LAT Systematics

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Motivation

- Systematics… that's just some number I add in quadrature to my statistical errors that doesn't really change things. *No!*

- Some recent historical examples of systematic error:
  - #GRBM31
  - BICEP2
  - The financial crisis (risk assessment)

What is a systematic error?

- “Any error that's not a statistical error”.
- “A systematic uncertainty is a possible unknown variation in a measurement, or in a quantity derived from a set of measurements, that does not randomly vary from data point to data point.”

How do you measure systematics?

- Data vs. Monte Carlo comparison
- Calibration measurements, taken separately from your data
- If data provides useful data about nuisance parameter, fit it from the data itself.

- Main culprits:
  - 1. Uncertainty in IRFs (mainly A_{eff}).
  - 2. Incomplete knowledge in modeling Galactic IEM.

- IRFs can be factored into three parts:
  - Effective area (Aeff)
  - Point-spread function (PSF)
  - Energy Dispersion / Scale

- for P7REP data, see instrument paper (a great resource!) doi:10.1088/0067-0049/203/1/4

IRF Uncertainties

- **Summarizing Table of Systematic Errors**

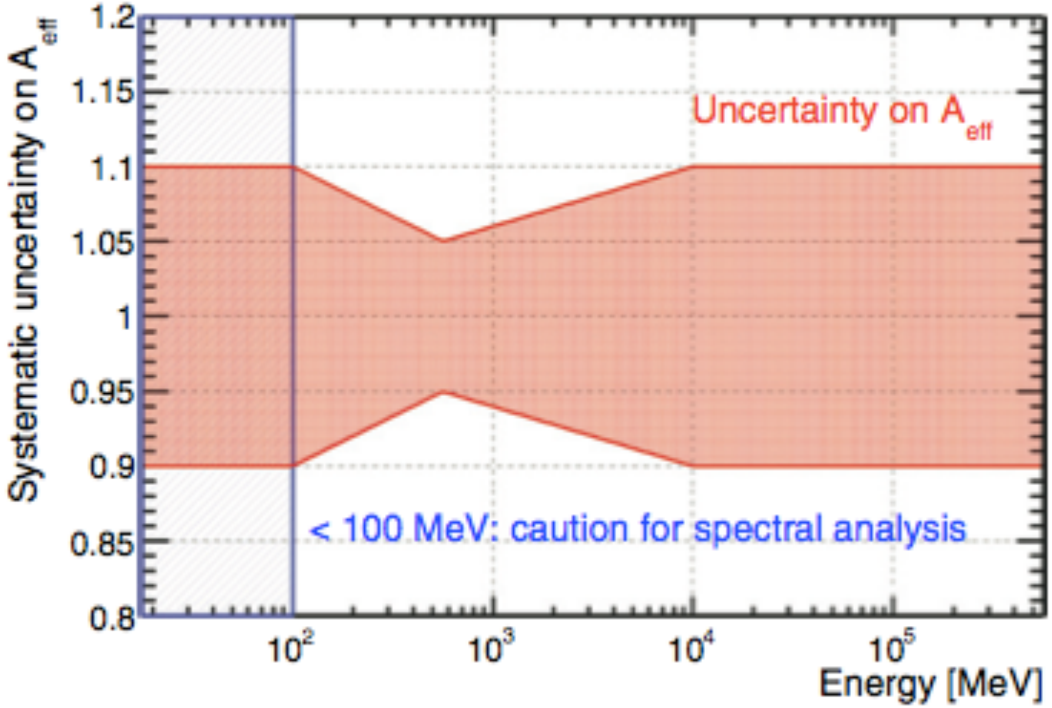
Quantity	$A_{\rm eff}$	PSF	Energy Dispersion	Energy Scale
F_{25}	$\sim 8\%$ (§ 5.7)	$\sim 8\%$ (§ 6.5)	$\sim 3\%$ (§ 7.4)	$+13\% - 5\%$ (§ 7.4)
S_{25}	$\sim 10\%$ (§ 5.7)	$\sim 6\%$ (§ 6.5)	$\sim 2\%$ (§ 7.4)	$+4\% - 2\%$(§ 7.4)
Γ	~ 0.09 (§ 5.7)	~ 0.07 (§ 6.5)	~ 0.04 (§ 7.4)	-
Variability	$\sim 3\%$ (§ 5.6)	$\sim 3\%$ (§ 6.5)	-	-
Localization	-	$\sim 0.005°$ (§ 8.2)[a]	-	-

These are just rough estimates of systematic errors on commonly measured quantities. (Section number refer to "performance paper").

It is not meant to replace actually estimating the systematic errors which are relevant for a particular analysis.

- **for P7REP data, see instrument paper (a great resource!) doi:10.1088/0067-0049/203/1/4**

