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The GCE in a new light: Disentangling the γ-ray sky with Bayesian Deep Learning

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Joint work with
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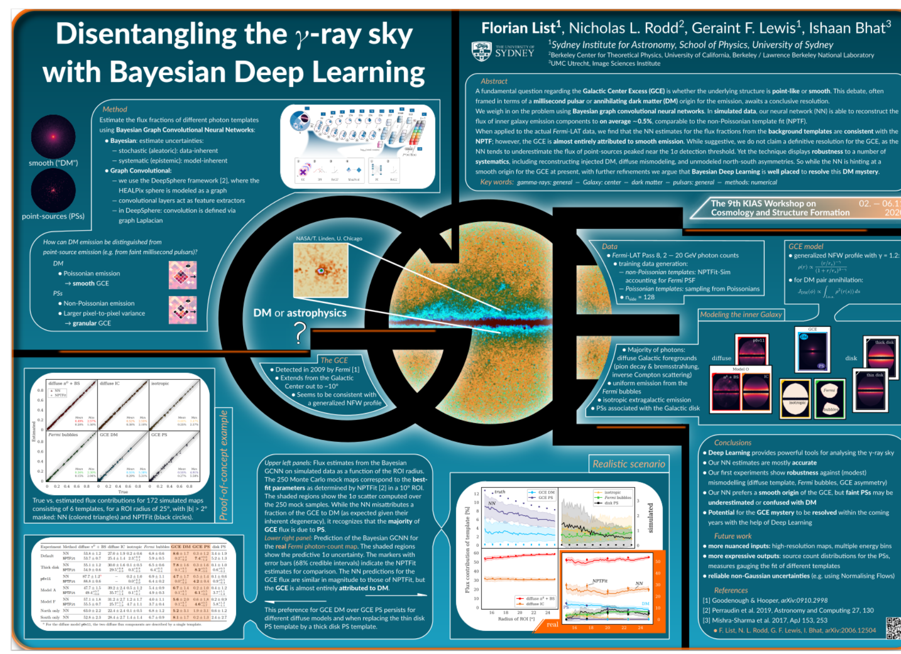

Based on arXiv:2006.12504
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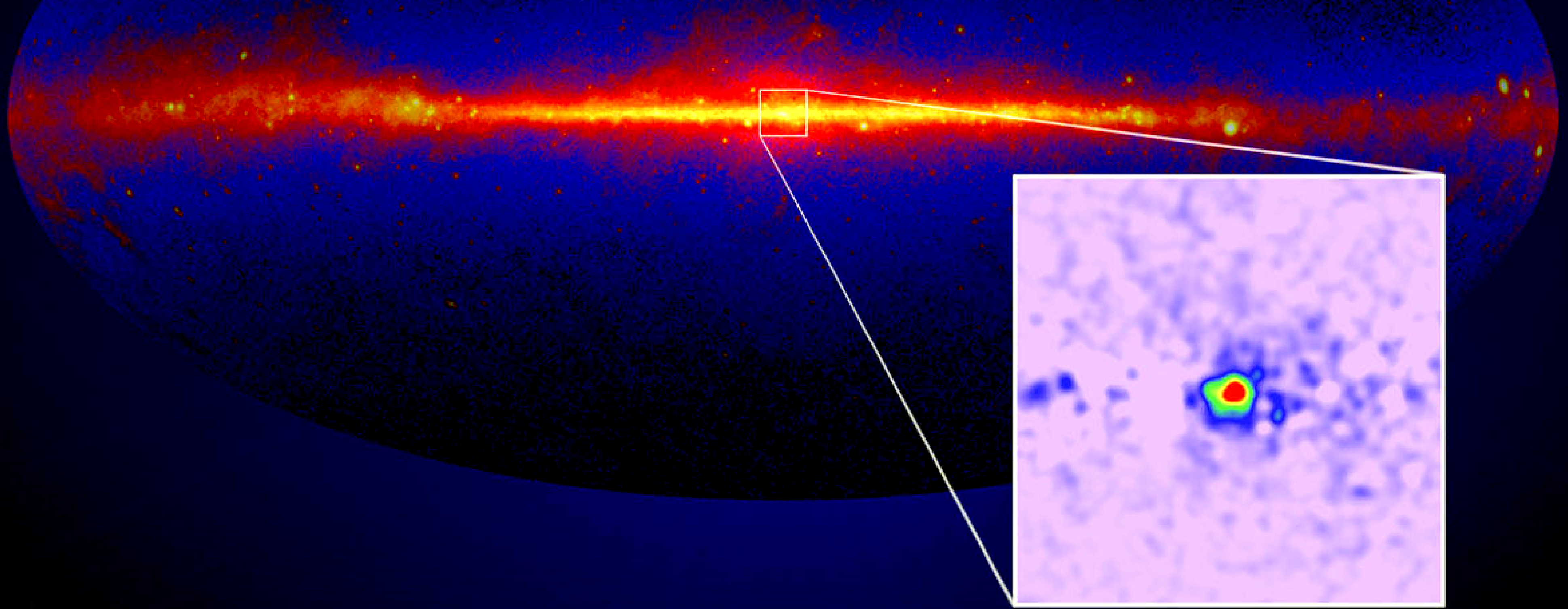
The γ-ray GCE

