The incremental 4FGL-DR4 catalog

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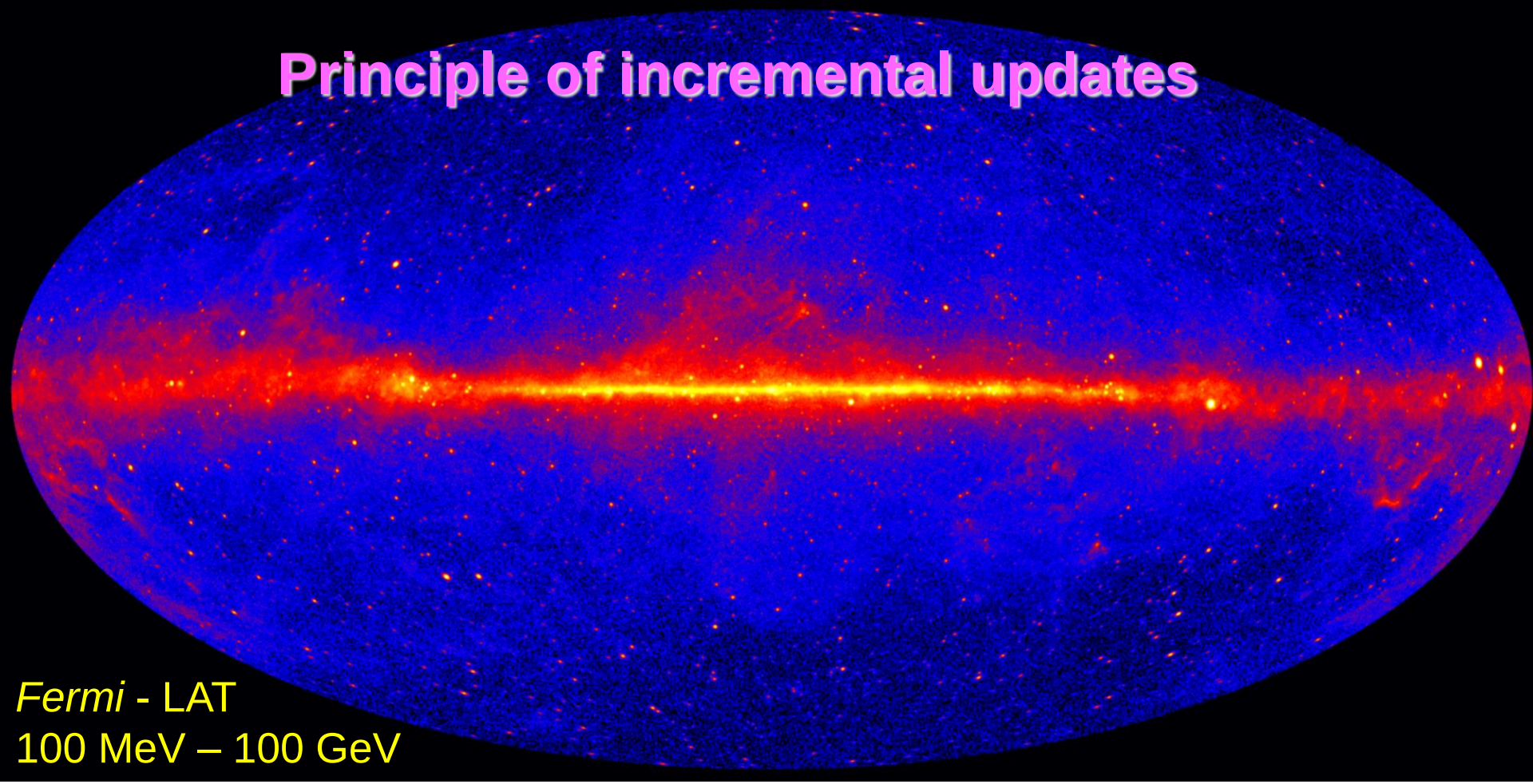
Principle of incremental updates