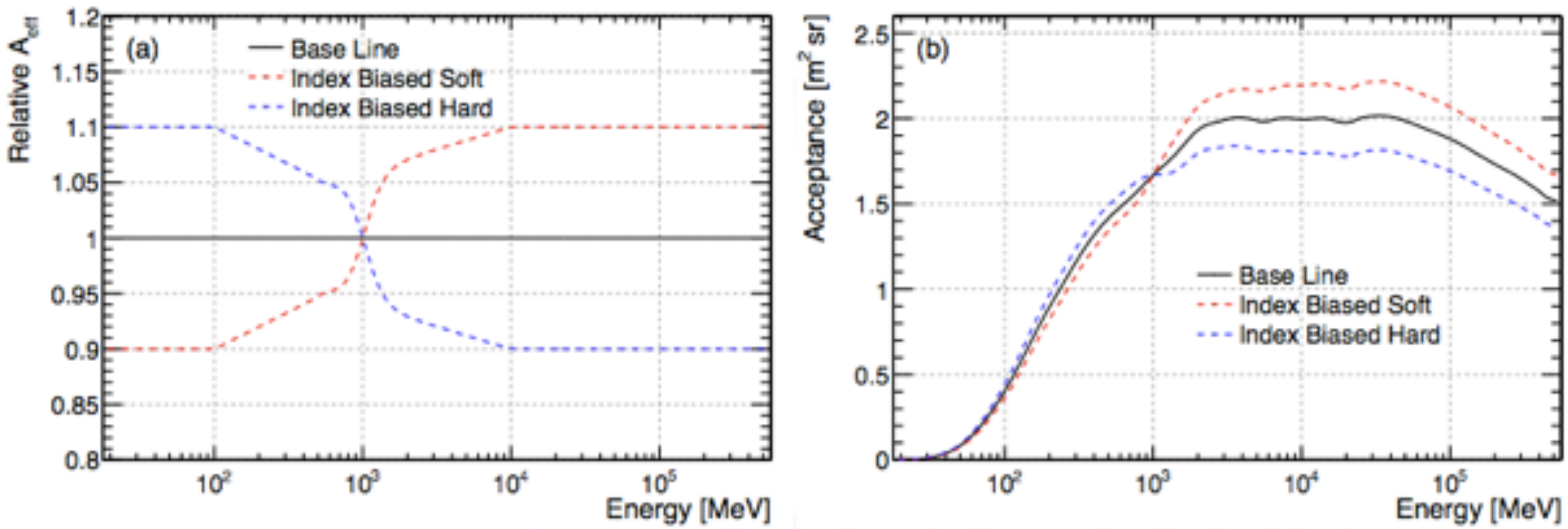
Effective Area Validation



- <u>**This is just an error envelope:**</u> **No information about what deviations we might expect within the uncertainty band.**
- **Below 100 MeV the worsening of the energy resolution, coupled with the steep falling of the effective area make the effect of the energy dispersion potentially noticeable.**
- **Point-to-point correlations? Yes: strong correlation on energy scales much lower than half a decade**

$A_{\rm eff}$ BRACKETING FUNCTIONS

- Scale $A_{\rm eff}$ by the product of the relative error $\epsilon(E) = \frac{\delta A_{\rm eff}(E)}{A_{\rm eff}(E)}$ (see slide 25) and an arbitrary bracketing function $B(E)$:
  - $A'_{\rm eff}(E, \theta) = A_{\rm eff}(E, \theta) \cdot (1 + \epsilon(E) B(E))$.
  - Creating modified $A_{\rm eff}$ curves is as easy as opening the $A_{\rm eff}$ FITS files, doing some multiplications and saving new files.
- The most appropriate choice of the bracketing function depends on the quantity we're interested in:
  - $B(E) = \pm 1$ maximizes/minimizes $A_{\rm eff}$ within its uncertainty band leaving the spectral index $\sim$ unaffected.
- Note: the public Galactic and isotropic diffuse emission models are fit to the data using the standard effective area tables:
  - need to rescale the diffuse models by the inverse of $B(E)$ to ensure the expected numbers of counts are unchanged.
- Basic idea: repeat the analysis with a family of modified $A_{\rm eff}$ curves and see how the measured quantities change:
  - use the maximal changes to estimate the systematic errors.
- On a separate note: modified IRFs can be used with *gtobssim* too.



- Use a function that changes sign at the pivot (or decorrelation) energy (i.e., the energy at which the fitted index and normalization are uncorrelated):
  - for example $B(E) = \pm \tanh\left(\frac{1}{k}\log(E/E_0)\right)$;
  - $k = 0.13$ corresponds to smoothing over twice the LAT energy resolution.

- **See talks by Luca Baldini, 2012 Fermi summer school: <u>fermi.gsfc.nasa.gov/science/mtgs/summerschool/2012</u>**

Calculating the Decorrelation Energy

- from: http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/python_tutorial.html

Calculate Decorrelation Energy

The decorrelation energy can be calculated using the following formula (note that the derivation and explanation of this can be found in the Cicerone).

$$logE_0 = \frac{logE_1 - \epsilon logE_2}{1-\epsilon} - \frac{1}{1+\gamma} - \frac{cov_{I\gamma}}{Icov_{\gamma\gamma}}$$

where E_1 and E_2 are the LowerLimit and UpperLimit of the model respectively, ϵ is $(E_2/E_1)^{1+\gamma}$ and γ is negative. So, let's calculate this number along with some sanity checks:

```
>>> E1 =
like2.model['_2FGLJ1555.7+1111'].funcs['Spectrum'].getParam('LowerLimit').value()
>>> E2 =
like2.model['_2FGLJ1555.7+1111'].funcs['Spectrum'].getParam('UpperLimit').value()
>>> gamma =
like2.model['_2FGLJ1555.7+1111'].funcs['Spectrum'].getParam('Index').value()
>>> I =
like2.model['_2FGLJ1555.7+1111'].funcs['Spectrum'].getParam('Integral').value()
>>> cov_gg = like2.covariance[16][16]
>>> cov_II = like2.covariance[15][15]
>>> cov_Ig = like2.covariance[15][16]
>>> print "Index: " + str(gamma) + " +/- " + str(math.sqrt(cov_gg))
Index: 1.65492100947 +/- 0.0329019273833
>>> print "Integral: " + str(I) + " +/- " + str(math.sqrt(cov_II))
Integral: 0.511056958739 +/- 0.0304686651178
>>> print E1,E2
200.0 300000.0
>>> epsilon = (E2/E1)**(1-gamma)
>>> logE0 = (math.log(E1) - epsilon*math.log(E2))/(1-epsilon) + 1/(gamma-1) +
cov_Ig/(I*cov_gg)
>>> E0 = math.exp(logE0)
>>> print E0
2533.11310982
```

fermi
Gamma-ray Space Telescope

LAT Systematics

Part 2:
Uncertainty due to Galactic Interstellar Emission Models

The Standard IEM

- **IEM = Interstellar Emission Model**
- **Assume CRs uniformly penetrate all gas phases of the ISM**

  => model as a linear combination of gas column densities (HI, CO) and an inverse Compton (IC) intensity map

- **Cavaets:**
  - **HI spin temperature assumed to be 200 K**
  - **We know CO does not trace all H2 gas! (dark)**

- **IEM was developed for analysis of point sources (and marginally extended sources <~2 degrees)**

The Standard IEM (2)

- IEM is derived from a physical model, but fit to the LAT data.
- CR gradient modeled by splitting into Galacto-centric rings based on line velocities and Galactic rotation.
- Each IEM is made using a specific event class and isotropic model. Thus it will not give a good/consistent fit to other data sets (e.g. P6_V11 data using P7REP IEM).
  - => Other models won't give you a meaningful measure of systematic errors in the IEM.

- <u>How do I estimate uncertainties?</u>

  There is no preferred general method for studying diffuse emission and extended sources. But we prefer that you do.

