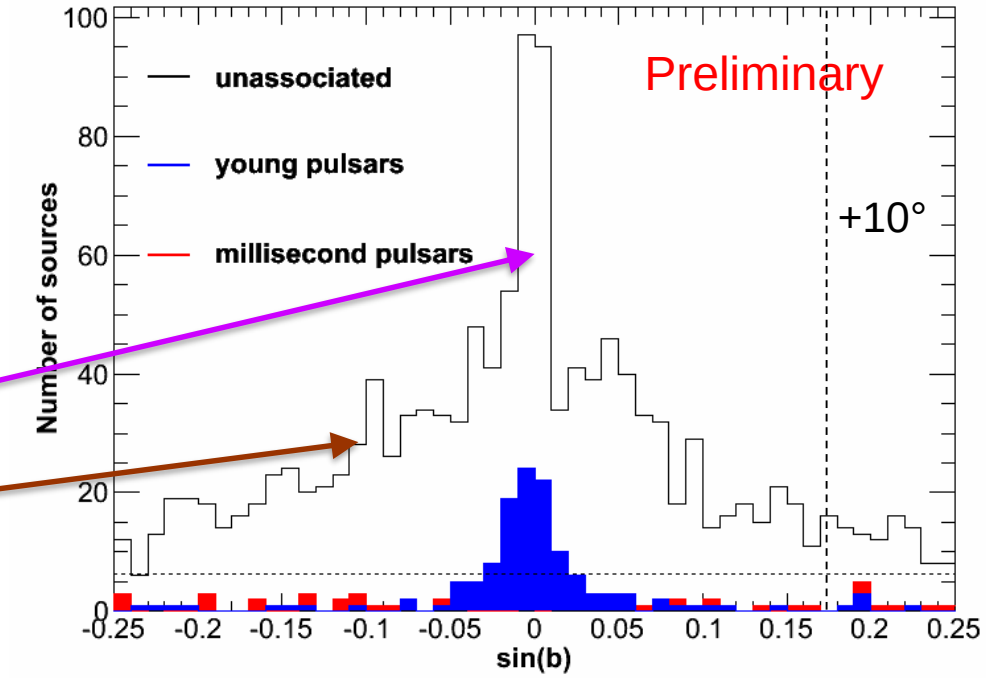
GUs = unassociated sources at |GLAT| < 10°

Low-significance (median Signif_Avg = 5.76 σ) but 165 (14.5%) have Signif_Avg > 10 σ

Latitude distribution: **central spike** (within 1° of the plane) plus **broad shoulder**

Central spike even narrower than **PSR** distribution

Broad shoulder much broader than **PSRs**, but much narrower than **MSPs**



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Central spike even narrower than **PSR** distribution

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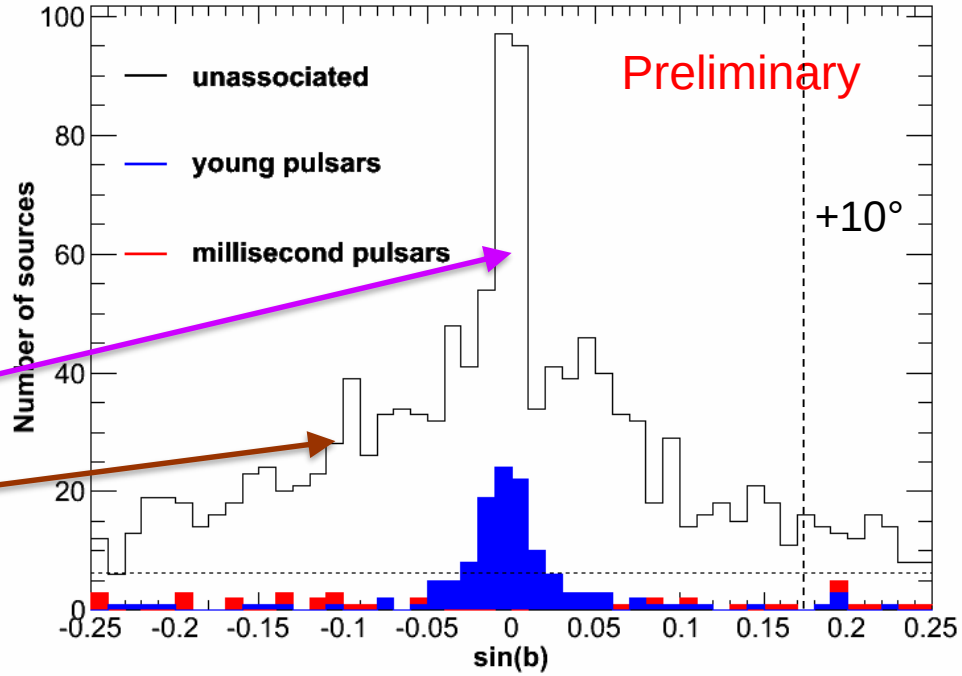
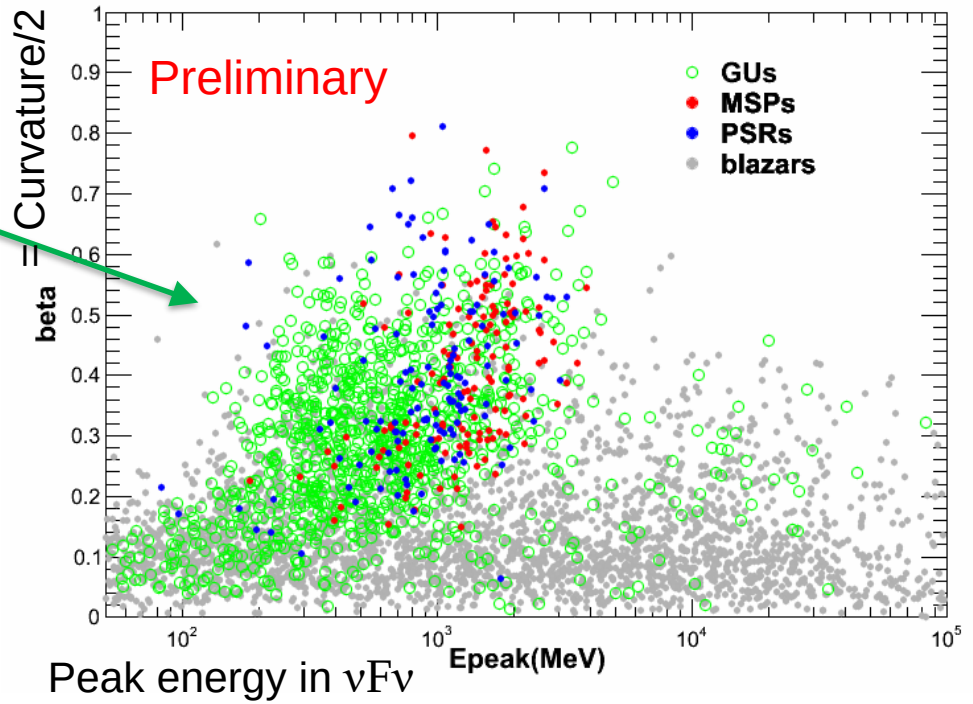
Specific spectral characteristics: **lower LP_EPeak than the pulsars** (and larger curvature than the blazars)

