Assessing the Impact of Likelihood-Based Inference Techniques on Galactic Center Excess Studies

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To appear in a paper soon

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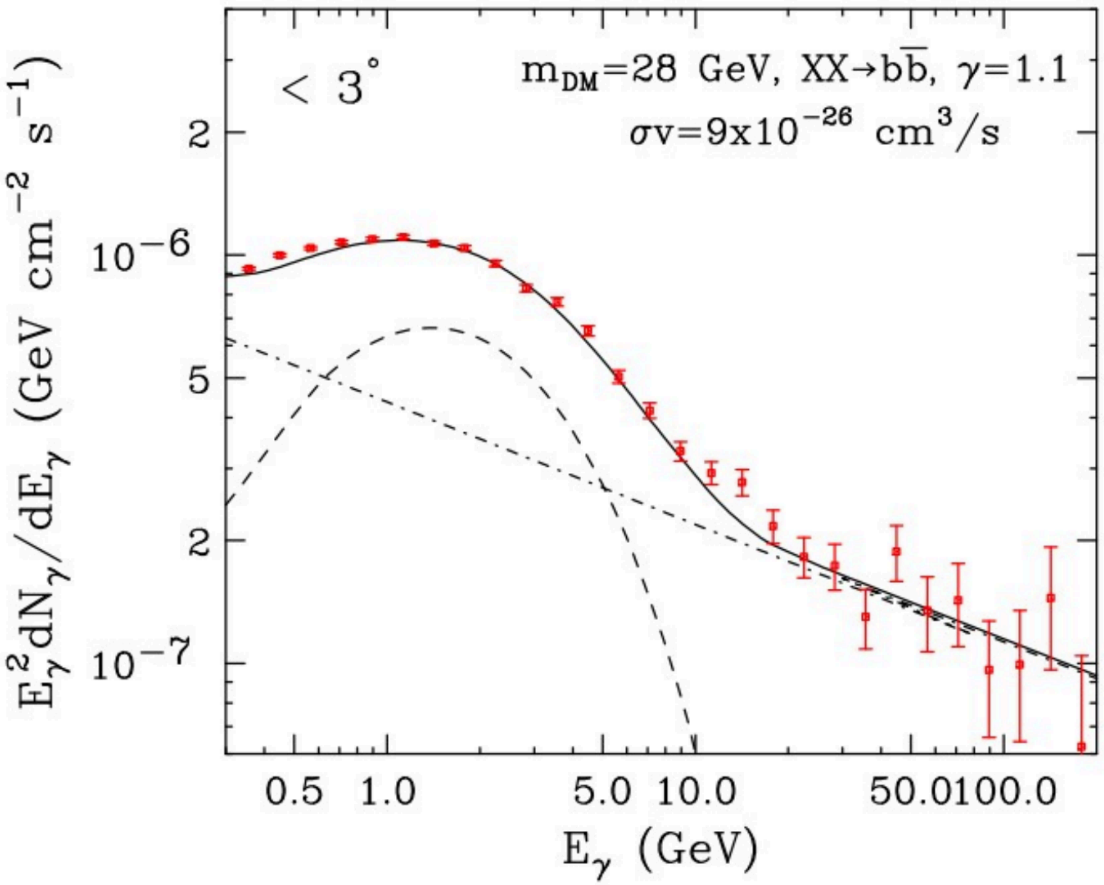
The Galactic Center Gamma-ray Excess

Galactic Center Excess (GCE)

- A significant excess of gamma-rays has been detected by the Fermi-LAT space telescope in the direction of the Galactic center



Goodenough+Hooper ‘09

Origin?

- ➢ Annihilating **Dark Matter**?
- ➢ A large population of centrally located Millisecond **Pulsars**?

GCE: Dark Matter or Point Sources?

- **2009** : Inner Galaxy Excess Found
- **2014** : “A Compelling Case for Annihilating Dark Matter”
- **2015** : Pulsars (point sources) As the Excess
- **2019** : “Dark Matter Strikes Back at the Galactic Center”

  -> **Bias search** using simulated data

Daylan et el, arXiv:1402.6703

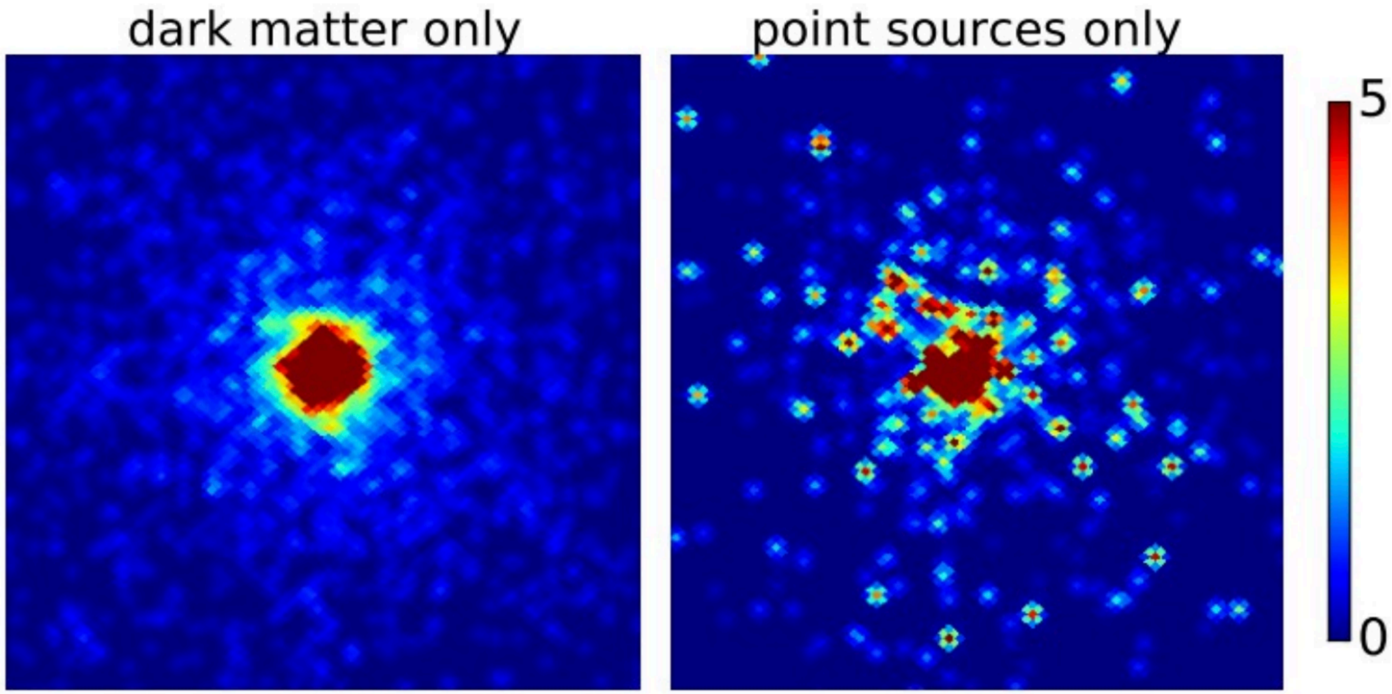
Leane and Slatyer, arXiv:1904.08430

How we distinguish DM vs PS?

Dark Matter

Smooth continuous emission

❖ **Poissonian**



Lee, Lisanti and Safdi ‘15

Unresolved Point Sources

dim and clumpy individual sources

❖ **Non-Poissonian**

Use **Statistics! => Template Fitting**

Tools :

Non-Poissonian Template Fitting (NPTF)

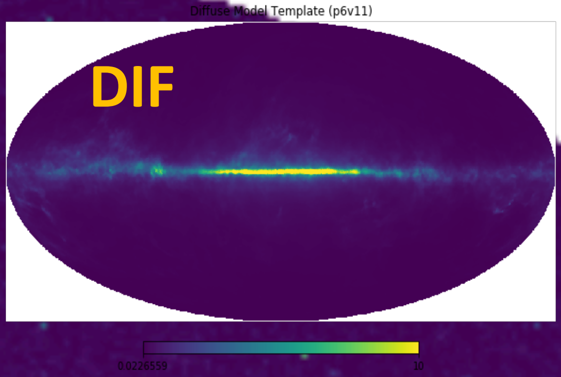
Compound Poisson Generator (CPG)

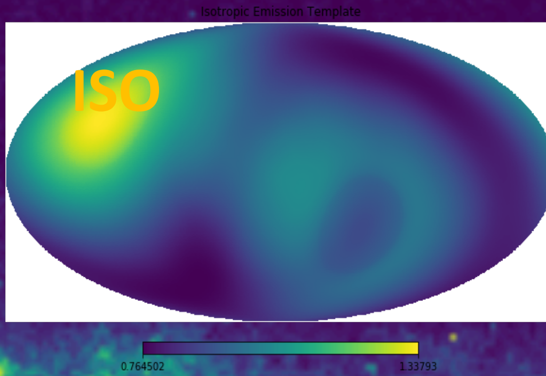
Templates for Statistics

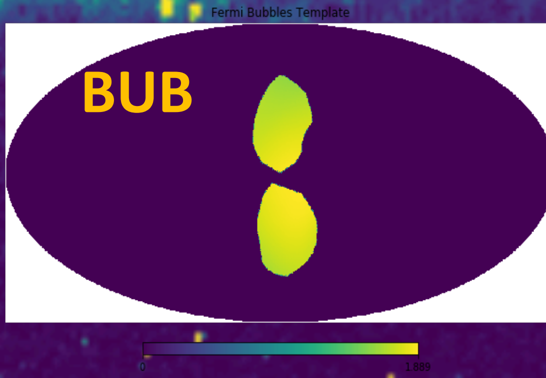
Sources for the observed gamma-rays are:

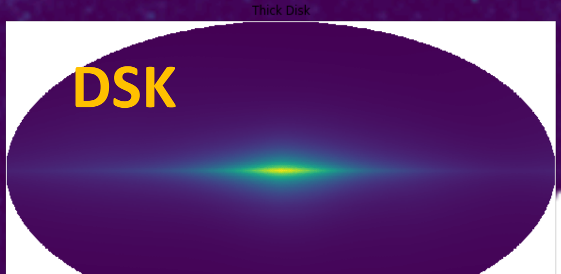
- **Galactic Diffuse Emission (models : A, F, O, p6v11)**
  - Decay of pions
  - Bremsstrahlung radiation
  - Inverse Compton scattering
- **Extragalactic Isotropic** (fermi exposure corrected)
- **Fermi Bubble**
- **Disk**

  point sources correlated with the disk of the Milky Way





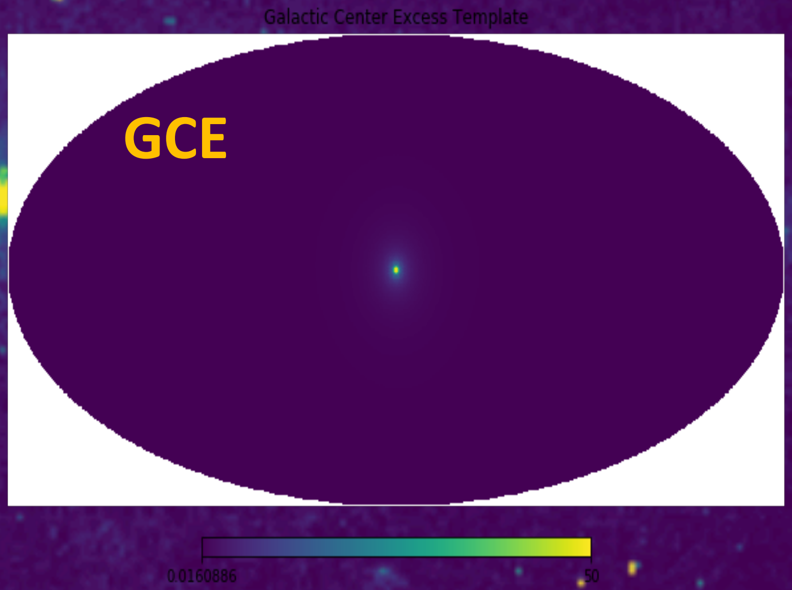


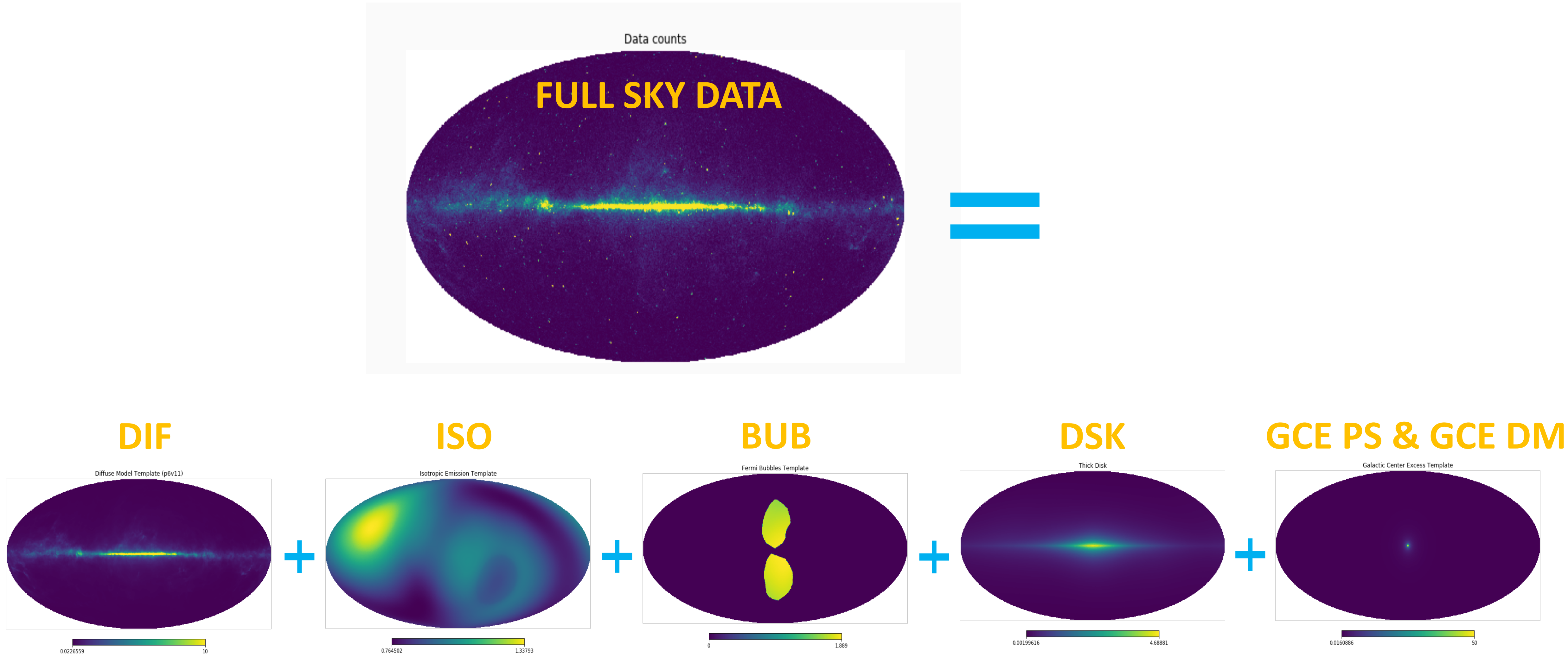


Templates for Statistics

Sources for the observed gamma-rays are:

- **GCE DM (Dark Matter) :** Poissonian
- **GCE PS (Point Source) :** Non-Poissonian





- Using these Poissonian/Non-Poissonian templates, **scan Fermi data to find best fit values!**

Strategies

I. Using NPTF with new prior, analyze Fermi data

II. Using CPG, analyze Fermi data

A Follow-up Study of :

G. H. Collin, N. L. Rodd, T. Erjavec, and K. Perez. *A Compound Poisson Generator Approach to Point-source Inference in Astrophysics*. The Astrophysical Journal Supplement Series, 260(2):29, 2022. 10.3847/1538-4365/ac5cb7.

NPTF with New Prior

Collin, Rodd, Erjavec and Perez '21

If we have a population of dim point sources, there's a limit in which the sources are so dim that this distribution becomes indistinguishable from Poisson emission

$$\lambda = N\,\mu \;\; when\; N \gg 1\; and\; \mu \ll 1$$

In this limit,

$\Rightarrow$ **Standard Coordinate System (Old prior)**

$$\frac{\mathrm{d}N}{\mathrm{d}F} = A \begin{cases} \left(\frac{F}{F_{b(2)}}\right)^{-n_2} & F \leq F_{b(2)} \\ \left(\frac{F}{F_{b(2)}}\right)^{-n_1} & F_{b(2)} < F \end{cases},$$