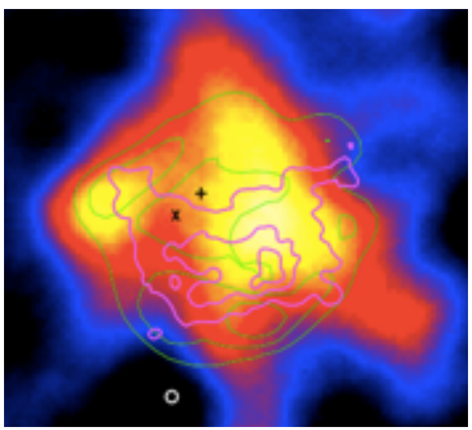
An Illustration: SNR HB 9

- **We know the current** *gll_iem_v05.fits* **represents an incomplete knowledge of the Galactic diffuse emission… because it does not include molecular hydrogen (CO map) in the outer Galaxy (for R>10kpc).**

An Illustration: SNR HB 9

- **We know the current *gll_iem_v05.fits* represents an incomplete knowledge of the Galactic diffuse emission… because it does not include molecular hydrogen (CO map) in the outer Galaxy (for R>10kpc).**
- **Let's quantify what effect this "systematic error" in the diffuse model had on a recent publication…**

Submitted to MNRAS



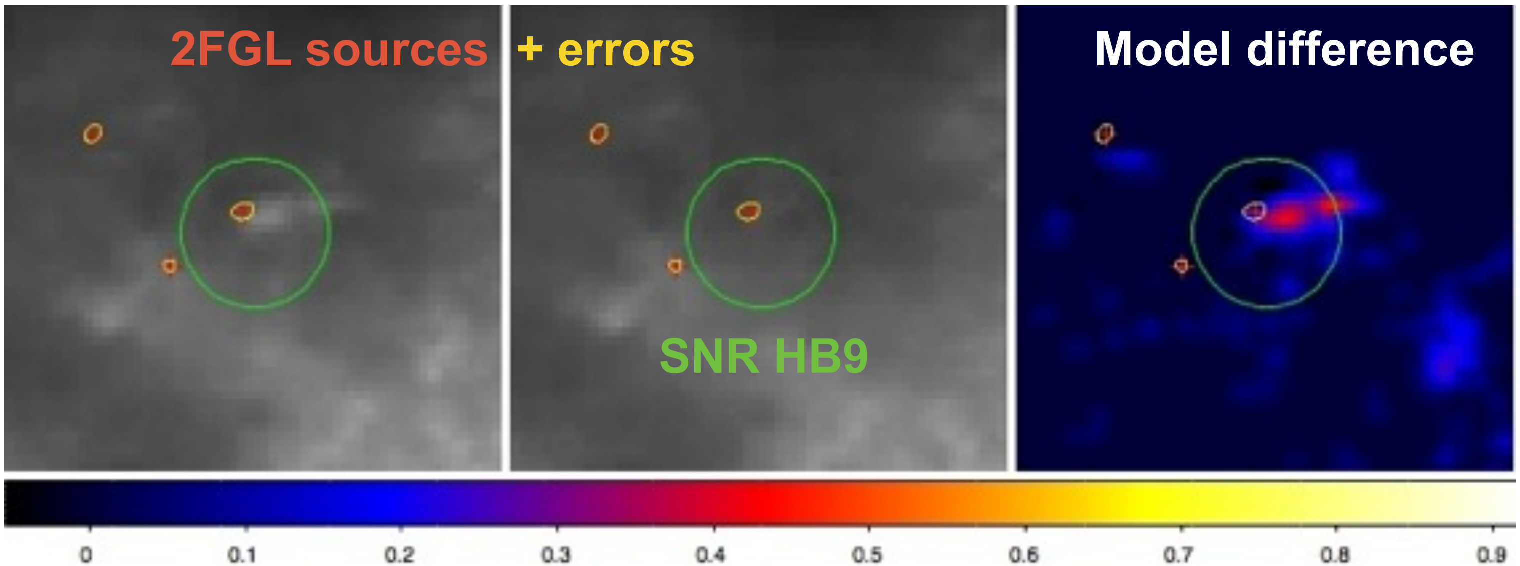
Counts map of SNR HB9 above 1 GeV

Fermi LAT Observation of Supernova Remnant HB9

A 5.5-year *Fermi* LAT gamma-ray observation shows significant extended emission at the position of the supernova remnant HB9 (G160.9+2.6). The significance of the detection above the background for photon energies above 0.2 GeV is 21σ. The gamma-ray flux above 0.2 GeV is $(3.2 \pm 0.2_{stat}) \times 10^{-8}$ photons $\mathrm{cm^{-2}s^{-1}}$, and the corresponding luminosity above 1 GeV is 1.5×10^{33} erg $\mathrm{s^{-1}}$ (for a source distance of 1 kpc). The spectrum of the source is best described by a power-law with an exponential cutoff in energy ($dN/dE = N_0 E^{-\Gamma} \exp(-E/E_c)$), with index $\Gamma = (1.7 \pm 0.3_{stat})$ and cutoff energy $E_c = (2.5 \pm 1.5_{stat})$ GeV. The gamma-ray spectrum of the source is consistent with both leptonic and hadronic models, and the relevant physical parameters in each case are derived. More studies on the ambient density in the region of HB9 should be carried out to rule out or confirm hadronic and non-thermal bremsstrahlung scenarios for the gamma-ray emission.

An Illustration: SNR HB 9

- A comparison of the two diffuse models, shows CO gas that was not included overlapping with the SNR, and nearly coincident with a 2FGL source



- Reanalyze the ROI using two different Galactic diffuse models (with and without CO cloud) to determine systematic change in source TS, flux, and index

An Illustration: SNR HB 9

- Analysis: 5.7 yrs of P7REP_SOURCE_V15 data, 10° ROI, front+back, 1-300 GeV, binned gtlike.
- HB9 source model is a uniform disk of radius 1.27° centered at $\alpha,\delta_{(J2000)}$ = 75.17, 46.61

Diffuse model	Global LL	-2*ΔLL	TS(HB9)	Prefactor	Index
gll_iem_v05	146253.1	0.0	191.8	6.59(0.70)	3.01(0.19)
gll_iem_v05_rev1	146242.4	21.4	105.7	4.44(0.84)	3.29(0.34)

- Prefactor = 4.44 +/- 0.84 $_{stat}$ +/- 2.1 $_{sys}$
- Index = 3.29 +/- 0.34 $_{stat}$ +/- 0.28 $_{sys}$

How can I quantify diffuse systematics?