➔ **GUs are not like associated Galactic sources**





GUs vs diffuse emission

Interstellar emission dominates the LAT counts

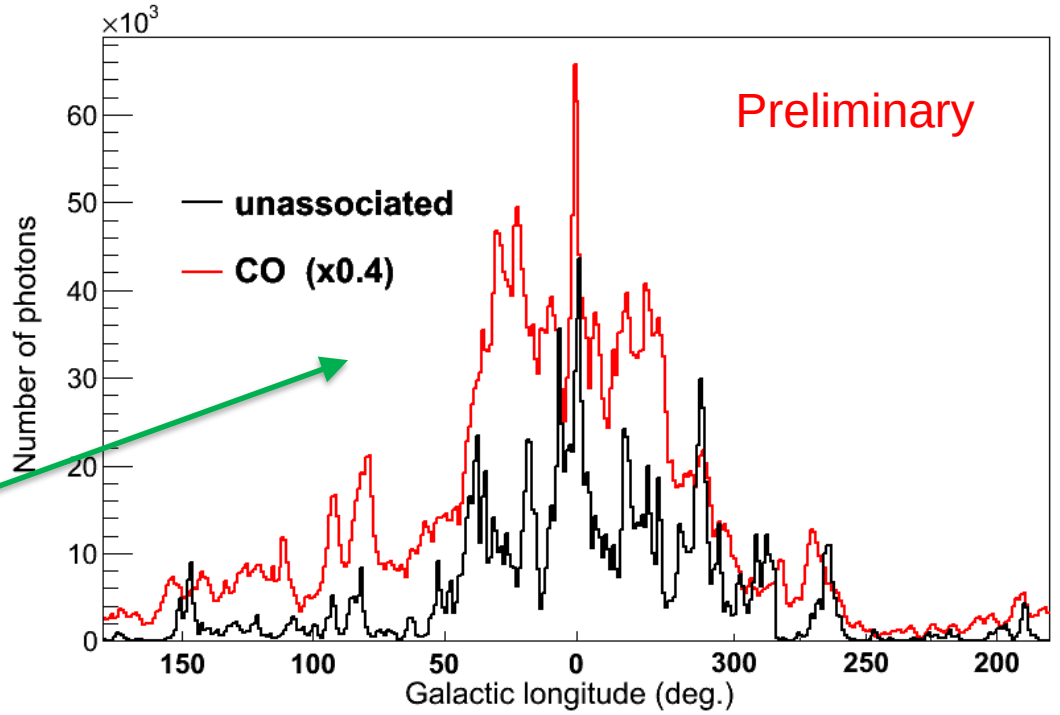
Can GUs be due to an imperfect model?