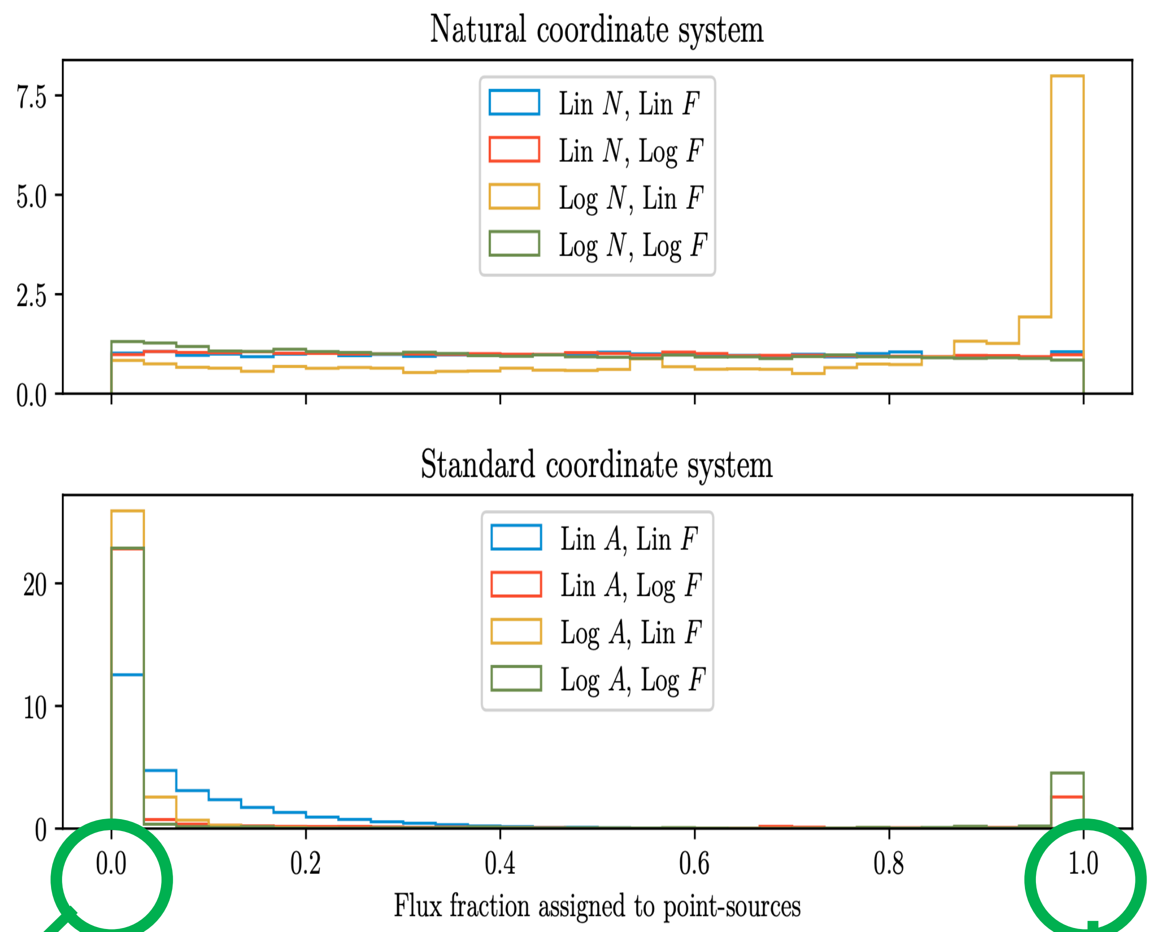
$\Rightarrow$ **Natural Coordinate System (New prior)**

Total Number or Sources

$$N = A\,F_b \left(\frac{1}{n_1 - 1} - \frac{1}{1 - n_2}\right)$$

Total Flux

$$F_T = A\,{F_b}^2 \left(\frac{1}{n_1 - 2} - \frac{1}{2 - n_2}\right)$$



Poissonian emission

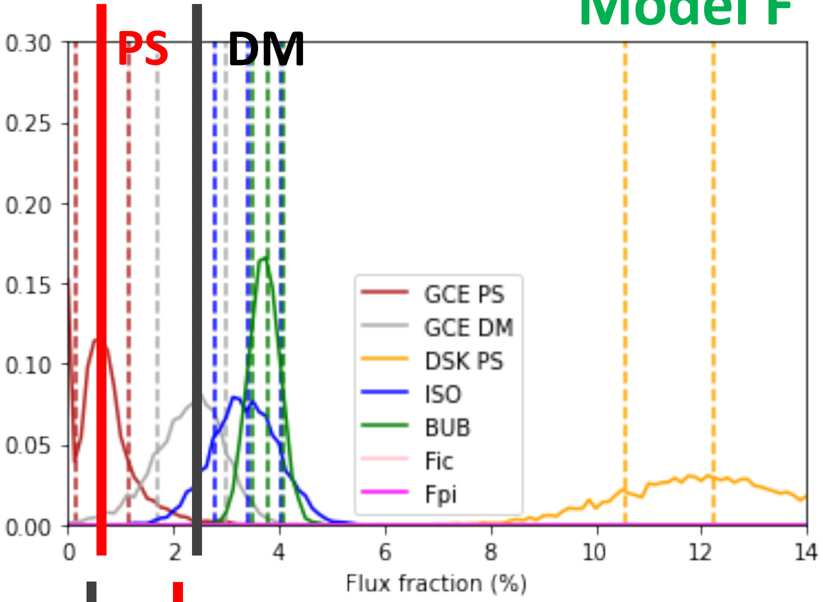
Point-Sources (Non-Poissonian)