- **Do not know how our Galactic diffuse model is incomplete**
  Similar to the effect of an unmodeled source
- **<u>Quick check:</u>** To determine the importance of diffuse uncertainty estimate the source-to-background ratio by comparing a map of only your source (gtmodel, edited XML) to the Galactic IEM.

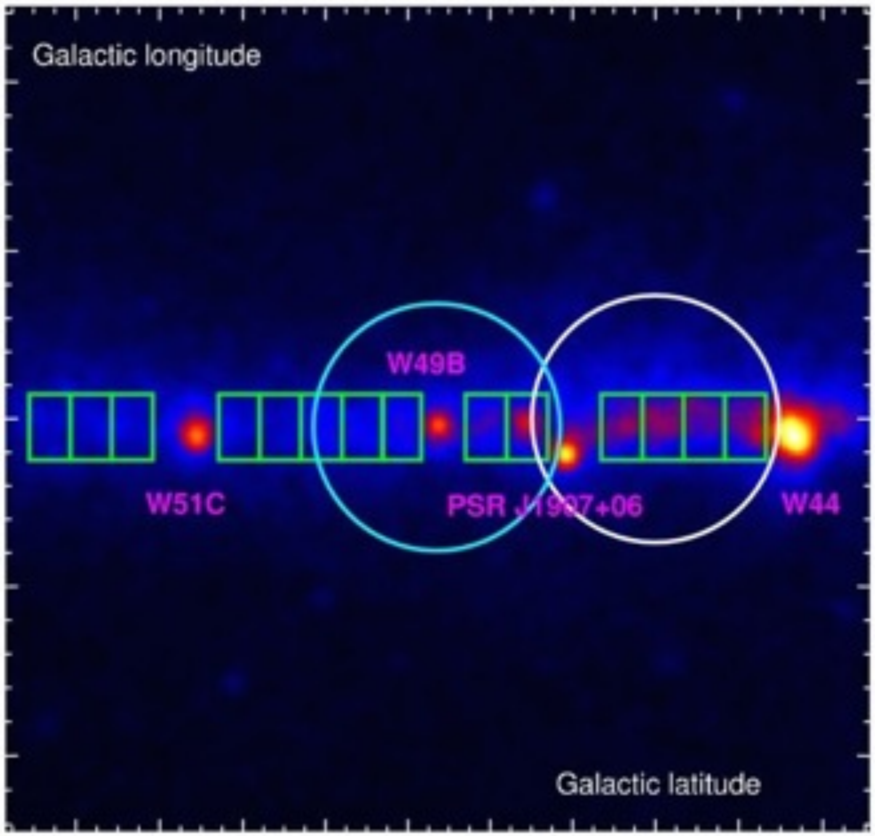
- **Methods to estimate the bounds of our uncertainty:**
  - **1. Scale the IEM by some uncertainty estimated from the fit to nearby regions.**
  - **2. Create alternative IEMs to those parameters you are most uncertain about.**
  - **3. A dedicated analysis of diffuse emission in your ROI**

Scaling the IEM

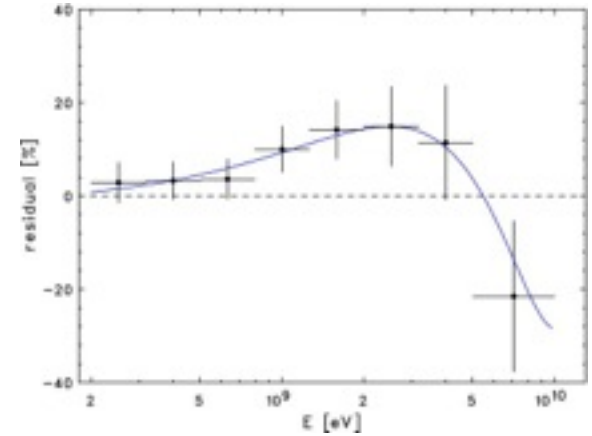
- Measure uncertainty for a collection or regions, or nearby regions.
- Some papers that have used this method:
  - SNR W49B: doi:10.1088/0004-637X/722/2/1303
  - SNR S147: doi:10.1088/0004-637X/752/2/135
  - 2PC (Section 6.1): doi: 10.1088/0067-0049/208/2/17
- Pros: It’s easy and quick
- Cons:

Scaling the IEM: W49B

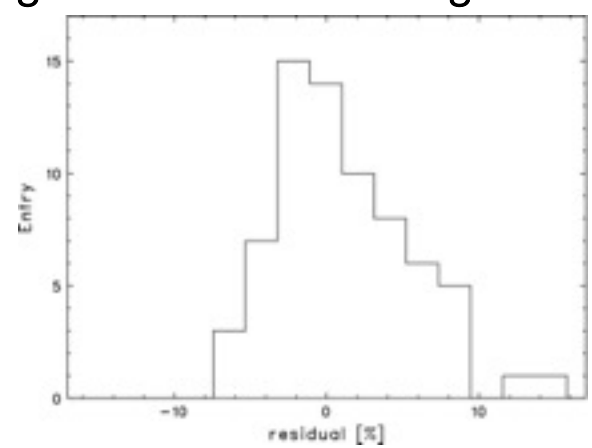
- **Measure uncertainty for a collection or nearby regions.**