- Same data (P8_P305) and diffuse model (gll_iem_v07) as 4FGL (2019)
- More exposure (DR1: 8 yr, DR2: 10 yr, DR3: 12 yr, DR4: 14 yr)
- 4FGL sources are left in the model (even when TS < 25)
- Add new sources (**DataRelease** > 1)

4FGL vs DR3

4FGL		DR3
8 years P8R3_Source_V2	**Data**	12 years P8R3_Source_V3
PSF types, zmax depend on energy	**Selection**	Idem
ST v11r7p0, 50 MeV – 1 TeV	**Main fit**	FT 1.4.7, 50 MeV – 1 TeV
Weights, energy dispersion	**Method**	Updated weights, edisp_bins = – 2
gll_iem_v07	**Interstellar**	Idem
Hard limits	**Diffuse parameters**	**Bayesian priors**
75	**Extended sources**	78 (3 new + 4 updated)
Cutoff as $\exp[-aE^b]$	**Pulsars**	Cutoff as $\exp\left[-d/b^2(E/E_0)^b\right]$
TSCurv > 9 (3 σ)	**Curved spectra**	**TSCurv > 4** (2 σ)
7	**SED bins**	**8**
2-month + 1-year bins	**Light curves**	1-year bins (**not 2-month**)

Modulating the diffuse background

Problem: Diffuse parameters fit in each Region of Interest (RoI), resulting in small but **sharp changes at RoI boundaries**

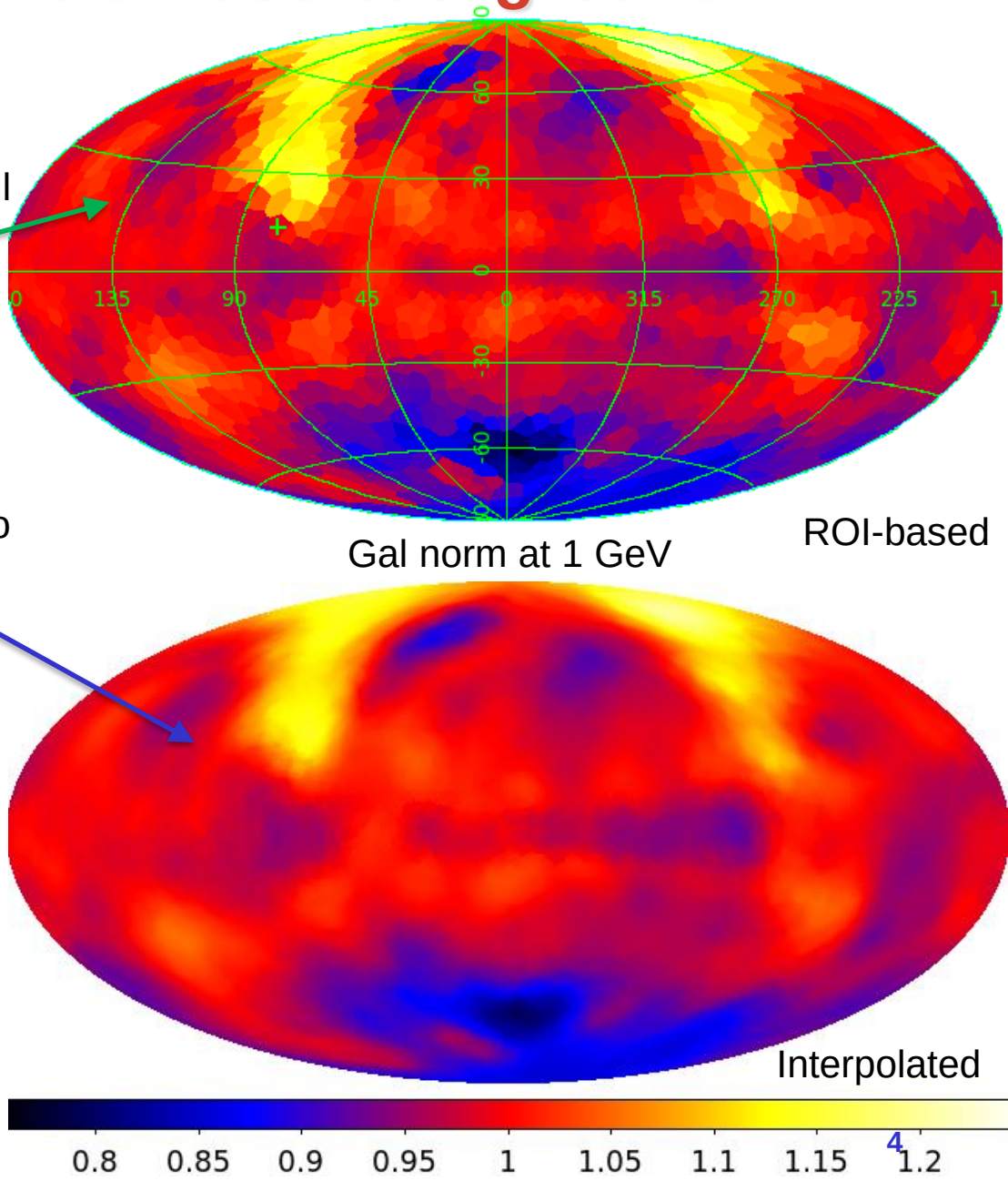
Solution: Interpolate over diffuse parameters to make them vary smoothly over the sky. Fix isotropic and apply **LP modulation** to the Galactic diffuse