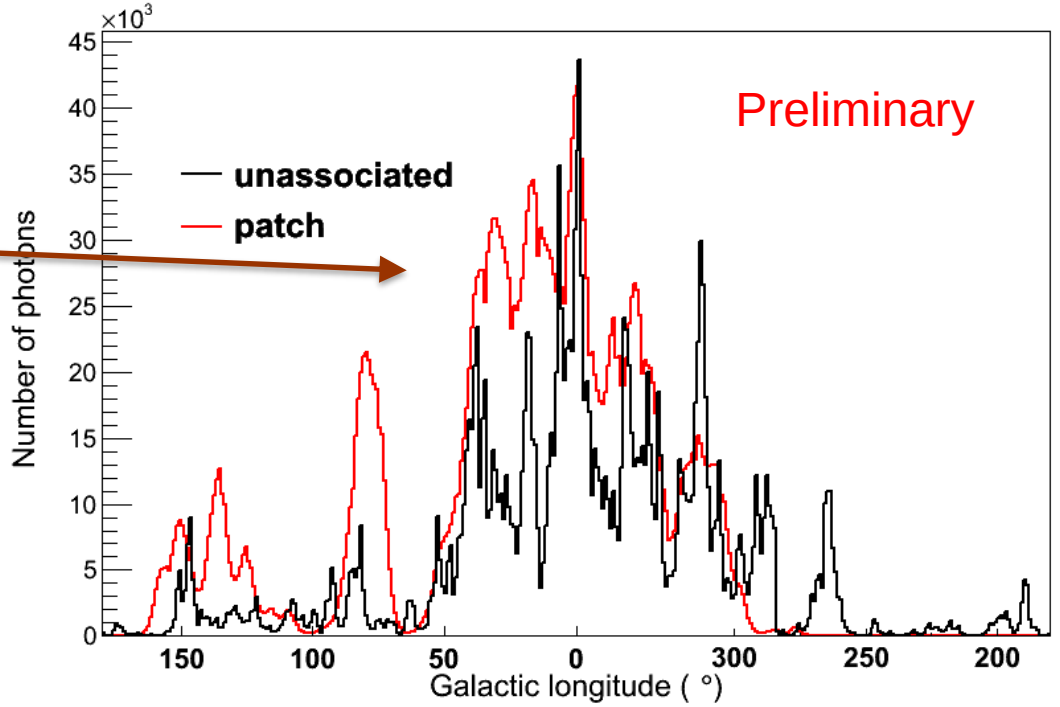
How do they compare to the diffuse components?

Total emission due to GUs is about **1/6 that of CO**, and longitude distributions not very different, so a modest increase in CO could potentially work

The **"patch"** is large-scale diffuse emission added to the model by hand because residual emission could not be fit by known gas templates

Total emission due to GUs is **close to that of the patch**, so comparable to what was attributed to diffuse emission already





GUs vs diffuse emission

The spatial structure of interstellar emission is uncertain, but its **spectrum is very characteristic**

Do the unassociated sources look like diffuse emission spectrally?

Build the total spectrum of all sources in a class (assuming the LP model) and compare to the diffuse emission (/ 10)

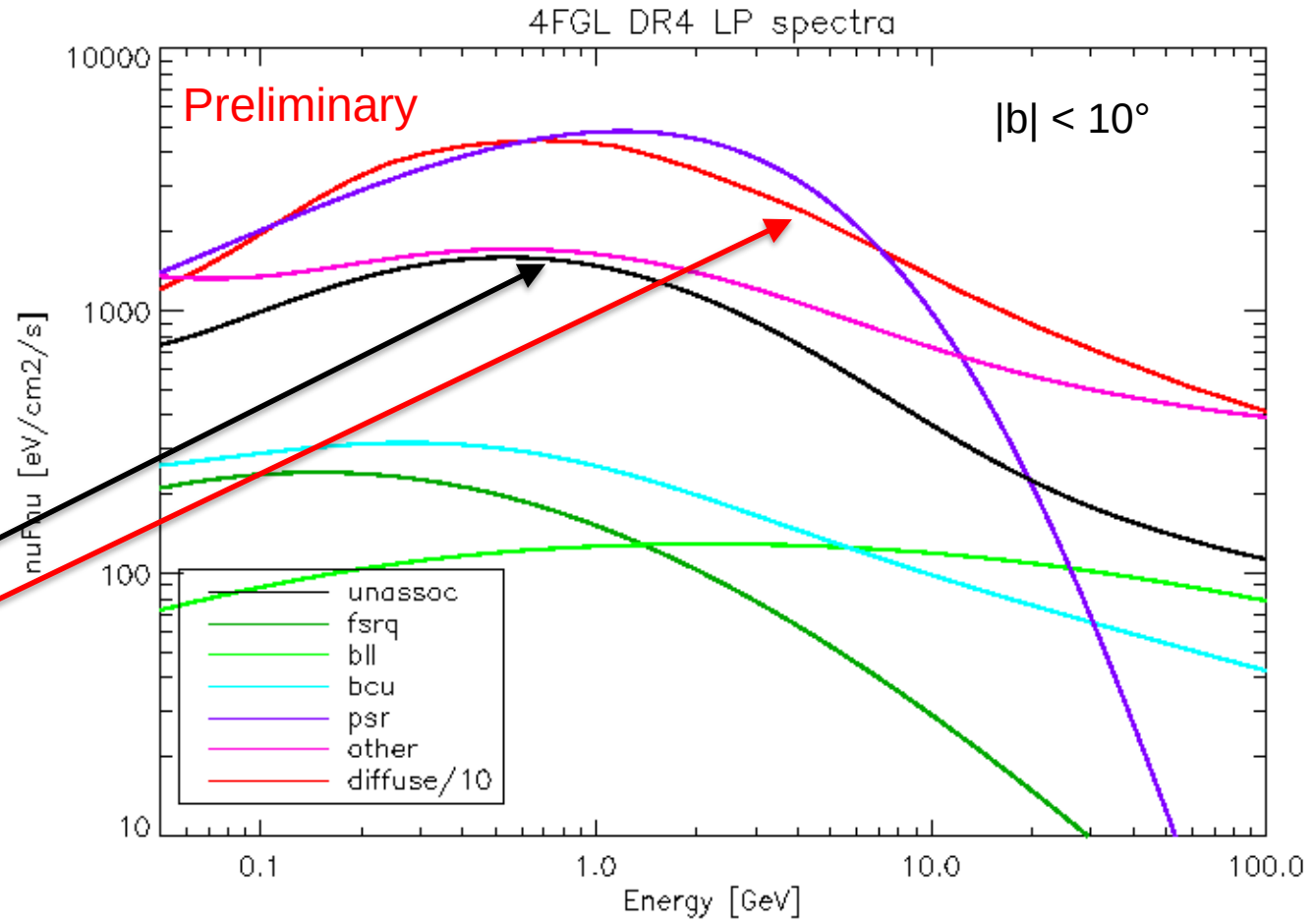
Pulsars dominate the source contribution