(observed-model)/model in white circle



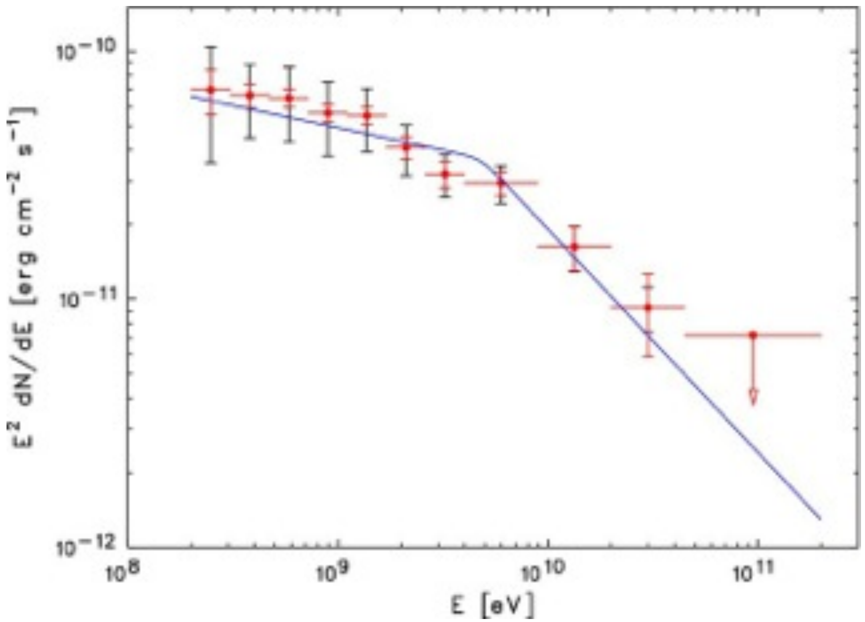
Histogram of residuals in green boxes



"We obtain an estimate of uncertainties as ≤30% for below 1 GeV, ≤20% in 1–2 GeV, and ≤10% above 3 GeV."

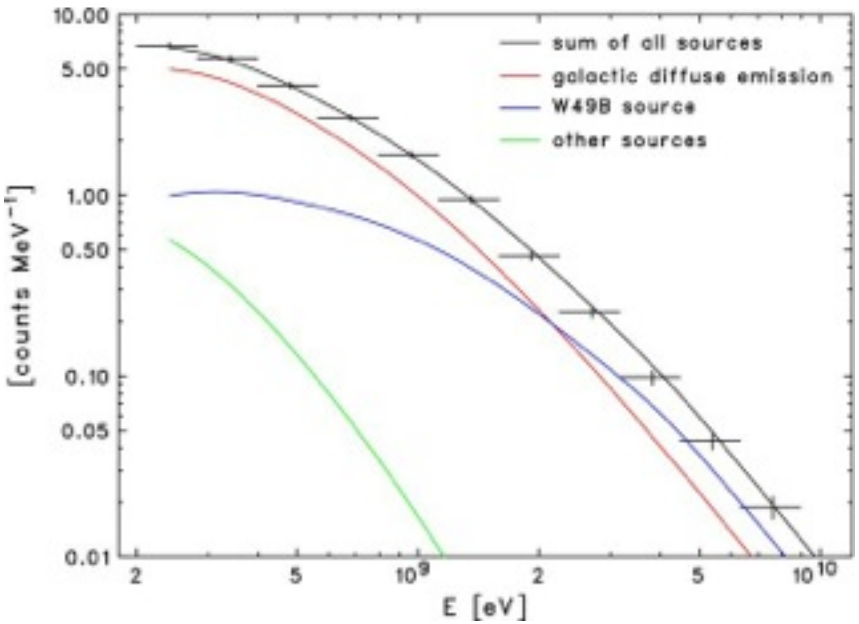
Scaling the IEM: W49B

- **"We obtain an estimate of uncertainties as ≲30% for below 1 GeV, ≲20% in 1–2 GeV, and ≲10% above 3 GeV."**



SED for W49B with statistical errors in red and systematic errors in black (from diffuse and Aeff added in quadrature)

Note how systematic errors scale with strength of Galactic diffuse



Scaling the IEM: 2PC

- 2PC = 2nd Pulsar Catalog (study of 117 ɣ-ray pulsars.)
- Distribution of Galactic diffuse normalization parameters: Mean of 1.01 with 1σ deviation of 4%.

- Repeat analysis with the normalization of the Galactic diffuse fixed to (1 ± 0.06)x best-fit value (±1.5σ deviations)

Average and largest deviations for Index, E_{cutoff}, Flux

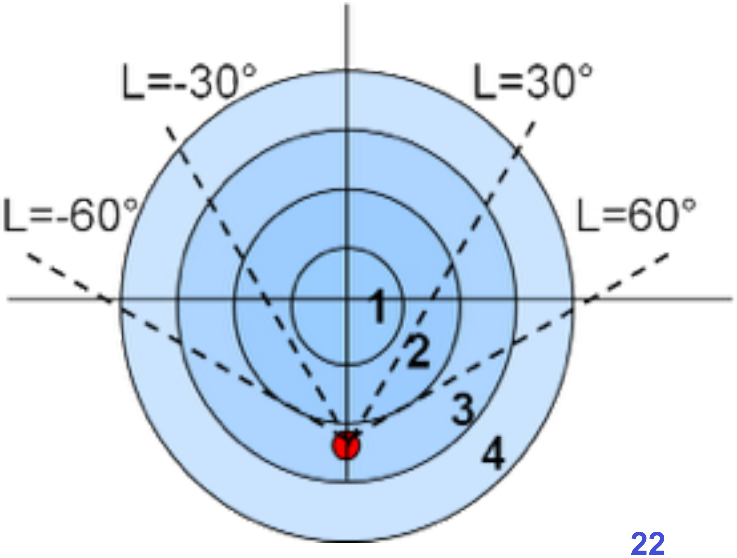
Systematic Deviations on Pulsar Spectral Parameters

Systematic	$\langle\Delta\Gamma\rangle$ (%)	$\langle\Delta E_{cut}\rangle$ (%)	$\langle\Delta F_{100}\rangle$ (%)	$\max(\Delta\Gamma)$ (%)	$\max(\Delta E_{cut})$ (%)	$\max(\Delta F_{100})$ (%)
Galactic Diffuse	14	4	16	80	27	65
Bracketing IRFs	5	4	8	21	11	13

Alternative IEMs

- Adopt a different model-building strategy to probe effects of varying a few important input parameters:
  - HI spin temperature (150 K, optically thin)
  - Halo height (4 kpc, 10 kpc)
  - CR source distribution (SNR, Lorizmer)

- Allow more freedom by separately scaling the IC, HI and CO emission in 4 Galacto-centric rings with boundaries at 0, 4, 8, 10, 30 kpc.
- Study is limited to data >1 GeV



Note: These are not GALPROP models!
These models are fit to LAT data.

Alternative IEMs

Caveat: These 8 models do not span the complete uncertainty of the systematics. We also note that the methodology in creating this model differs from that used to create the official Fermi-LAT interstellar emission model so these 8 models do not bracket the official model.