- γ-ray excess emission peaks at energies ~ 1 – 3 GeV
- Detected in 2009 by the Fermi Telescope Goodenough & Hooper 2009
- Extends from the Galactic Centre out to ~ 10°
- Seems to be consistent with a generalised NFW profile

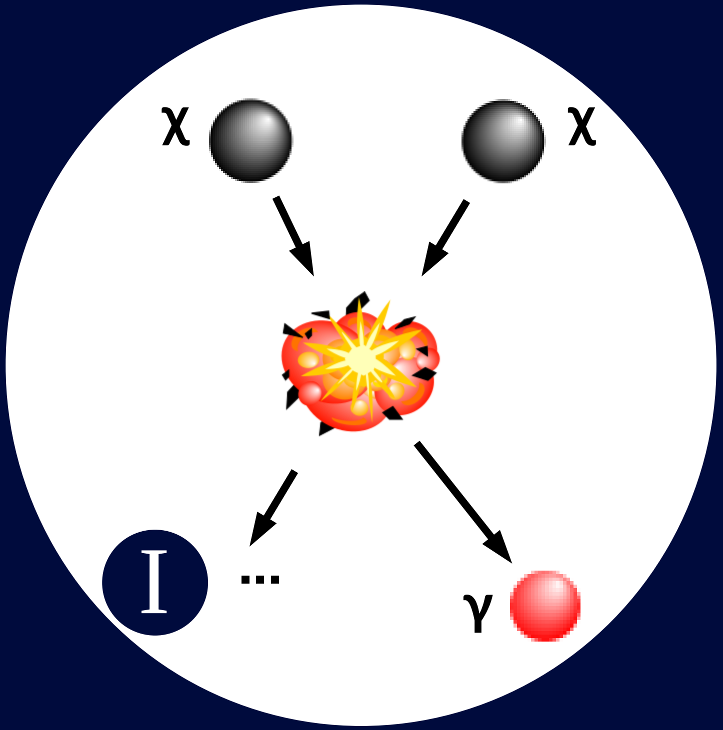


Credit: NASA/T. Linden, U. Chicago

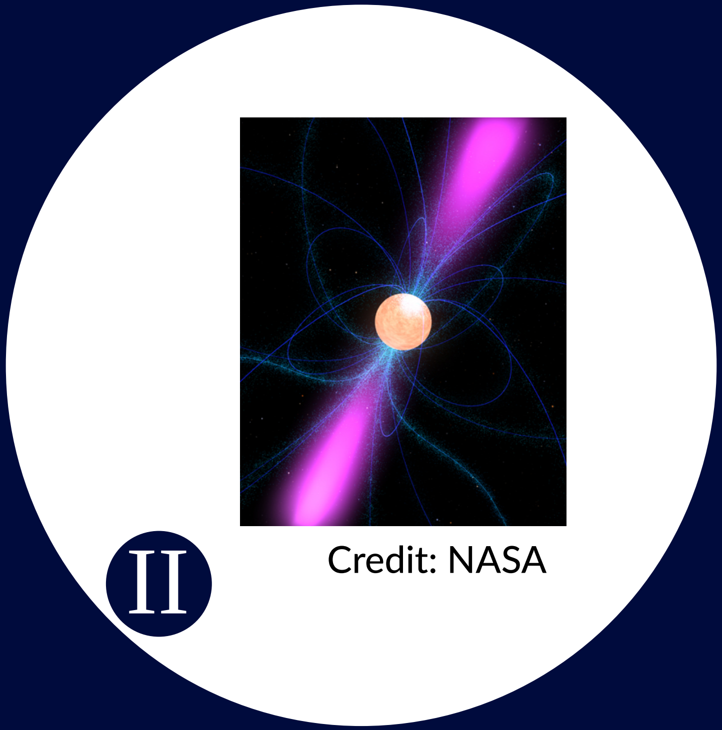
The γ-ray GCE

What is the explanation?

annihilating DM?