Blazars are a minor component in the plane

Total emission due to **Galactic Unassociated** is somewhat softer than **diffuse emission**

But a collection of point sources naturally misses high-energy emission where the PSF is much better

➔ **Simulations**



Additional diffuse emission

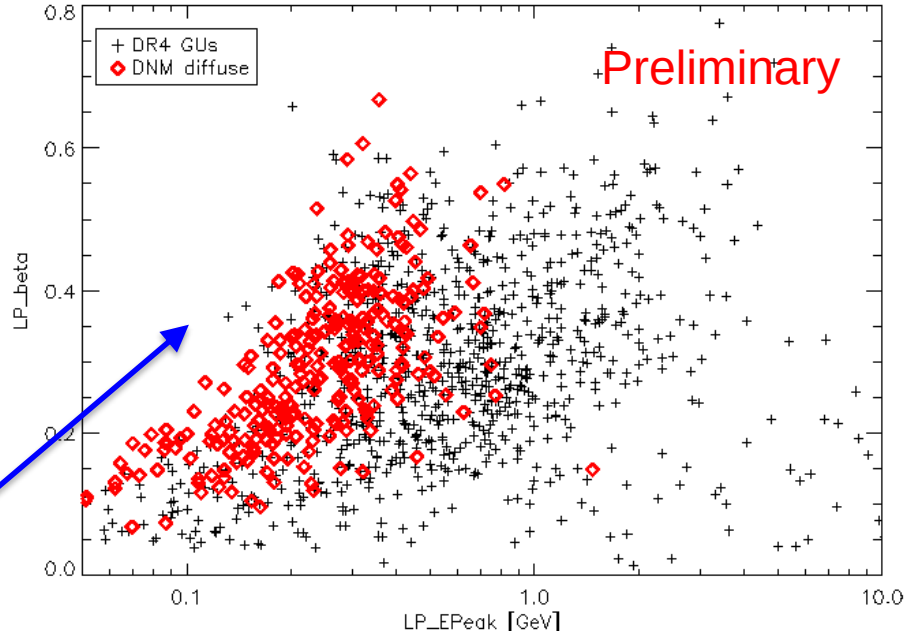
Simulations done on 12 years of data

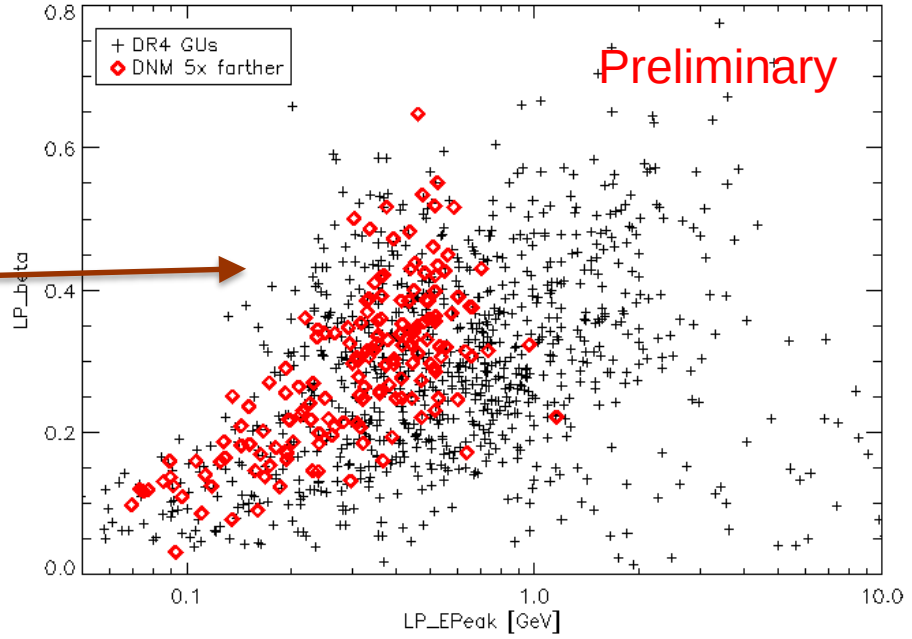
Start with the standard LAT diffuse model (no point source)