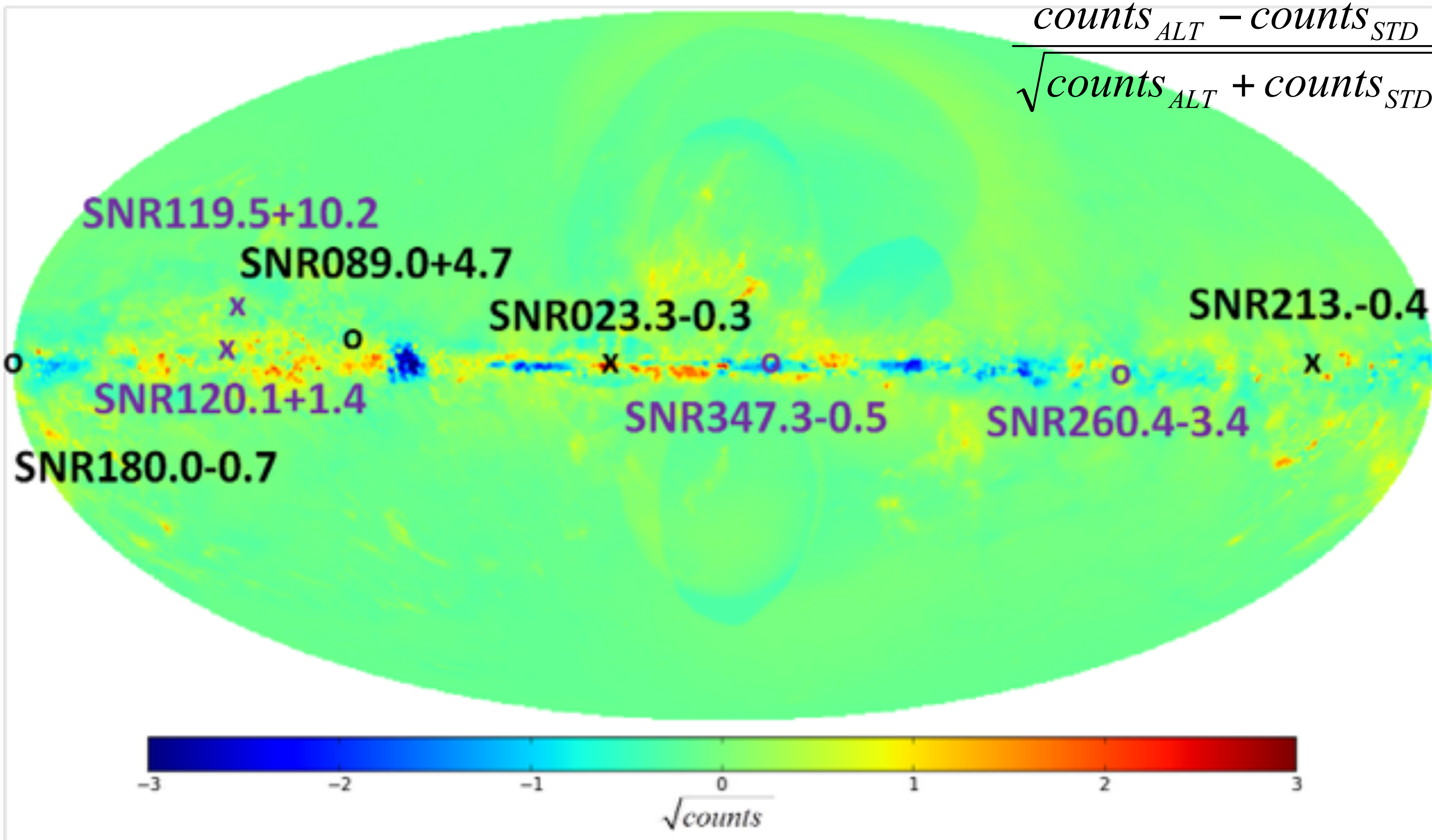
All this & more can be found in a Fermi Symposium Proceedings!