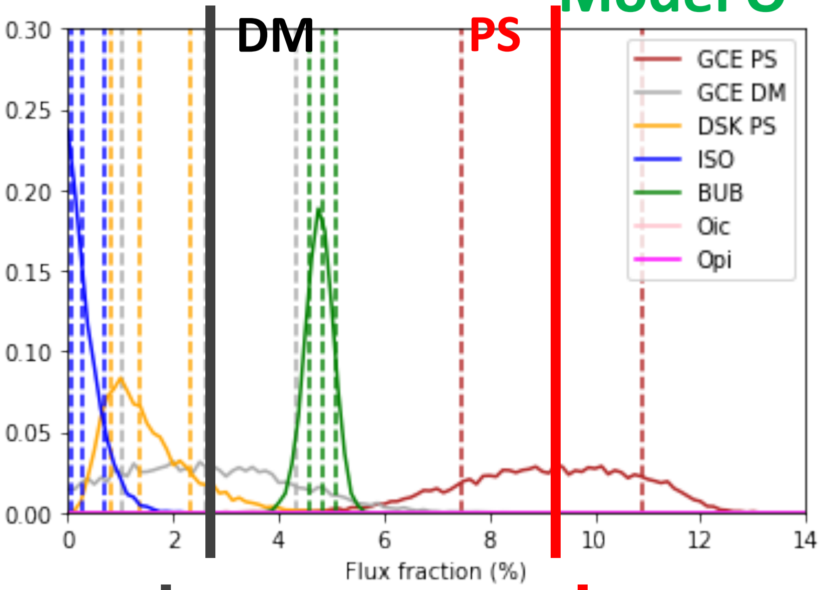
NPTF with New Prior

Model F

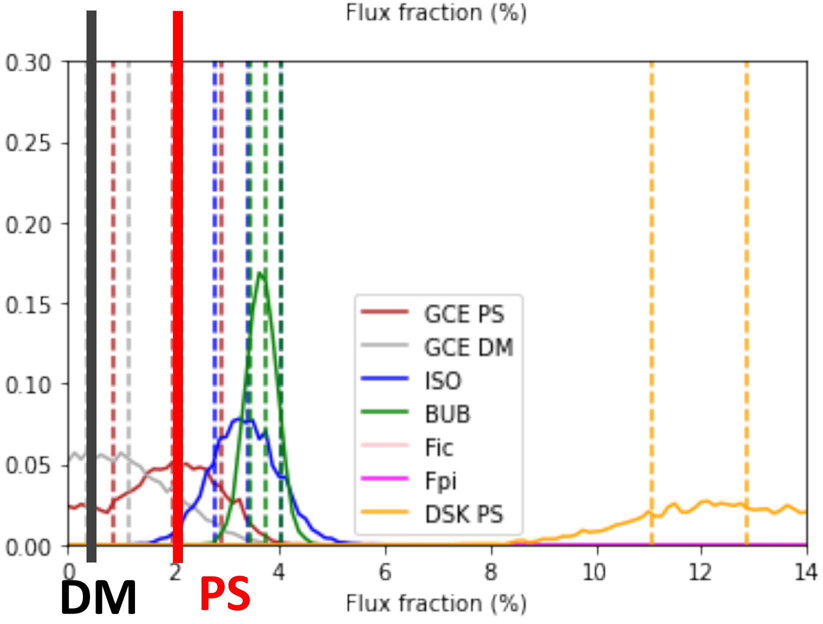
Model O

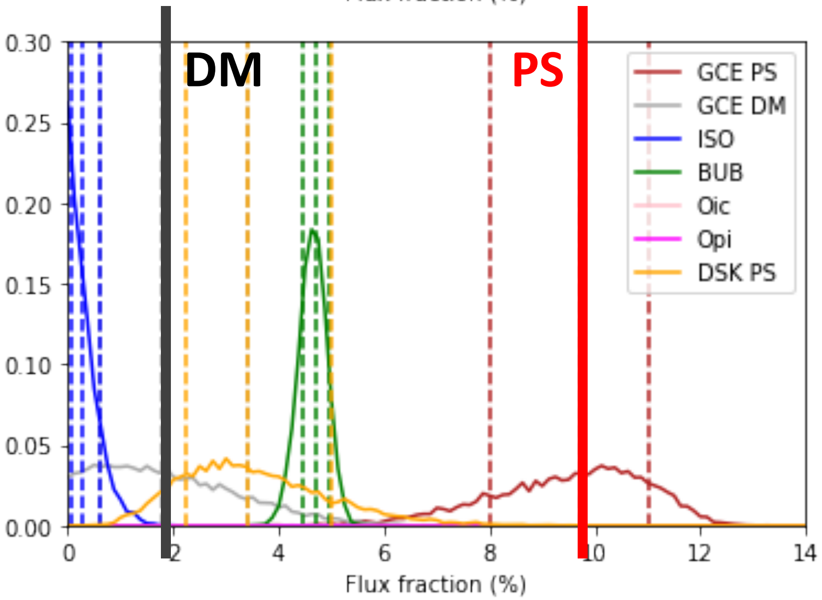
[A,n1,n2,Sb]
Old priors





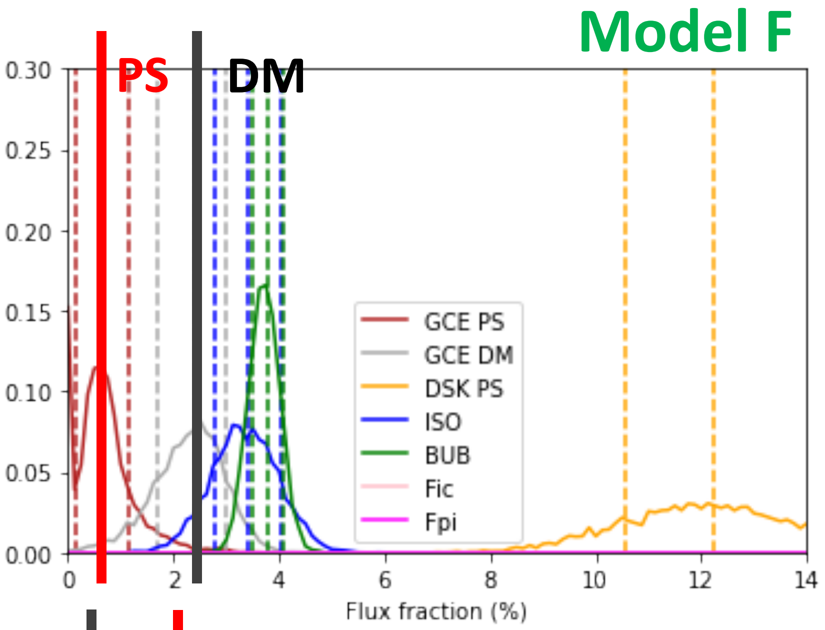
[N,n1,n2,ST]
New Priors



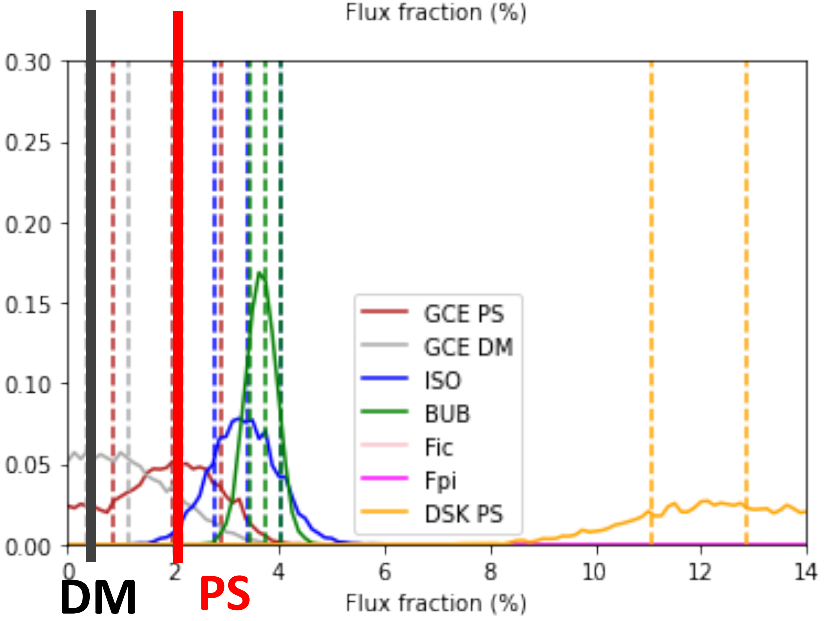


NPTF with New Prior

[A,n1,n2,Sb]
Old priors



[N,n1,n2,ST]
New Priors



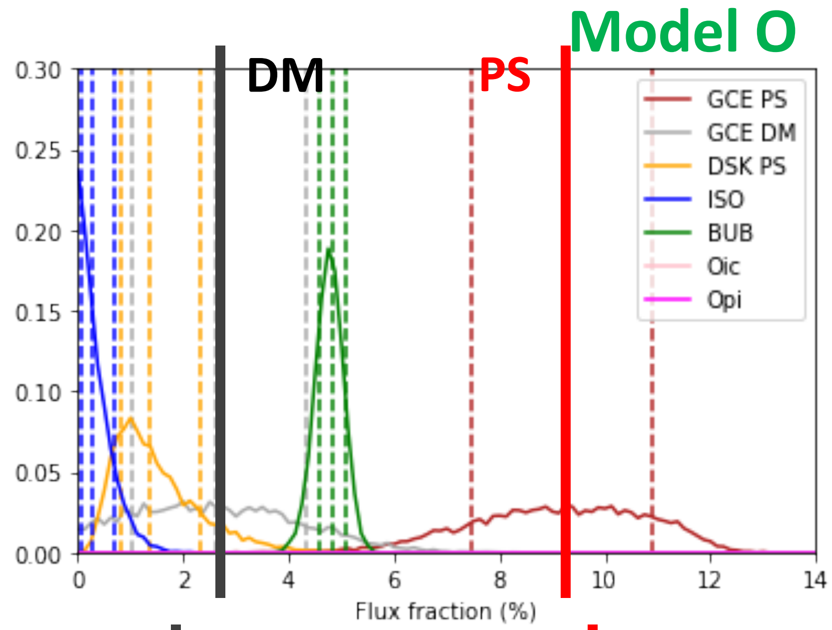
- Only for model F, the prior change has an impact on **GCE**.
- The preference between **PS** and **DM** is flipped and now **GCE** prefers **PS**.

NPTF with New Prior

- Model O : the most current model.

- No much changes in both of GCE, Still prefers PS.

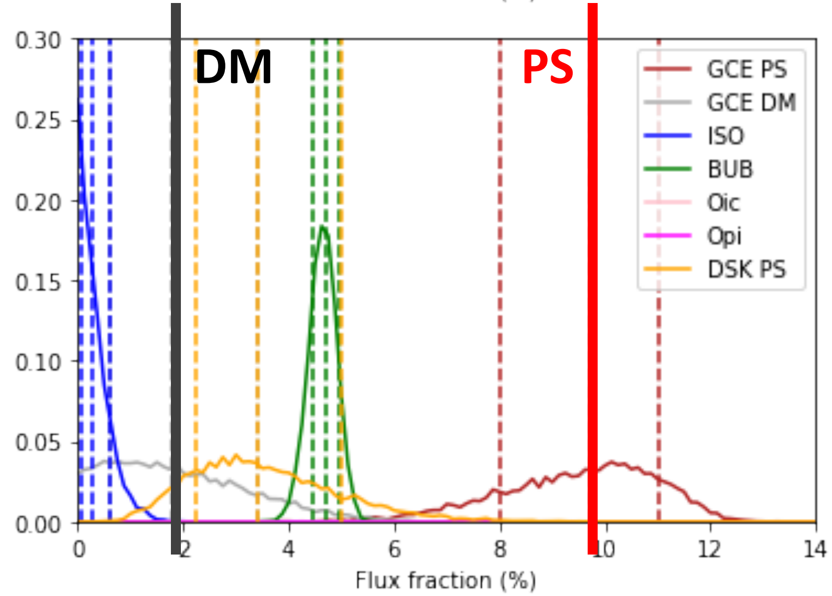
[A,n1,n2,Sb]
Old priors



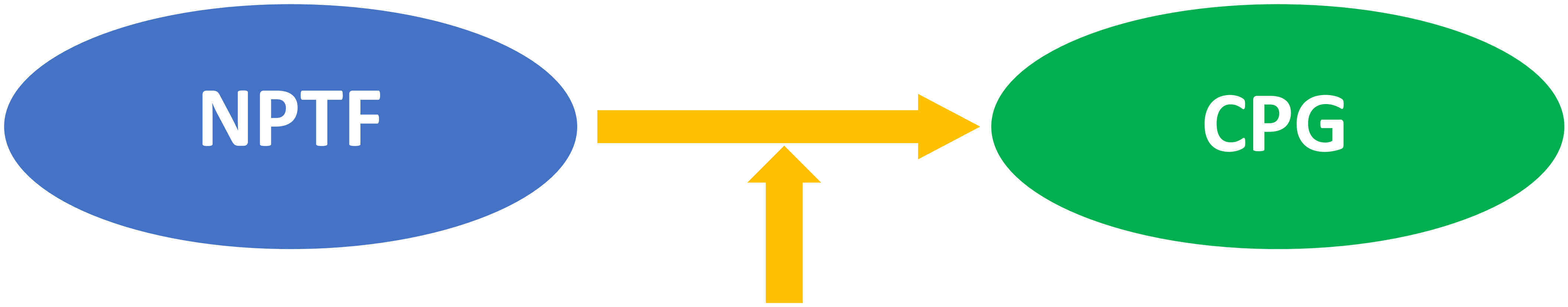
➢ In general, changing the prior has a **minimal impact on the GCE** except for the model F

➢ Even we removed the potential biases**, GCE is still better explained by PS than by DM**

[N,n1,n2,ST]
New Priors



CPG vs NPTF



Likelihood functions

- Poissonian
- Non-Poissonian :
  1. Probability to find sources in a pixel
  2. Probability those sources give a certain number of photons