Add an **additional diffuse component**

Find point sources and fit them in the standard way with the standard diffuse model modulated by a power law

1. Simulate **dark gas** (DNMp), with its true intensity
   - 336 point sources are found (median Signif 5.9 σ), but **too soft** (EPeak < 500 MeV), because point sources miss the high-energy diffuse emission (that effect is too strong)
2. Simulate DNMp with smaller spatial scales (**push it to 5x larger distance** by formally reducing the pixel size in the model)
   - 196 point sources are found (median Signif 5.7 σ). EPeak is a little larger but not enough





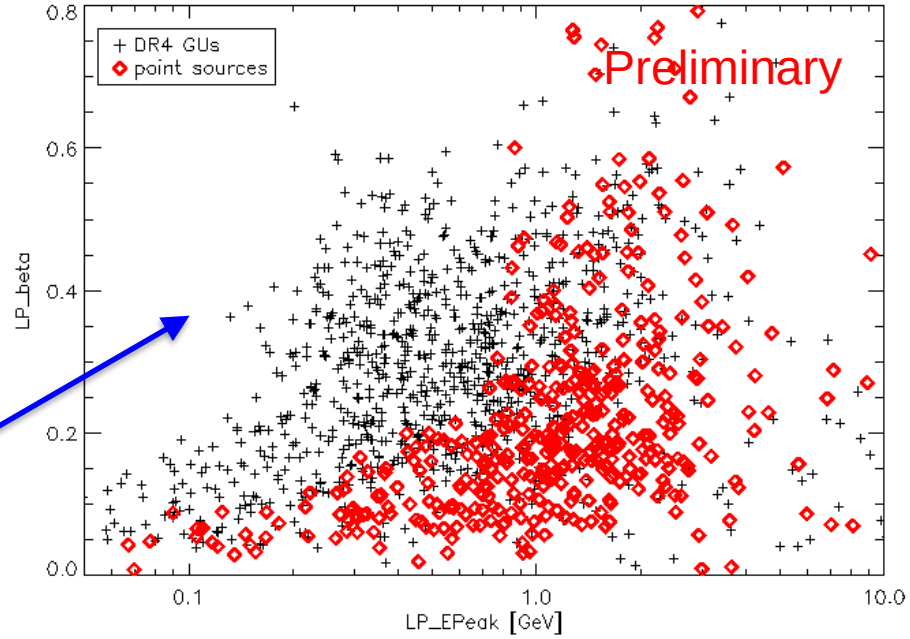
Force spatial scale

Start with the standard LAT diffuse model (no point source)

Add **sources with the diffuse model spectrum**

Find point sources and fit them in the standard way with the standard diffuse model modulated by a power law

1. Simulate **point sources** on a regular grid, all with the same flux (median Signif 6.1 σ)
    - 466 point sources are found, but **too hard** (EPeak > 700 MeV) or not curved enough, because GUs are somewhat softer than diffuse emission