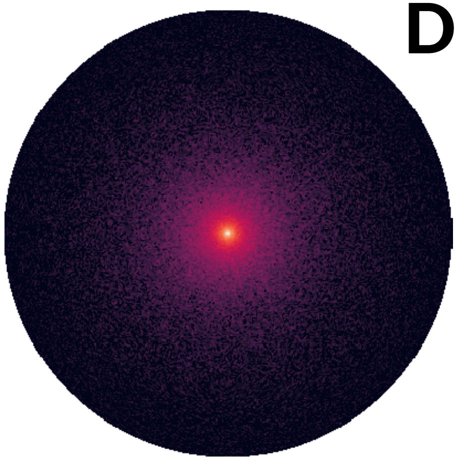


point sources
(millisecond pulsars, cosmic rays, ...)?



The γ-ray GCE

How could annihilating DM and PSs be distinguished?



DM

smooth GCE,
Poissonian emission

PSs

granular GCE,
larger pixel-to-pixel variance,
non-Poissonian statistics

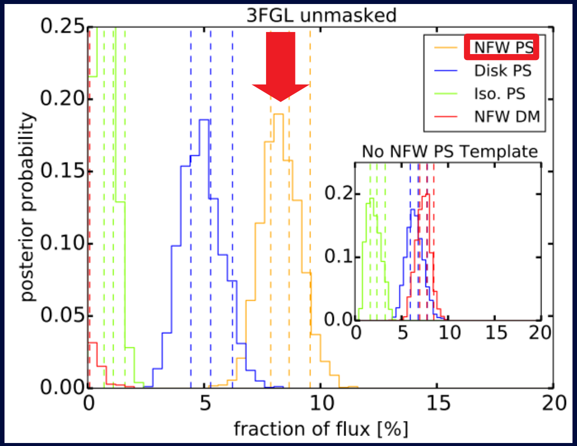
Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Hooper & Slatyer (2013)
Huang et al (2013)
Mirabal (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Zhou et al (2014)
Daylan et al (2014)
Petrovic et al (2015)
Calore et al (2015)
Cholis et al (2015)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Yuan & Ioka (2015)
O'Leary et al (2015)
Brandt & Kocsis (2015)
Carlson et al (2015, 2016)
Yand & Aharonian (2016)
Horiuchi et al (2016)
Lee et al (2016)
Bartels et al (2016)
Linden et al (2016)
Ajello et al (2016)
Ackermann et al (2017)
Ploeg et al (2017)
Macias et al (2018, 2019)
Bartels et al (2018)
Caron et al (2018)
Clark et al (2018)
Leane & Slatyer (2019, 2020a, 2020b)
Zhong et al (2019)
Chang et al (2020)
Abazajian et al (2020)
Buschmann et al (2020)
… *(not complete!)*