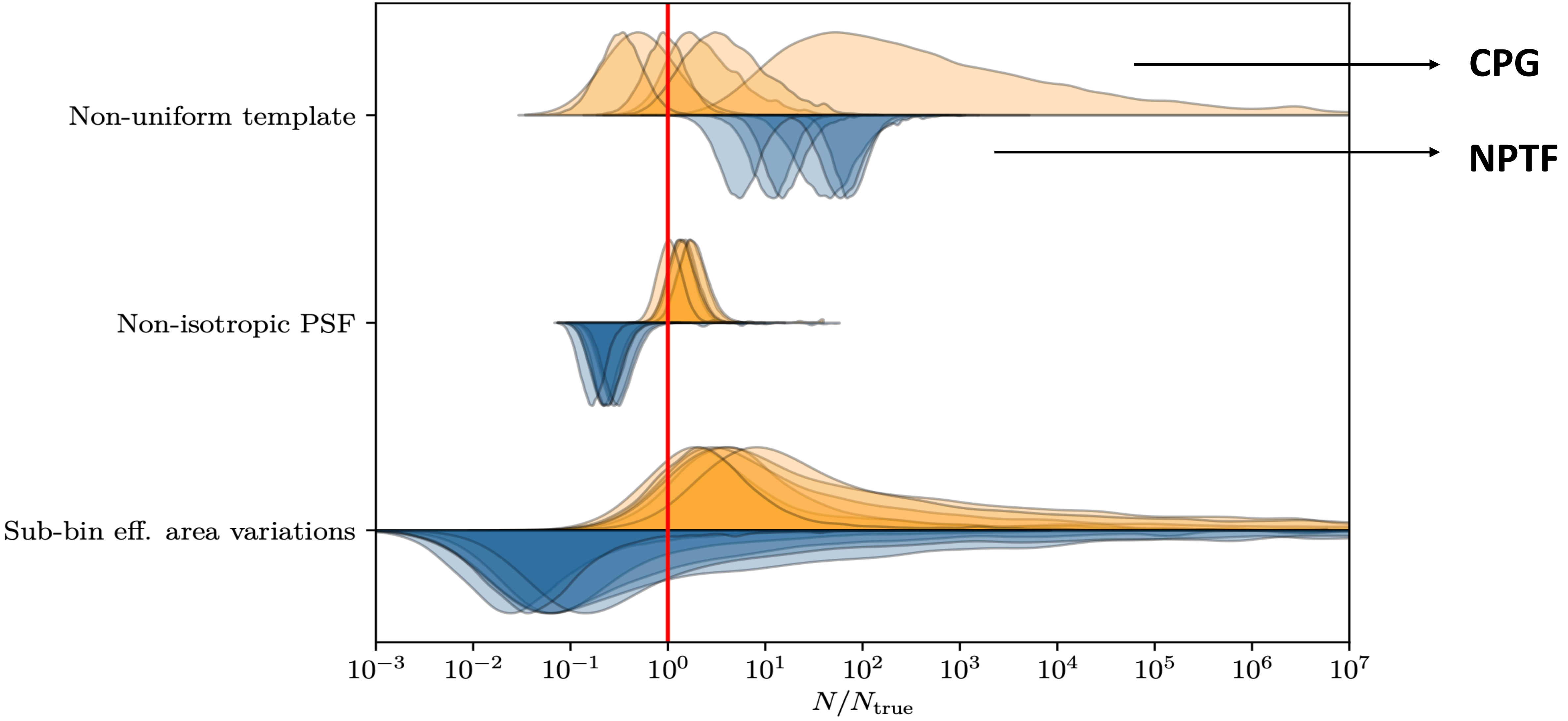
Instrumental effects

(Effective area, PSF, Detection prob. etc.)

$$\mu_B(\varepsilon) = \int d\boldsymbol{x} T(\boldsymbol{x}) \delta \left(\varepsilon - \kappa(\boldsymbol{x}) \int_{\Omega_B} \mathrm{d}\boldsymbol{y} \eta(\boldsymbol{y}) \phi(\boldsymbol{y}|\boldsymbol{x}) \right) .$$

$$G_{k_B}(z) = \exp\left[N \left(\int \mathrm{d}F \int \mathrm{d}\varepsilon e^{\varepsilon F(z-1)} \mu_B(\varepsilon) p(F) - 1 \right) \right]$$