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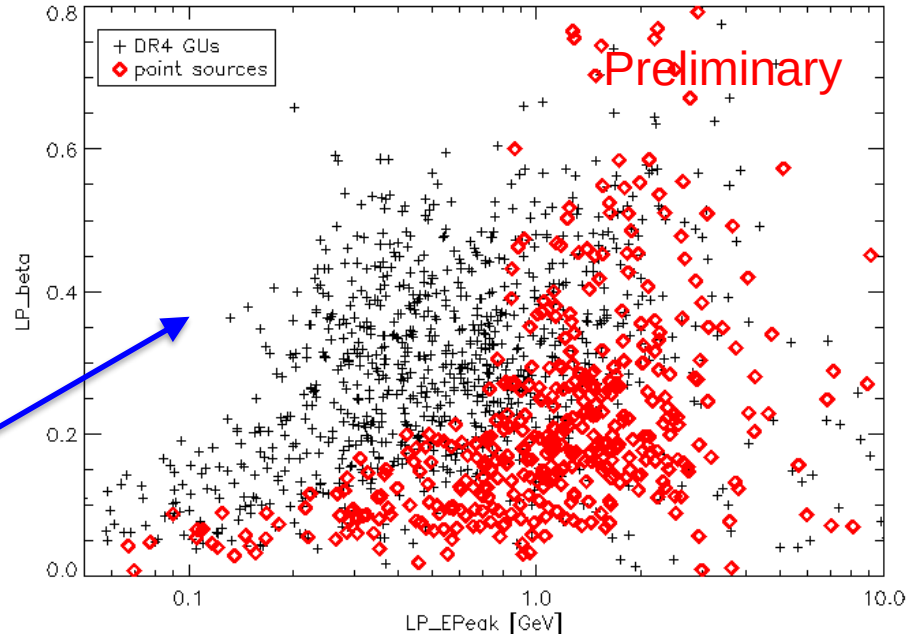
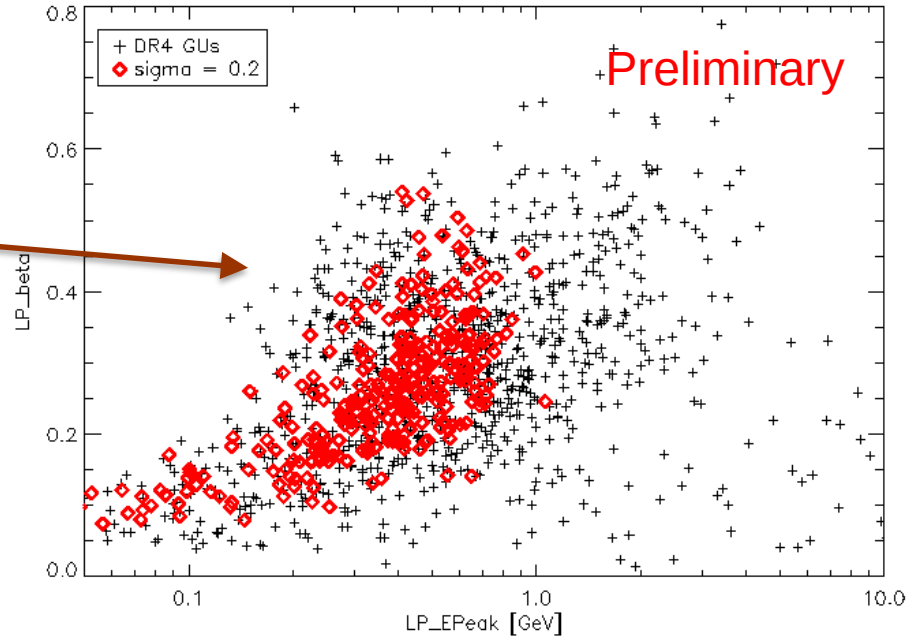
   - 466 point sources are found, but **too hard** (EPeak > 700 MeV) or not curved enough, because GUs are somewhat softer than diffuse emission
2. Simulate **extended sources** (Gaussian with **σ = 0.2°**) on a regular grid, all at the same flux (median Signif 8.8 σ)
   - 312 point sources are found. EPeak is somewhat too small (< 800 MeV)

➔ **Slightly extended diffuse features could work**





Adjust spatial scale

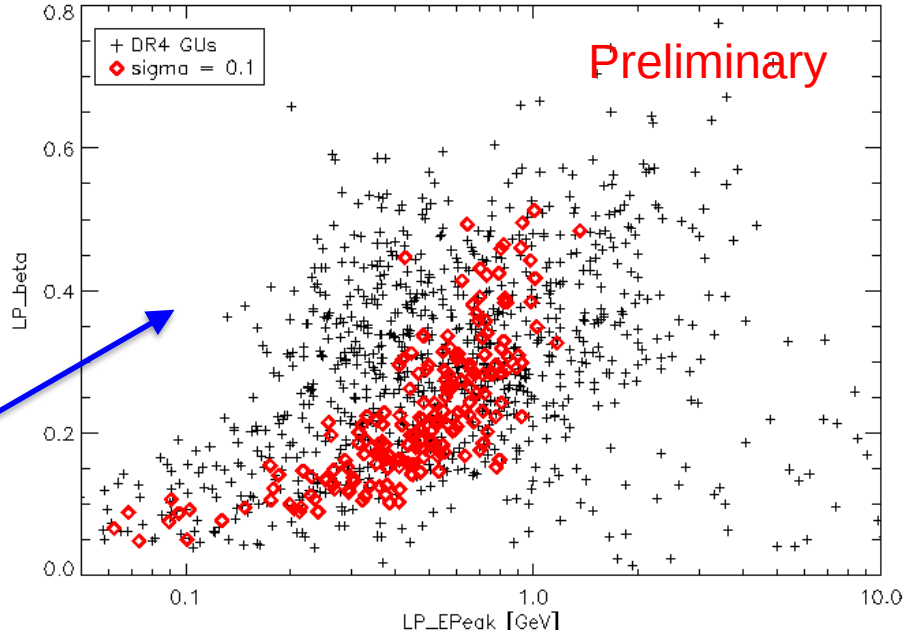
Start with the standard LAT diffuse model (no point source)