http://arxiv.org/abs/1304.1395

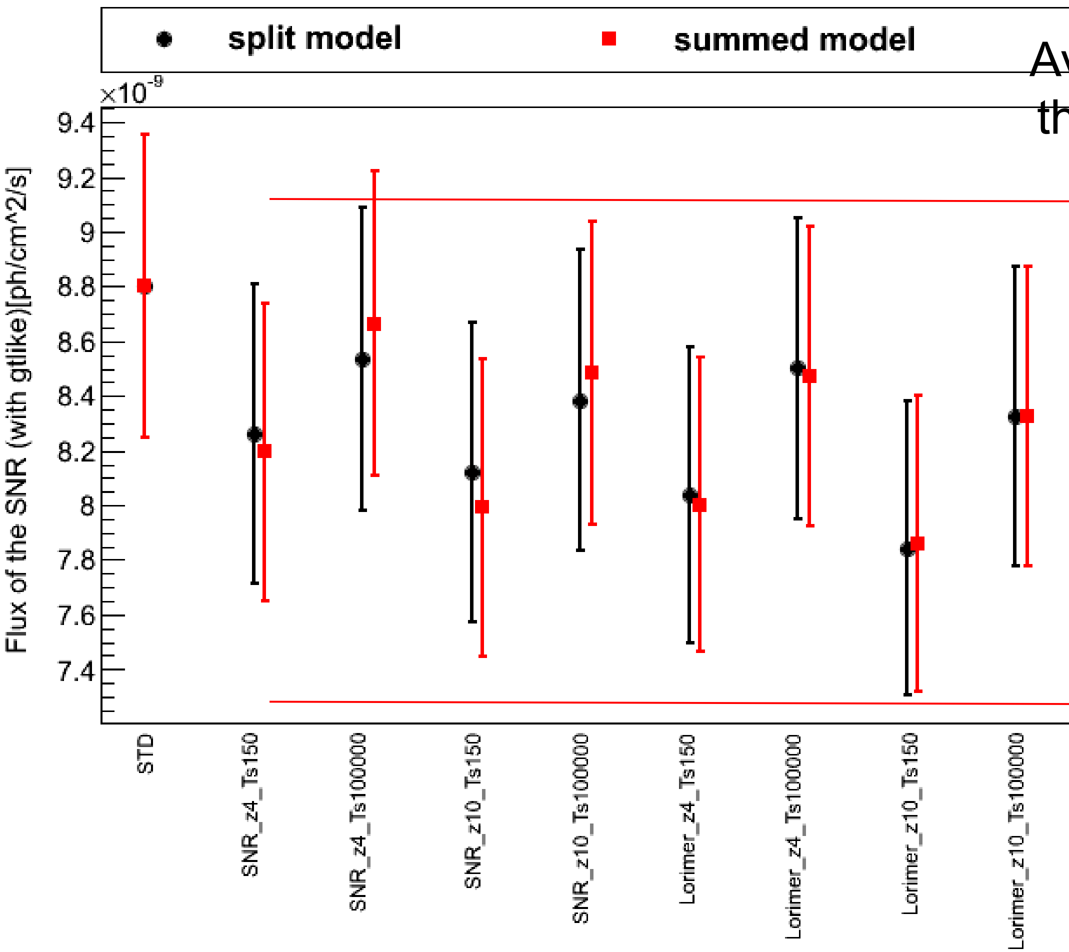
Alternative IEMs

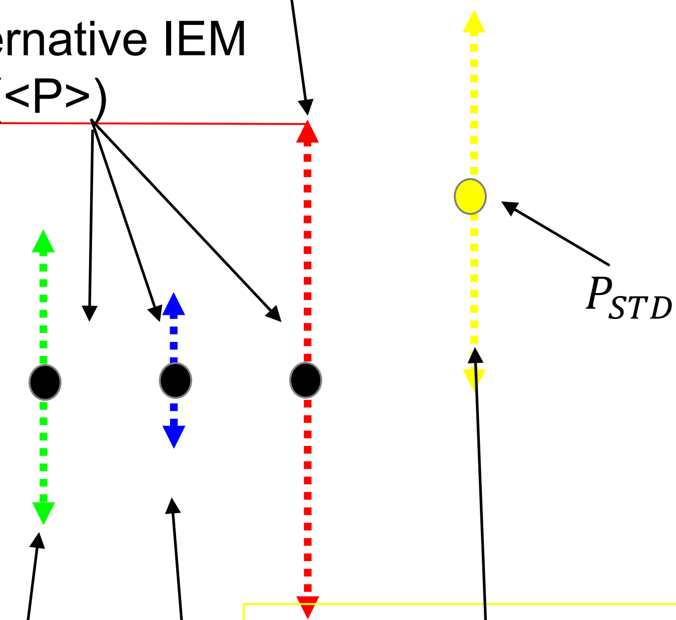
- **Study effect on 8 SNRs that span the range of flux and index seen for all LAT-detected SNRs.**

$$\frac{counts_{ALT} - counts_{STD}}{\sqrt{counts_{ALT} + counts_{STD}}}$$



Alternative IEMs





Extreme variation

Average value from the alternative IEM (<P>)

Systematic error: $\sqrt{(< P > - P_{std})^2 + \sigma^2}$

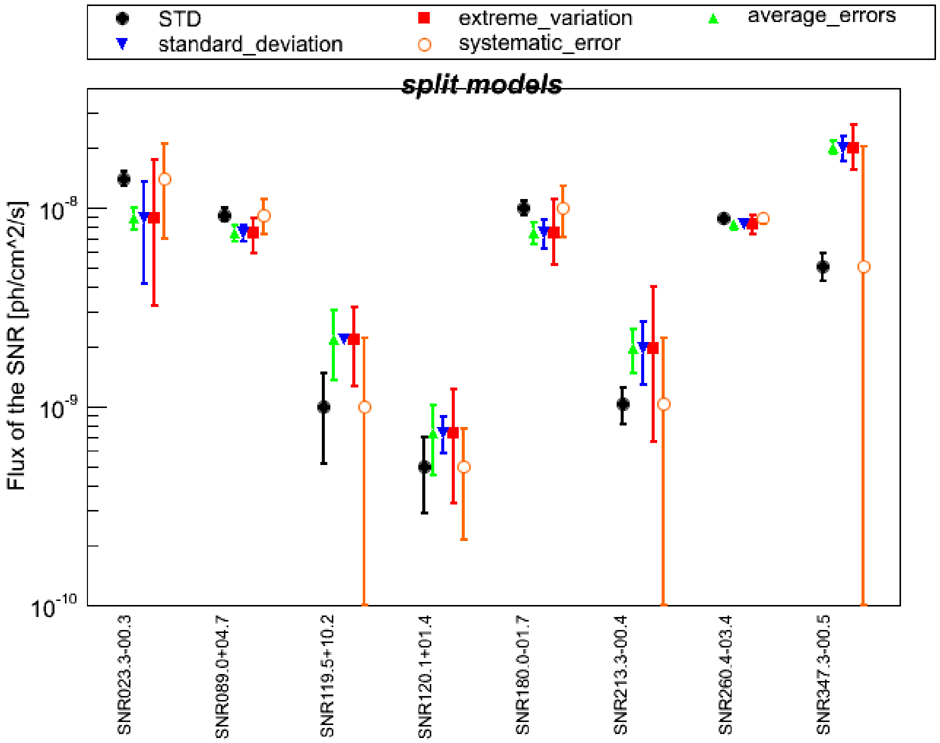
Standard deviation of the estimated values.(σ)