CPG vs NPTF

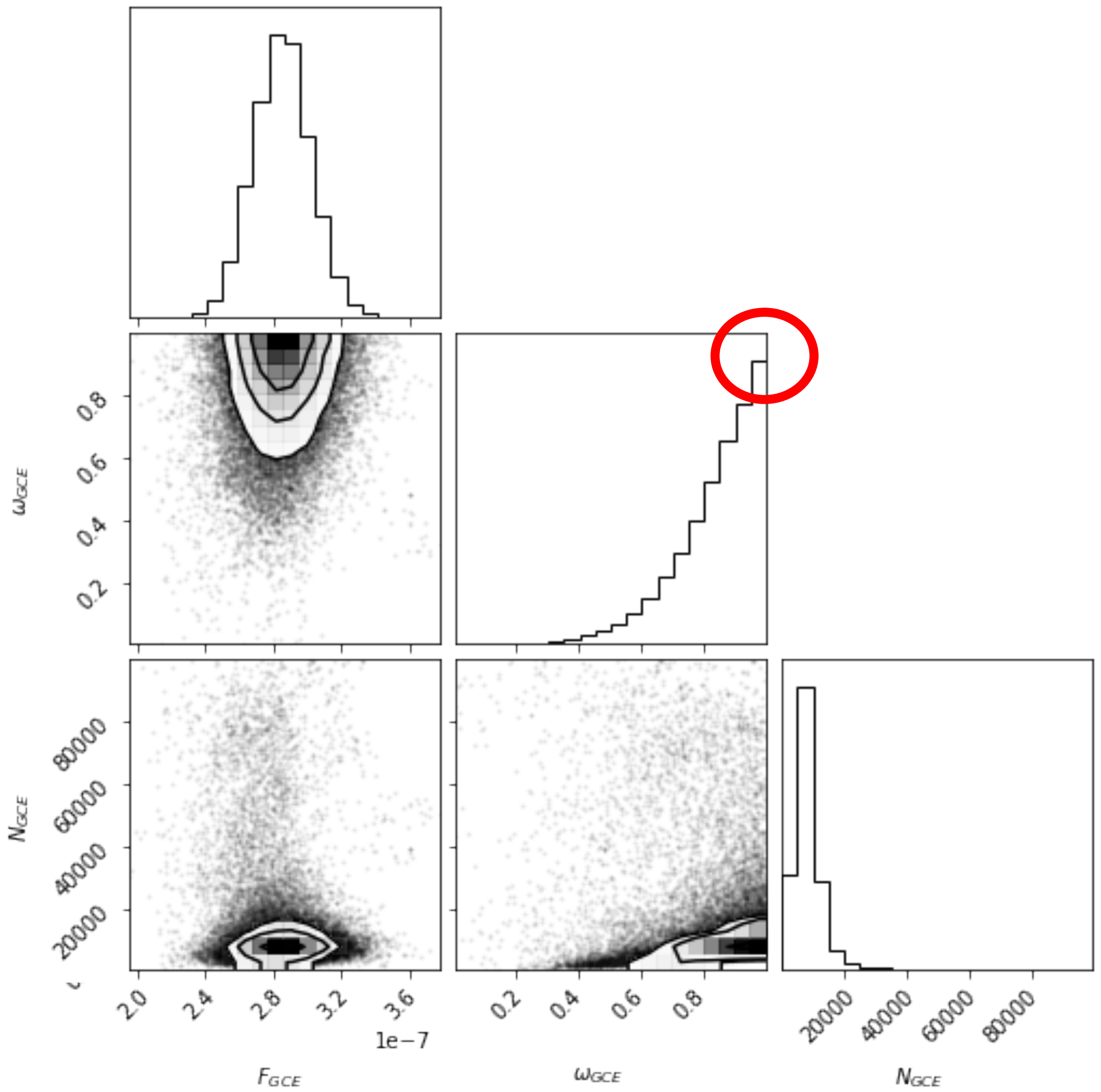


Collin et al, 1908.10874

CPG vs NPTF

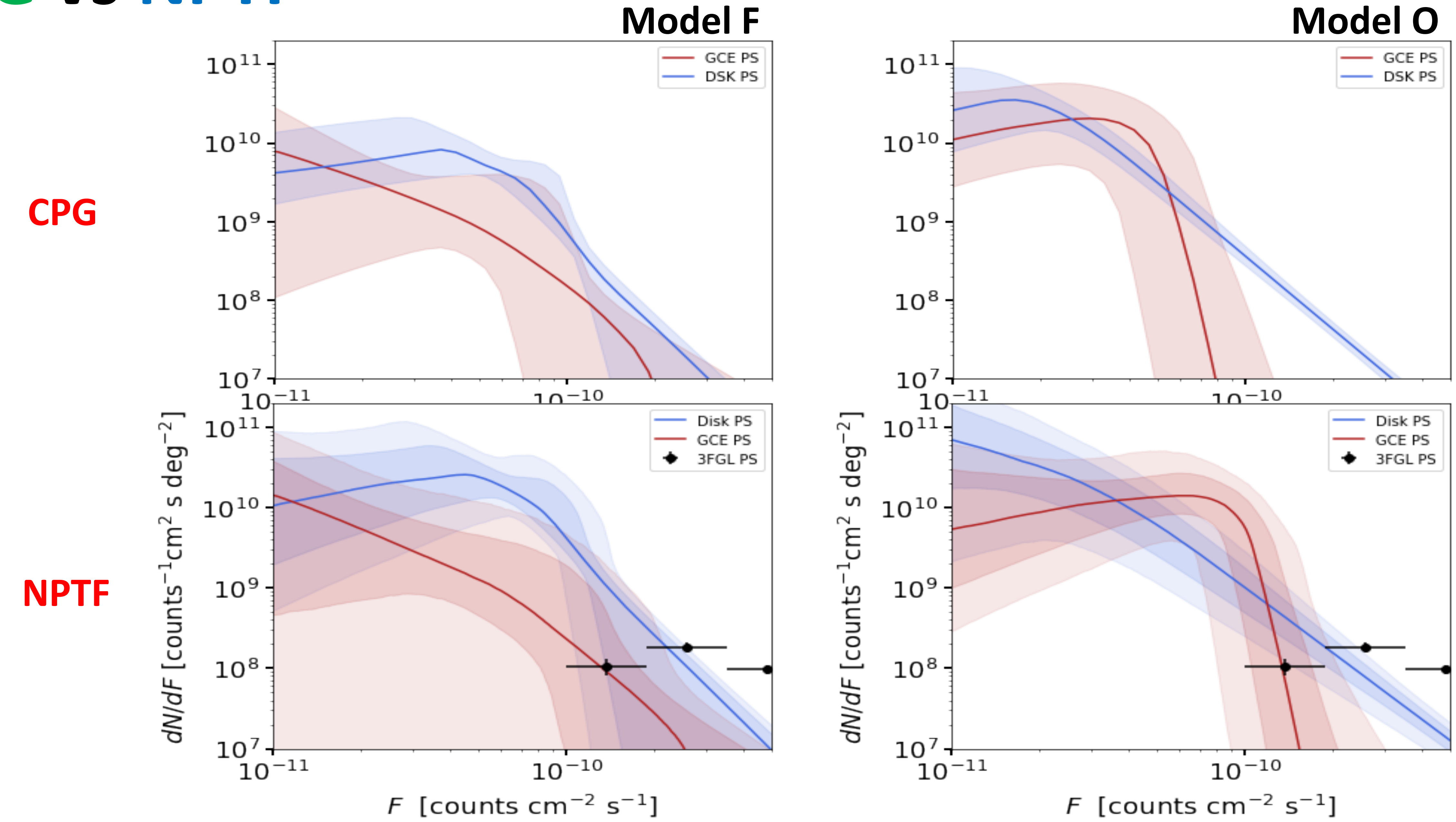
$$\omega_{GCE} = \frac{F_{GCE\ PS}}{(F_{GCE\ PS} + F_{GCE\ DM})} \sim 1$$

Fraction of flux assigned to Point Sources over DM emission



⇒ **GCE still prefers PS!**

CPG vs NPTF

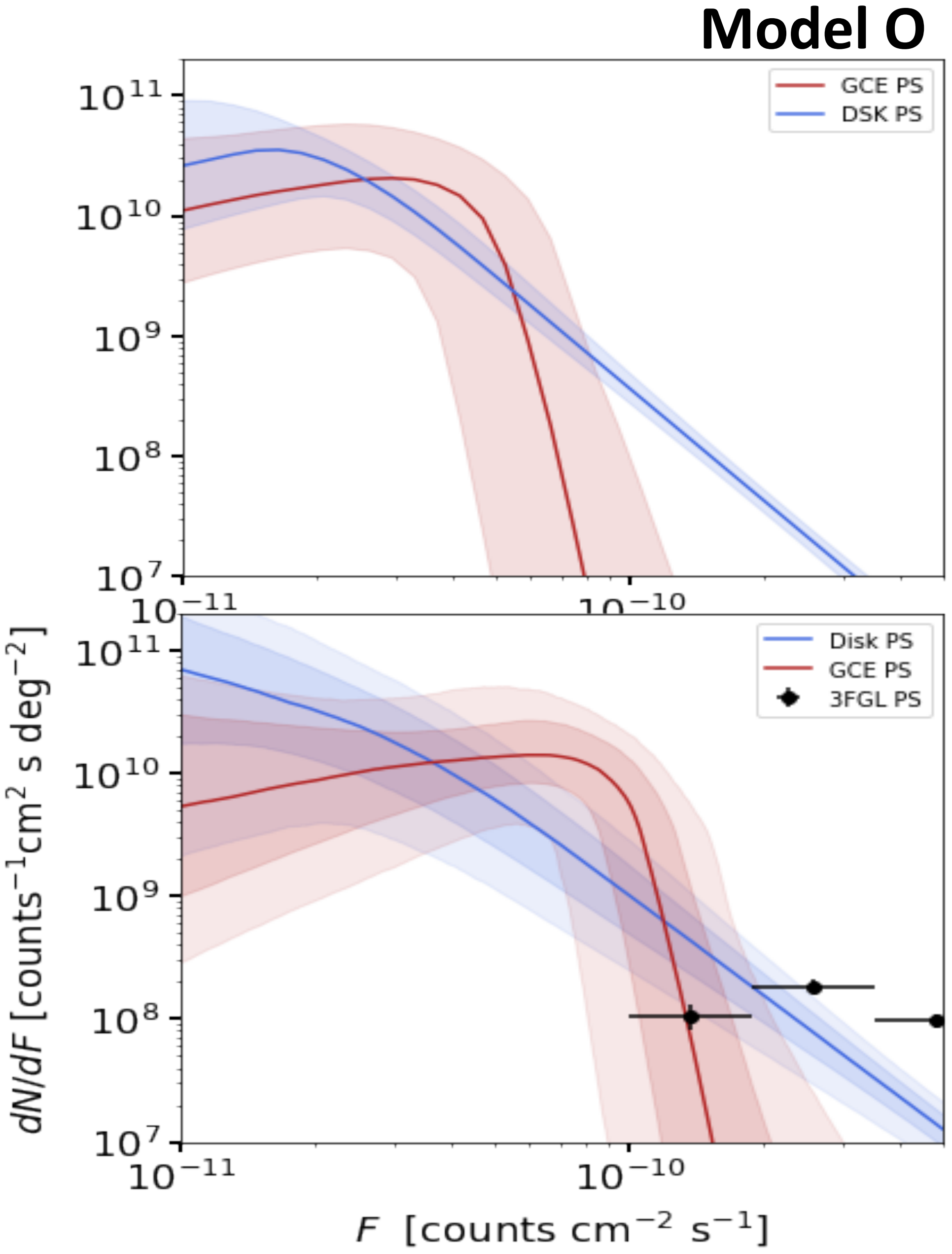

Model F
Model O
CPG
NPTF
GCE PS
DSK PS
Disk PS
GCE PS
3FGL PS
dN/dF [counts^{-1}cm^{2} s deg^{-2}]
F [counts cm^{-2} s^{-1}]
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{-11}
10^{-10}

CPG vs NPTF

- In all models, the **GCE** shows no significant difference between CPG and NPTF

- but **it's always slightly dimmer and more numerous in CPG**.
  - in line with other recent results finding reducing systematics in GCE studies leads to a dimmer dN/dF

- **The choice of the diffuse model** is much more important than the differences we're uncovering here, but it's very reassuring that the **CPG is converged near the NPTF**.



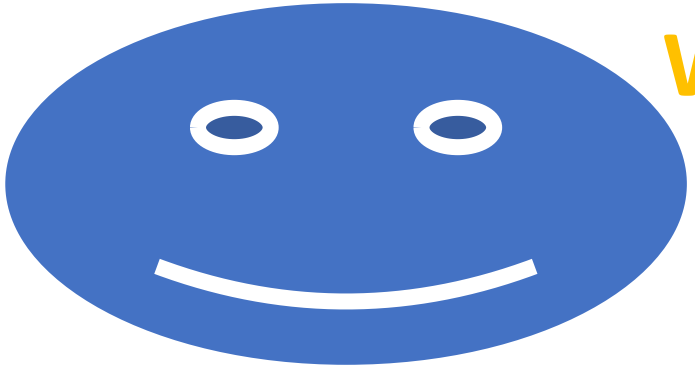
Conclusion

Origin of Galactic Center Excess (GCE)?

$\Rightarrow$ reassure that It’s originated from a large population of dim **point sources**!

LOSE

DARK MATTER



WIN!

PULSARS

Thank you!