Interpolation: Weighted average of up to 15 RoIs $w_i = (\max(D_i, R_i, 2)\sigma_i)^{-2}$
D_i: distance to RoI center
R_i: RoI radius
σ_i: uncertainty on parameter

LogLikelihood improves

Difficulty: Still requires first run with independent parameters. Small but significant fluctuations remain

Caveat: Do not use blindly instead of gll_iem_v07 (LP extrapolation > 10 GeV)



Gal norm at 1 GeV

ROI-based

Interpolated

Adding priors to spectral curvature

Problem: LogParabola β ~ 0.1 (low curvature) in bright AGN but unrealistic large β (very peaked spectra) in faint sources

Hard cut at 1 disrupts the covariance matrix.

Solution: Enter **priors on curvature parameters** to stabilize the model.

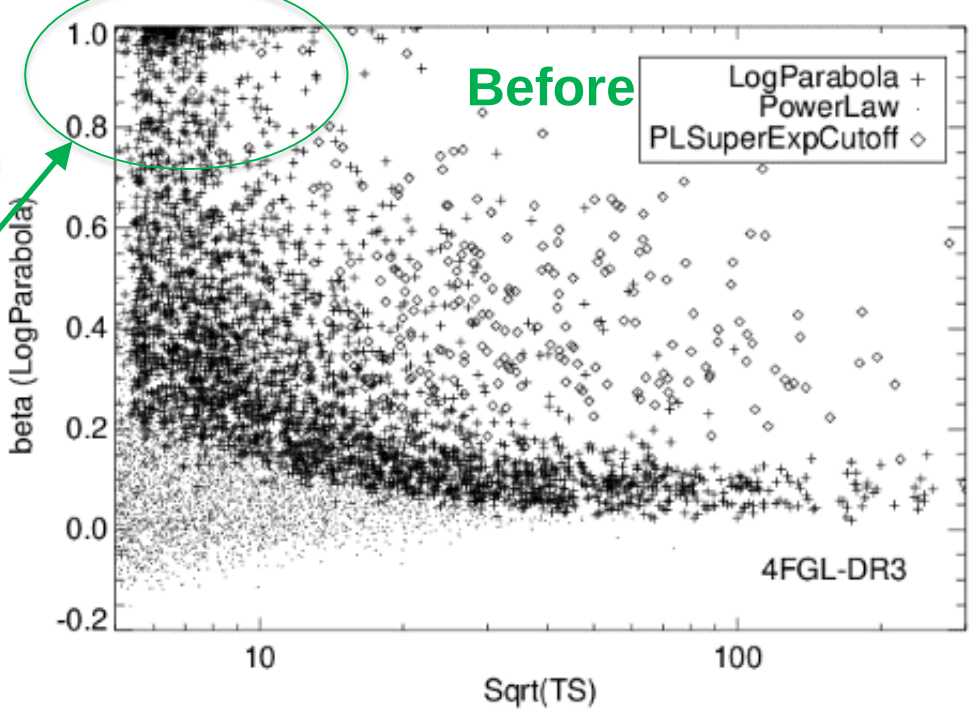
Difficulty: SNRs and pulsars are more curved than AGN and binaries.