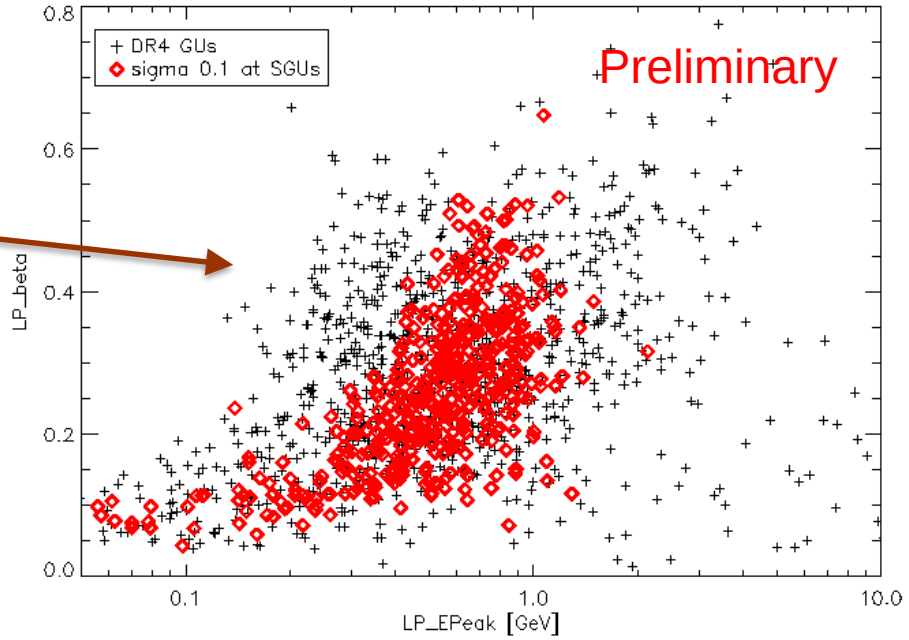
Add sources with the diffuse model spectrum

Find point sources and fit them in the standard way with the standard diffuse model modulated by a power law

1. Simulate **extended sources** (Gaussian with **σ = 0.1°**) on a regular grid, all with the same flux (median Signif 9.9 σ)
   - 200 point sources are found. **Same median EPeak as GUs**, but distribution too narrow
2. Simulate **extended sources** (Gaussian with **σ = 0.1°**) at the DR3 SGU positions, at median Signif 6.7 σ (closer to GUs)
   - 498 point sources are found. No major difference

➔ **A distribution of extensions between 0 and 0.2° could work**





Physical origin of additional diffuse emission?

What could be that additional interstellar emission?

1. **Missing gas** in the surveys that we use to build the LAT diffuse model (HI, CO, dust)
   - eg Karwin+ 2019 showed that considering ^{13}CO in the MOPRA survey can increase molecular gas column density by 20% in the strip $|b| < 0.5°$ and $300° < l < 350°$
2. Local **cosmic-ray excesses** illuminating known gas
   - Several papers have pointed at star-forming regions and young star clusters as possible LAT sources (eg Peron+ 2024 find that about 100 GUs are associated with the WISE catalog of HII regions)
   - The CR spectrum should not be much harder than the CR sea

Both are easier to find very close to the Galactic plane ($|b|<1°$)

Are DR4 GUs actually extended?

The simulations imply that GUs could be small interstellar features with Gaussian sigma around 0.1° (R_{68} = 0.15°)

Finding modest extension is possible for bright enough sources

Consider the **brightest GUs**, unk or spp (**66 at Signif > 14.5 σ**), select events > 1 GeV and test extension with fermipy

Nine are inside known extended sources

25/66 (38%) are found possibly extended with Sig_Ext > 2 σ, and Gaussian sigma around 0.1°