Back Up

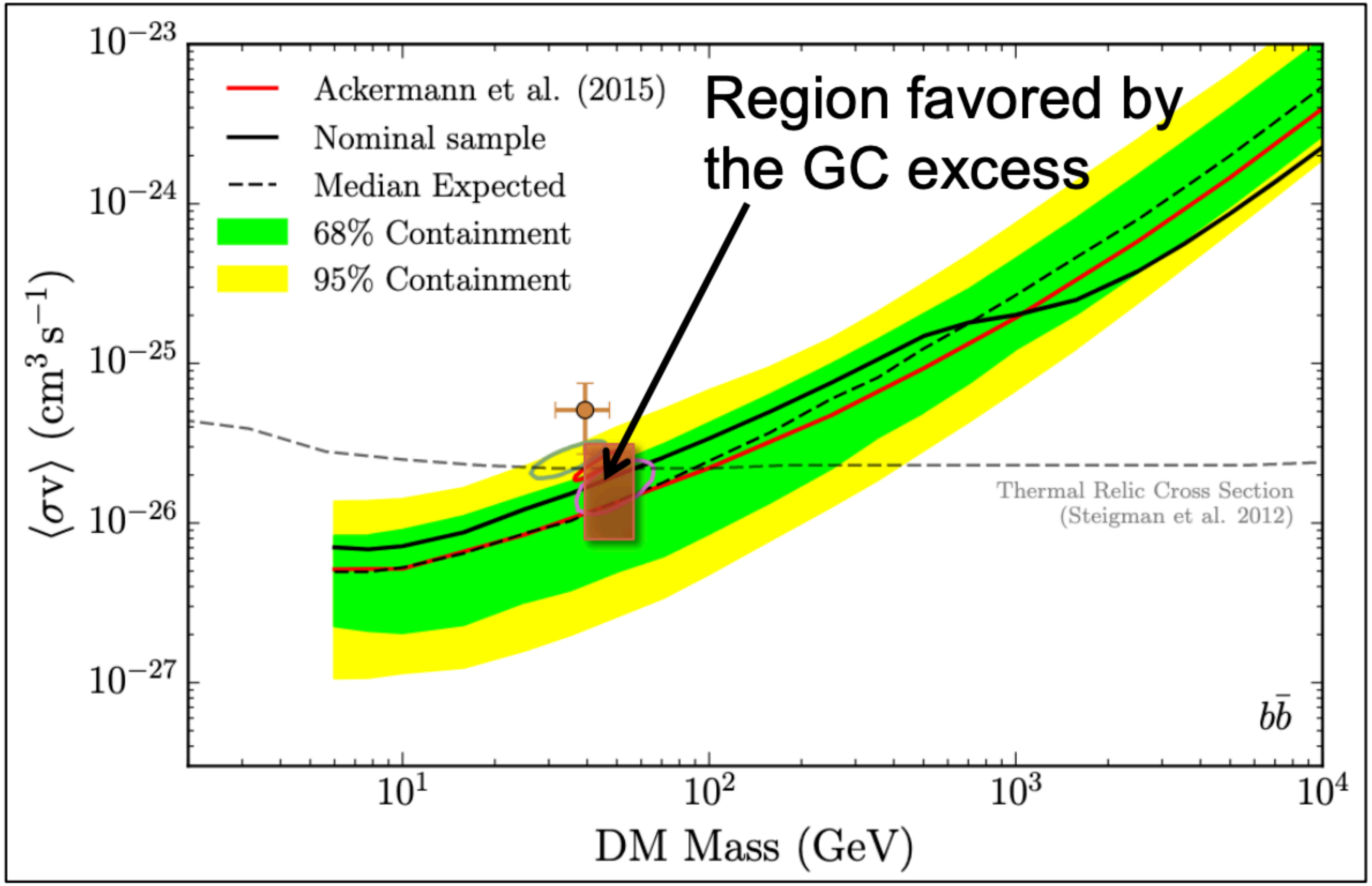
The G

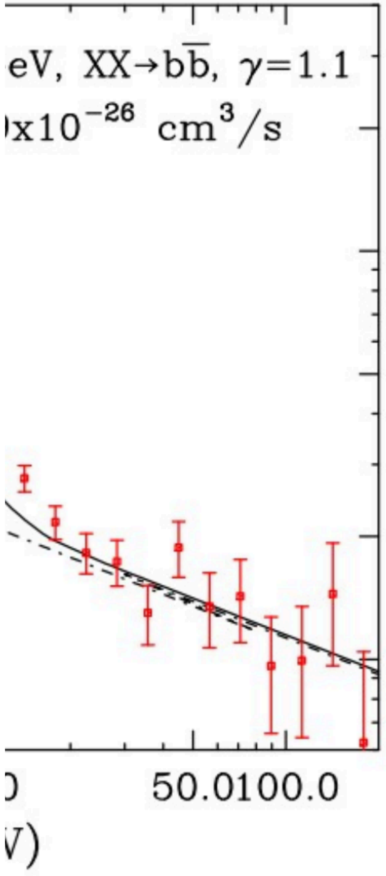
Galactic

- A signifi been de telescop Galactic

Origin?

- ➢ Annihil
- ➢ A large Millisec





Goodenough+Hooper '09

Fermi Collaboration, arXiv:1611.03184

Reparameterize priors in a new coordinate system and see how much impact the prior change can have

- Using **NPTF**, analyze Fermi data with some diffuse models : **p6v11, A, F, O**

- Change the priors : $[\, A, S_b, n_1, n_2 \,]$ -> $\boldsymbol{[\, N, S_T, n_1, n_2 \,]}$

  adopt **uniform priors** on the number and flux of sources

  goal is to have a fairer comparison between PS and smooth emission (both having priors that are ~flat in flux)

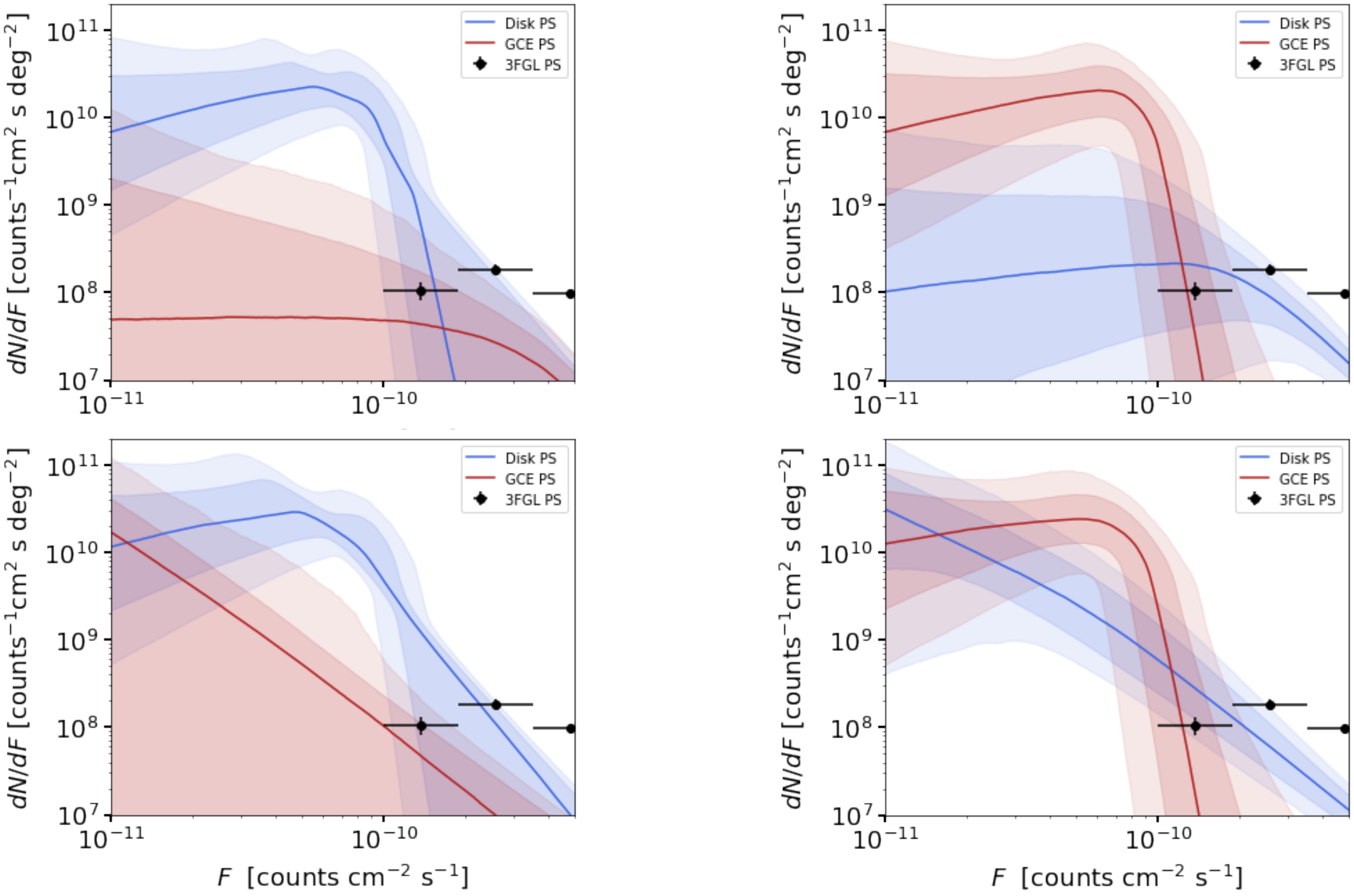
- In general, changing the prior has a noticeable impact on the **disk**, but minimal impact on the **GCE** except for model F

# dN/dF plots
gamma=1.0

Model F **Model O**

[A,n1,n2,Sb]
Old priors

[N,n1,n2,ST]
New Priors



Comparison of results between CPG and NPTF

- Run **CPG** with the **detector correction functions** $\boldsymbol{\mu(\varepsilon)}$ for each PS template, nfw (gamma=1.2) and dsk