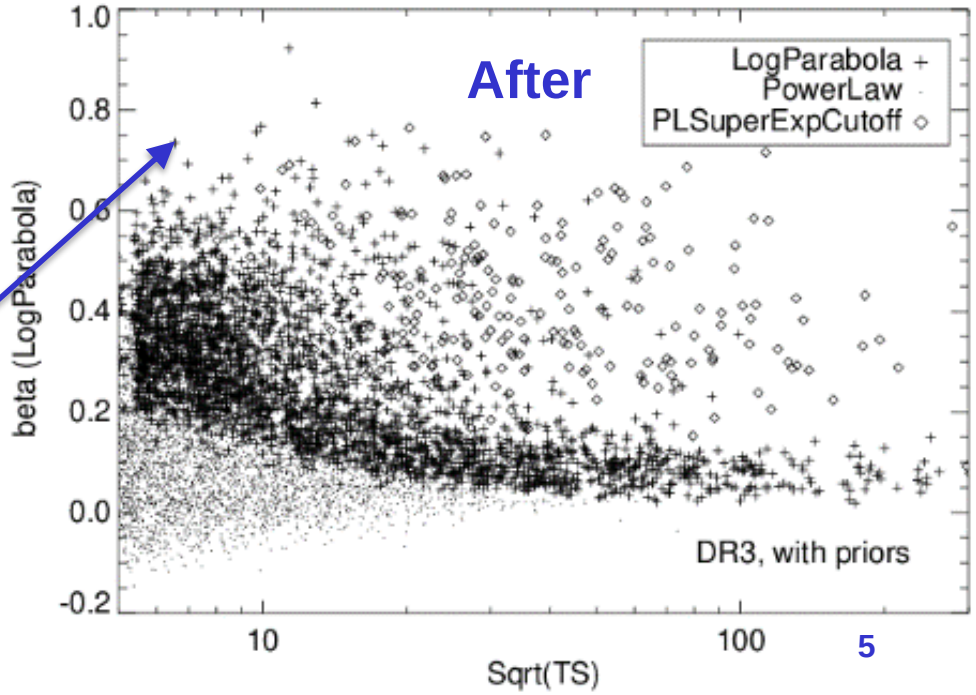
Soft priors to accommodate all:

- on LogParabola β: mean = 0.1, stdev = 0.3
- on PLEC4 ExpfactorS (~ 2β): mean=0.6, stdev=0.6

As expected, gets rid of the tail at large β

No impact on β error (< 0.3 at TS > 25)





Including transient sources

Problem: Transient sources are **diluted over many years** and can be too faint to appear in the general catalog

They can however be significant over 1 year and affect the light curves of nearby sources

Solution: Include transients that reach TS > 25 over 1 year

Too faint to fit spectral index over 14 years. Fit over best year

They are found by dedicated means:

- **4 novae** (V407 Cyg, V339 Del, V856 Sgr, YZ Ret) besides the 4 brighter ones that are detected over 14 years (V1369 Cen, V5668 Sgr, V906 Car, RS Oph)
  Positions fixed to the optical
- **10 monthly transients** (1FLT, iFLT, ASV) besides 9 that naturally appeared in DR4
  Positions taken from the dedicated search

4FGL DR4: 14 years

- Adopt much **better DR4 localization** for 9 DR1 and 1 DR2 sources
- Delete 14 sources in new extended sources or too faint/soft/hard
- 546 new sources (median energy flux = 0.9 eV/cm²/s). **7194** in all
- Replace 2 extended sources (Cygnus Loop and Puppis A) with MWL templates
- Add 4 new extended sources (3 around pulsars)

119 DR1, 82 DR2 and 106 DR3 sources end up in DR4 **with 6 < TS < 25**

Average **TS increase by 11%** with respect to DR3 at high latitude (17% exposure increase).