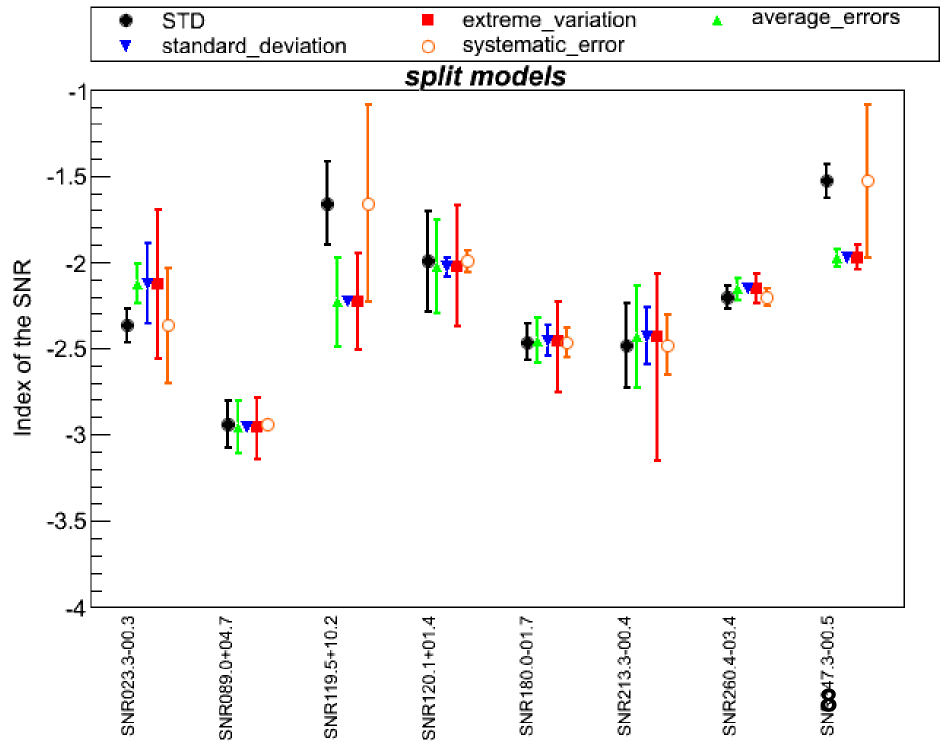
Average value of the statistical error with the various diffuses

SNR G260.4-3.4

Alternative IEMs

- **Variations from aIEM models are almost always larger than statistical errors, and vary greatly between sources.**

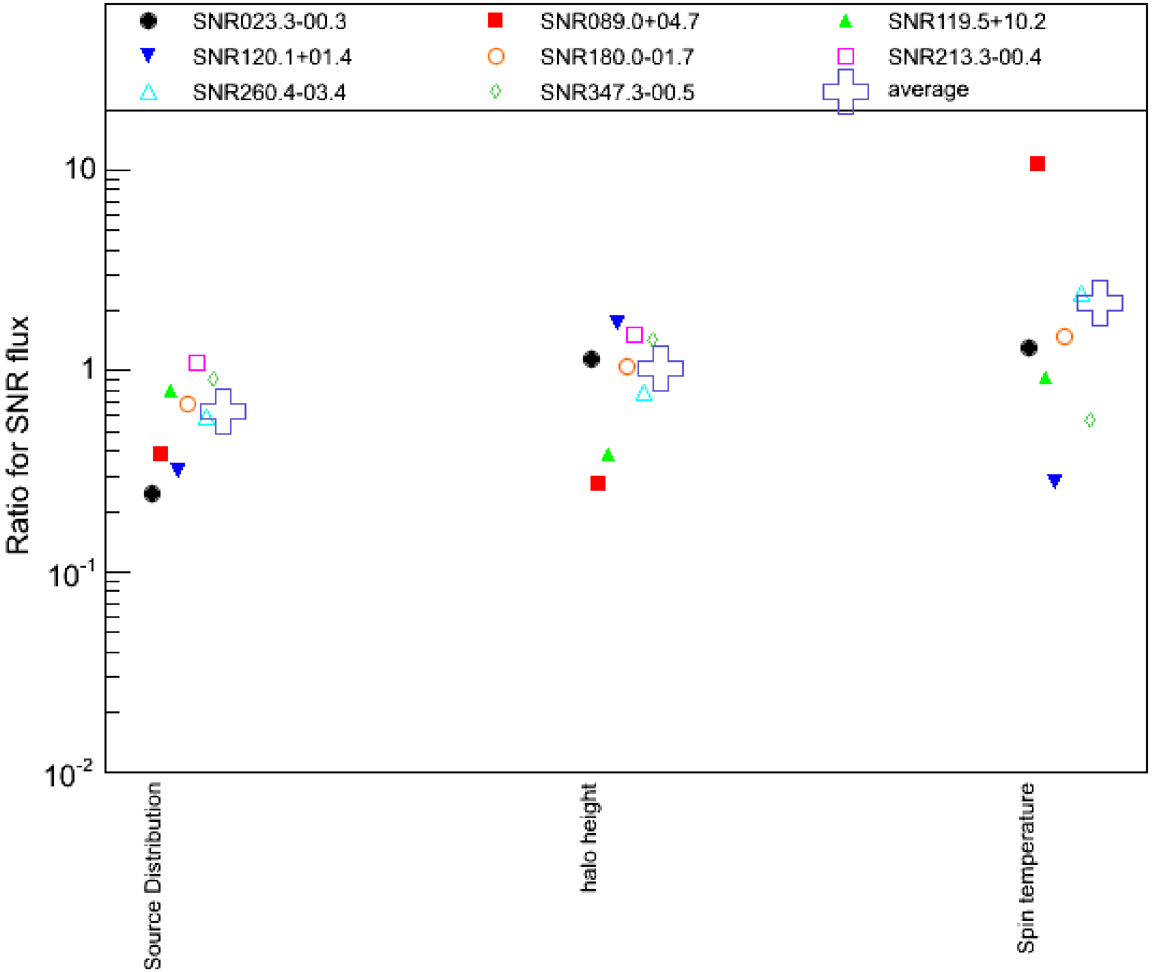




Alternative IEMs

- **8 Models is very computationally expensive… Does just one parameter dominate the systematics?**

No!



Roll your own diffuse model

- GALPROP is a widely used code for calculating the propagation of cosmic rays and their diffuse emissions.
- You can do something similar to what we have done for the SNR Catalog, using GALPROP:

  http://galprop.stanford.edu/webrun.php

- Provides IC, brems, pizero FITS files you can use as templates in a LAT analysis (but not fit to LAT data!)

  Caveat: I have not done this (well)

- Note: The alternative IEMs for the SNR Catalog are not GALPROP models! They are fit to LAT data.

Take Home Points

- There is not cook-book for quantifying systematic error. Art of thinking up experimental checks.
- <u>Do</u>
  - Consider systematics when interpreting your results
  - Estimate the source/background ratio
  - Ask others (paper authors) about their methods
- <u>Don't</u>
  - Assume your analysis is immune to systematics
  - Over-estimate your systematic (may miss exciting results)
  - Use IEMs for other datasets (P6) to assess systematics
- <u>At Minimum</u>, add Aeff uncertainty in quadrature with error to fit with scaled Galactic diffuse normalization.
- <u>Best Practice</u> is to employ bracketing IRFs and alternative IEMs constructed to probe diffuse systematics