- Analyze Fermi data with some diffuse models : p6v11, A, F, O

- To compare with the results from the NPTF, use the **same priors and masks**

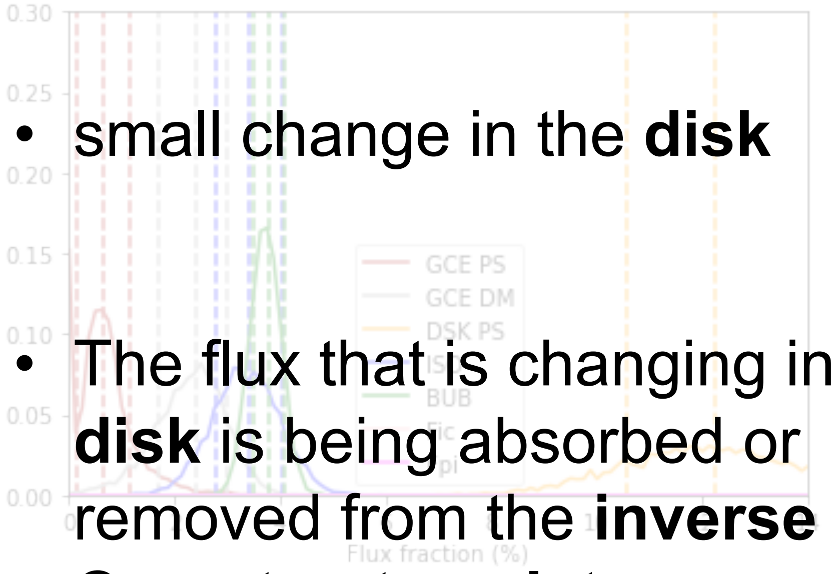
Flux Fraction plots gamma=1.0

Model F

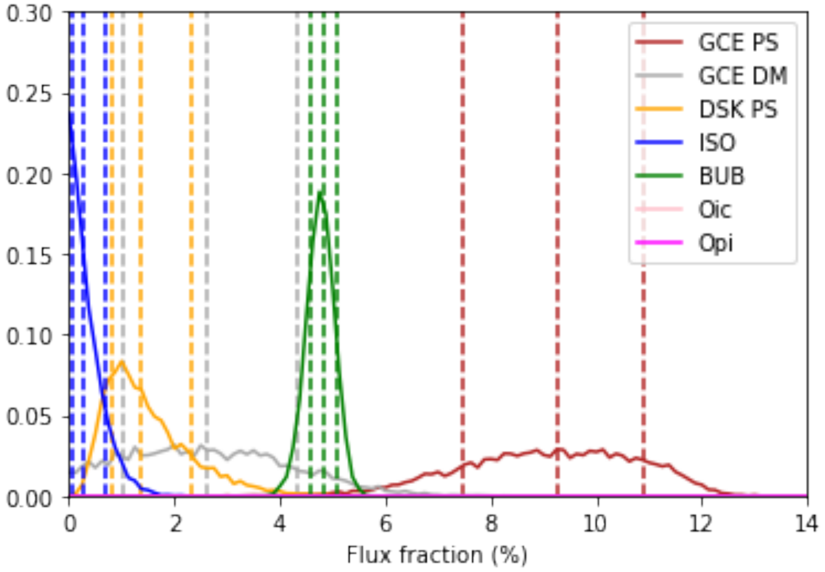
Model O

[A,n1,n2,Sb]

Old priors

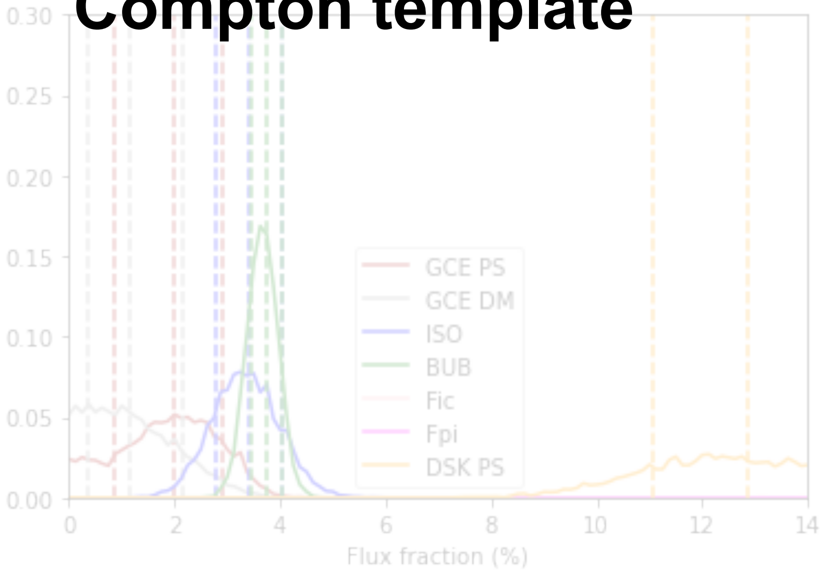


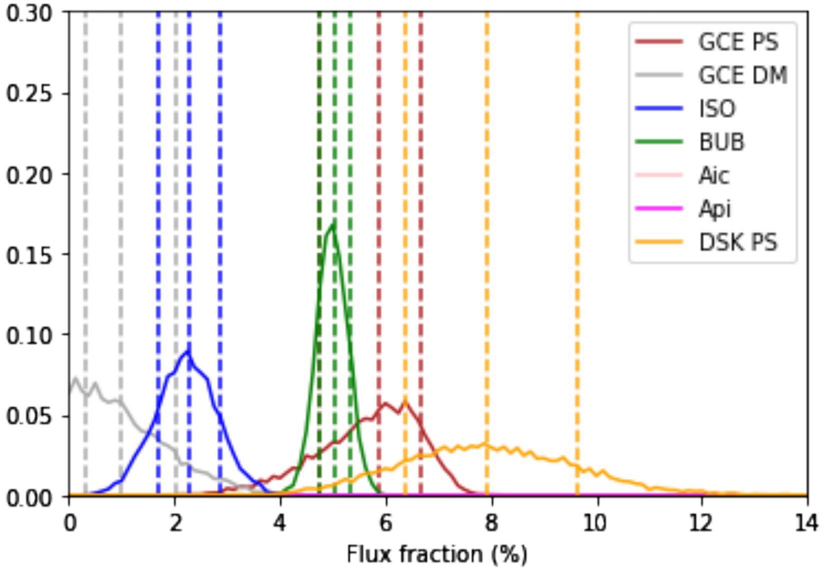
- small change in the **disk**
- The flux that is changing in the **disk** is being absorbed or removed from the **inverse Compton template**



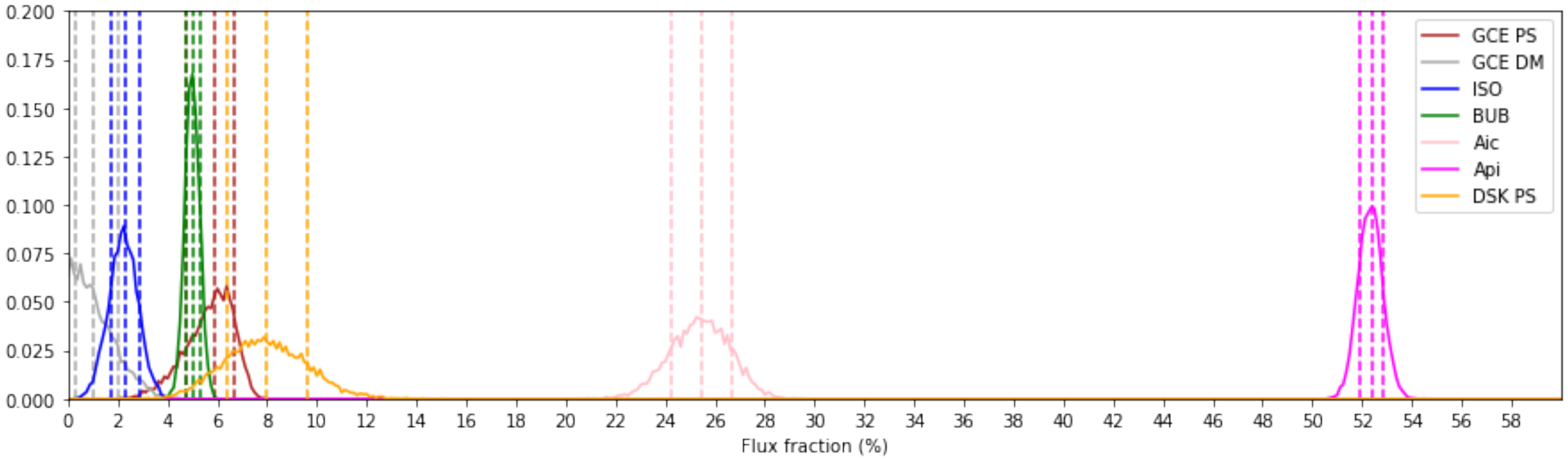
[N,n1,n2,ST]

New Priors





O_30 Template (roi=30)



O_25 Template