TS increase by only 7% at low latitude, limited by weights and confusion

Median log(energy flux ratio) is – 2 % (DR3 larger): selection bias

Spectral Shapes

Fewer curved sources due to the priors on curvature

277 pulsars (255 in DR3)

Spectral shape	4FGL	DR3	DR4
PowerLaw	70%	49%	53%
LogParabola	26%	47%	43%
PLSuperExpCutoff	4%	4%	4%

105 of the 199 DR4 sources at TS > 25 above 100 GeV are **not known TeV sources yet**

84 are BL Lacs.

TS > 25	4FGL	DR3	DR4
Above 30 GeV	618	907	1028
Above 100 GeV		172	199

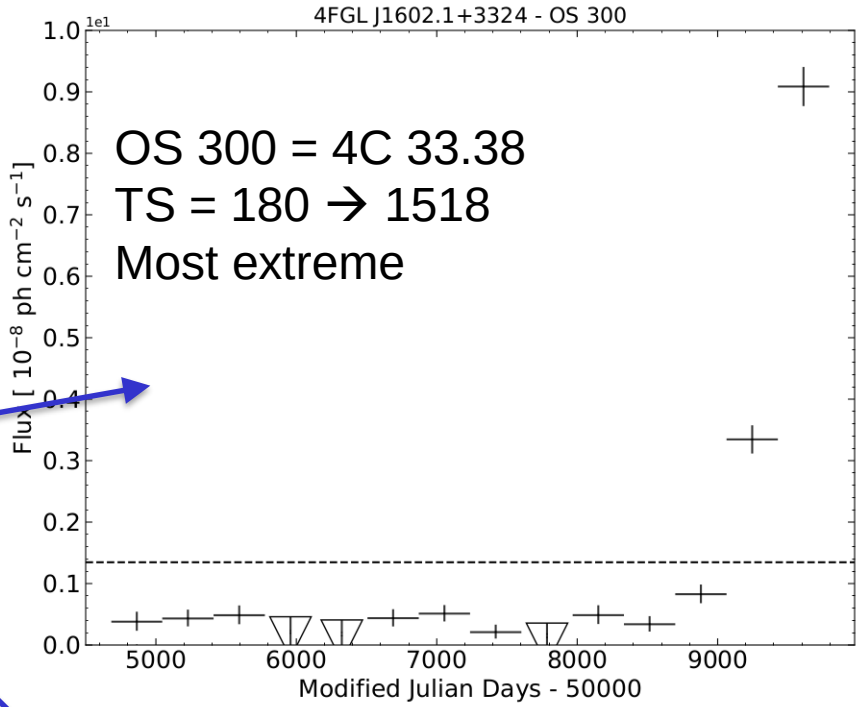
Light curves

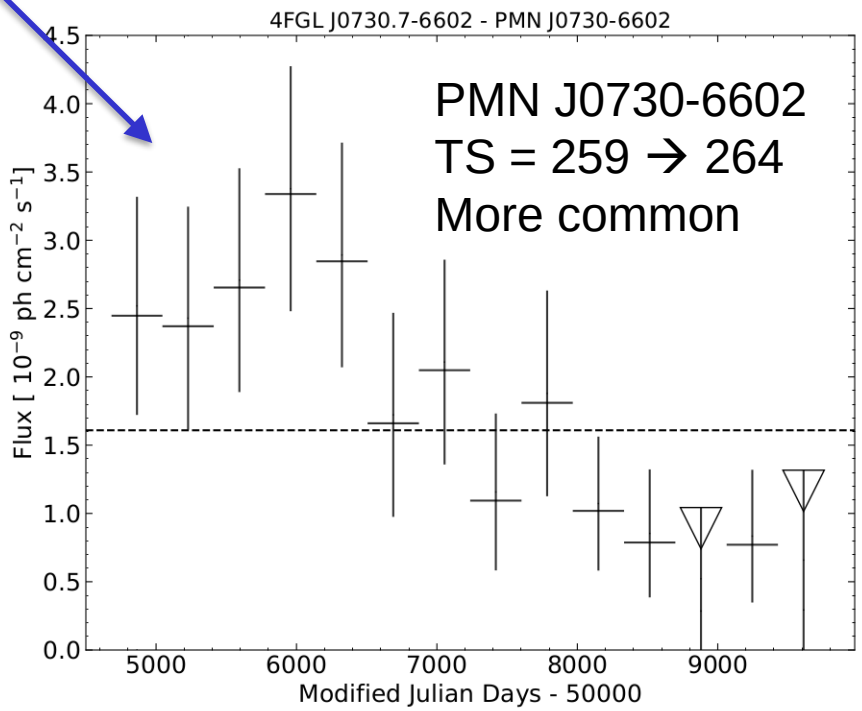
1825 significantly variable sources in DR4