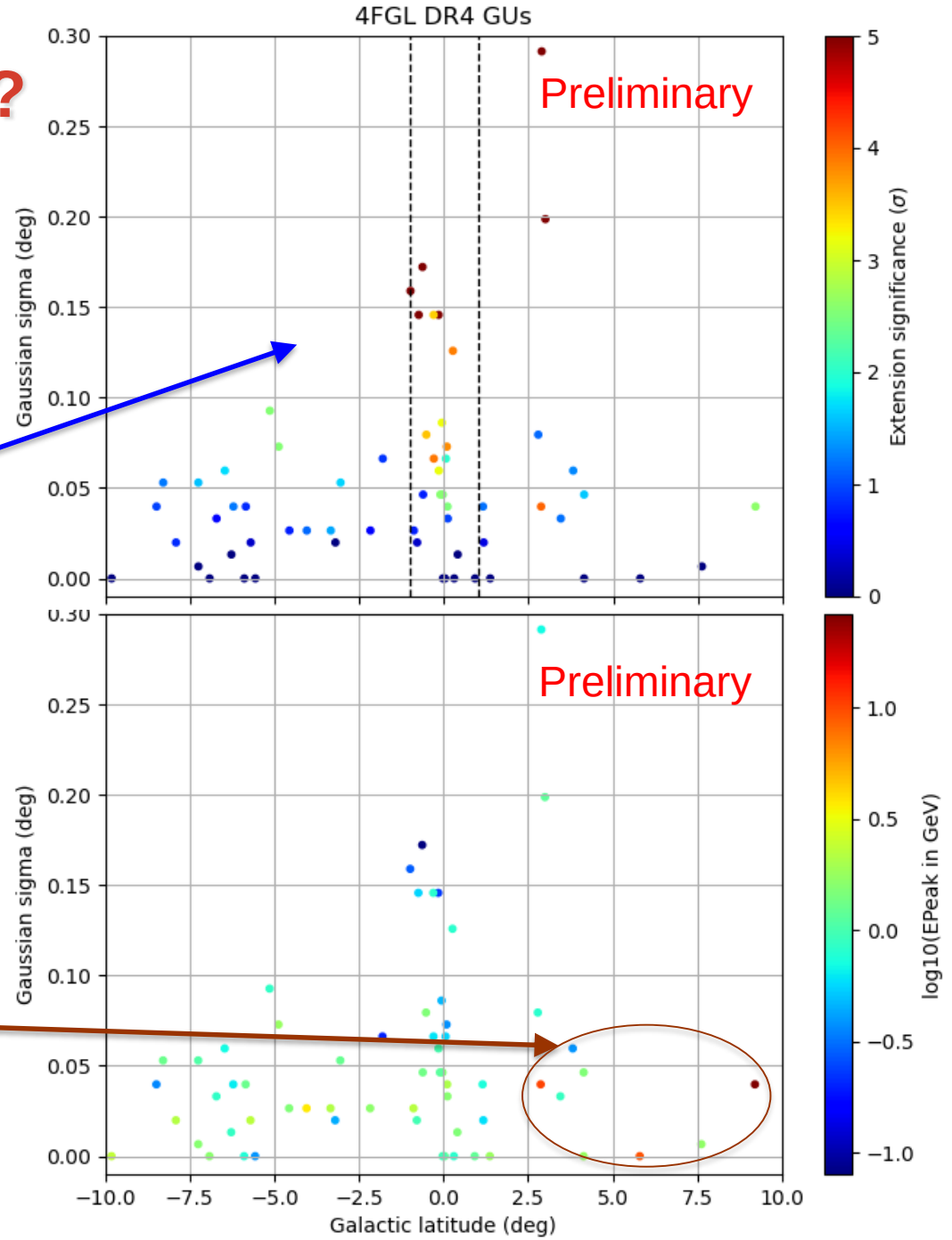
Most sources with Sig_Ext < 2 σ have 95% upper limits on extension below 0.1°

19/25 extended sources are at |b|<1°, compared to 9/41 among point sources (4.6 σ difference)

Four are found very large (σ > 0.3°). Three of those are in Carina or Cygnus, the other one is also within 1° of the Galactic plane

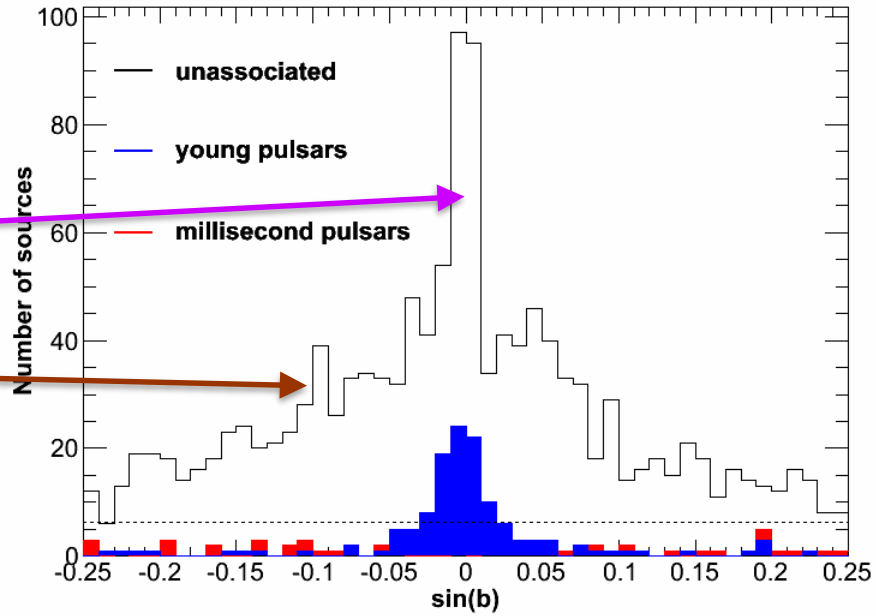
Three **hard sources**, among which two are found extended but with small extension (PWN?)

No difference between GUs and unk or spp



Conclusions and outlook

- Unassociated sources at low Galactic latitudes become more and more numerous at each LAT catalog version
- They cannot be just more pulsars
- They are comparable in integrated flux with minority components of the interstellar emission model
- They could be missing interstellar features, if those are much sharper (around 0.1°) than what we currently model
- They could also be CR excesses, if not much harder
- There are indications that GUs are indeed slightly extended, particularly in **the spike**
- GUs in **the shoulder** could be something else



A paper on GUs is in preparation in the LAT collaboration