179 DR3 sources newly variable
103 not variable any longer

Fraction of variable sources (from 1-year light curves) remains around 1/4 (1/3 at high latitude).

Fractional variability did not increase significantly going from 8 to 14 years, still peaking between 50 and 90%





DR4 associations

26 new associations among **former sources** (23 pulsars, 3 binaries)

2 changes (glc → MSP and nova → blazar)

14 class changes among AGN (mostly to BL Lac)

236 associations among **new DR4 sources**:

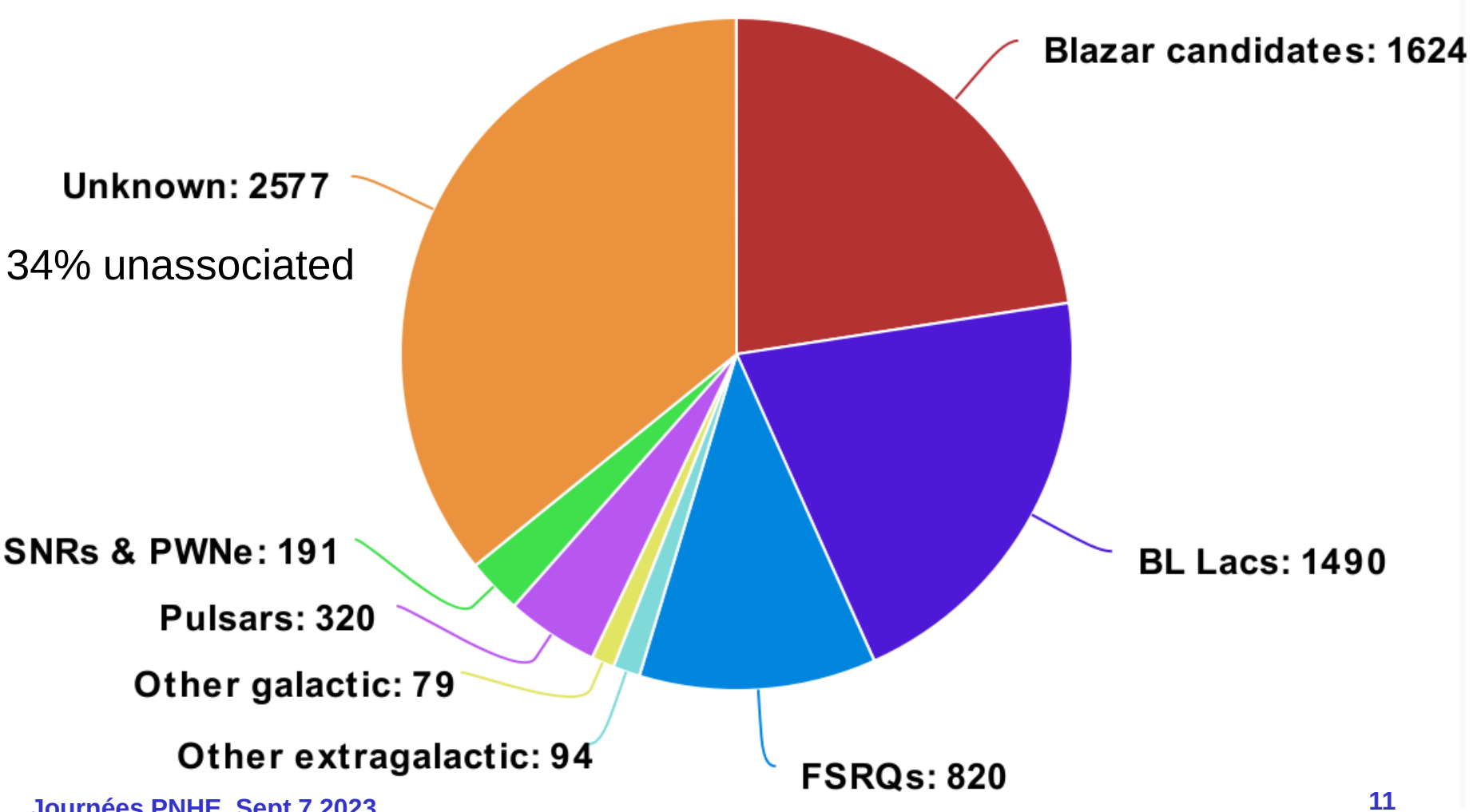
- 83% blazars (mostly uncertain type)
- 11% unclear (several options or unknown counterpart)
- 6% Galactic

57% of new DR4 sources are unassociated

DR4 associations

Since DR3 we distinguish **MSP**s (recycled) and **PSR**s (young) pulsars

Still 17% Soft Galactic Unassociated sources



Conclusions and outlook

- Incremental 4FGL versions every 2 years
- DR4 adds about **550 more sources**
- Smooth adjustment of interstellar emission model
- Prevents strongly curved spectra
- Includes bright transients
- Fraction of unassociated remains about 1/3

4FGL-DR4 is available at the FSSC

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/14yr_catalog/

Next may be full reanalysis with new interstellar emission model

Methodology

Reference Catalog (4FGL DRn-1)

pointlike

Refit diffuse components

Relocalize DRn-1 sources

Source detection

Source localization

Comparison for spectra (flags)

Comparison for localization (flags)

Merge

pyLikelihood

Official Fermi Tools and diffuse model

Original DRn-1 source localizations

Thresholding

Associations

Bayesian + Likelihood ratio

Incremental Catalog

With flags

pyLikelihood

Spectral characterization

Light curves

Run with alternative diffuse model (flags)

DR3 vs DR4

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12 years P8R3_Source_V3	**Data**	14 years P8R3_Source_V3
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gll_iem_v07	**Interstellar**	**LogParabola rescaling**
Bayesian priors	**Diffuse parameters**	Idem
78	**Extended sources**	82 (4 new + 2 updated)
None	**Transient sources**	**14**
Cutoff as $\exp[-d/b^2(E/E_0)^b]$	**Pulsars**	Idem
TSCurv > 4 (2 σ)	**Curved spectra**	Idem + **priors on curvature**
8	**SED bins**	Idem
1-year bins	**Light curves**	Idem

Extended sources

- 75 extended sources in 4FGL and DR2
- 6 **modified**, 3 **new**, 1 **point → extended**, 3 **around pulsars**
- **Deleted** 17 former sources inside those

	Source name	TS	Reference	Comment
DR3	HESS J1825-137	498	Grondin+ 2011	Correction
DR3	HB 21	2360	Ambrogi+ 2019	One more point source
DR3	SNR G106.3+2.7	43	Xin+ 2019	VER J2227+608
DR3	SNR G150.3+4.5	518	Devin+ 2020	Gaussian model
DR3	Vela X	499	Tibaldo+ 2018	Radio template
DR3	SNR G279.0+1.1	237	Araya 2020	Cluster of DR2 sources
DR3	HESS J1640-465	326	Marès+ 2021	HESS template
DR4	Puppis A		Mayer+ 2022	eROSITA template
DR4	Cygnus Loop		Tutone+ 2021	UV template
DR4	SNR G51.3+0.1		Araya 2021	Cluster of DR3 sources
DR4	3C 58		Li+ 2018	Around PSR J0205+6449
DR4	SNR G292.2-0.5		HESS+ 2018	Around PSR J1119-6127
DR4	CTB 80		Araya+ 2021	Around PSR J1952+3252