+ > 500 particle theory papers

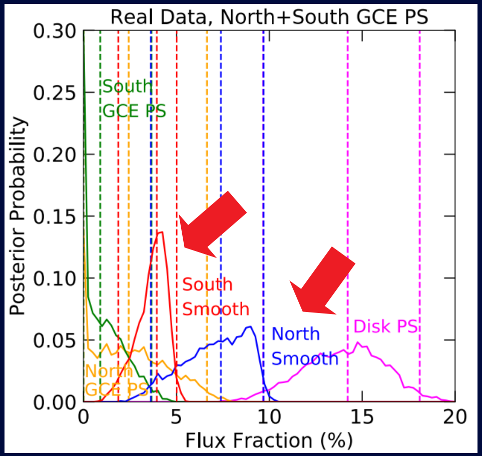
Traditional analysis methods

Template fitting and wavelet method

- Current analysis methods are subject to **systematics**



Lee et al. 2016

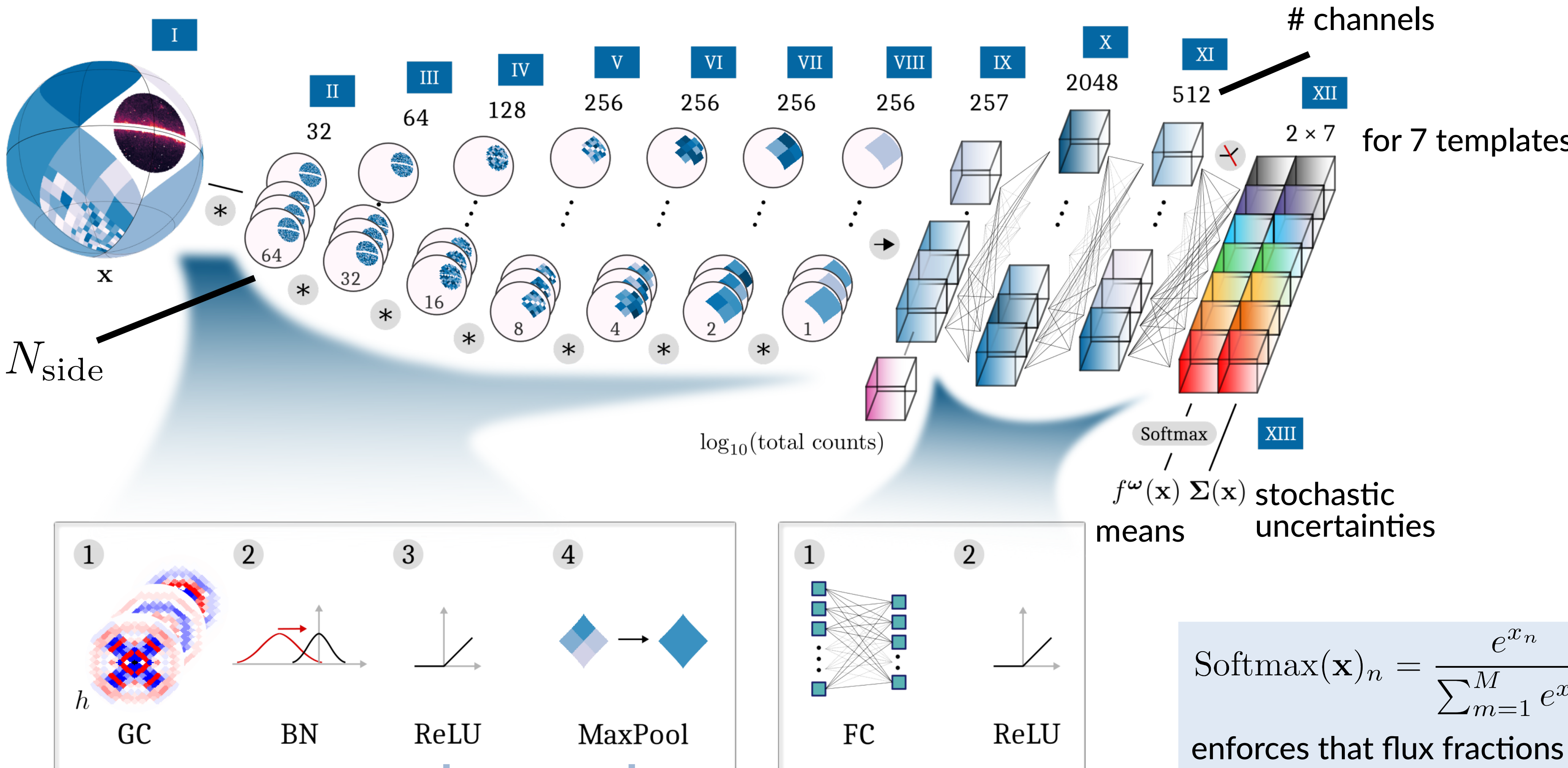


Leane & Slatyer 2020a

- See *Bartels et al. 2016, Lee et al. 2016, Leane & Slatyer 2019, Zhong et al. 2019, Chang et al. 2020, Leane & Slatyer 2020 a,b, Buschmann et al. 2020*

→ GCE mystery still awaits its resolution!

→ New method: Bayesian Convolutional Neural Networks



Convolutional blocks

Fully-connected blocks

ReLU: introduces non-linearity, sparseness

MaxPool: reduces spatial resolution

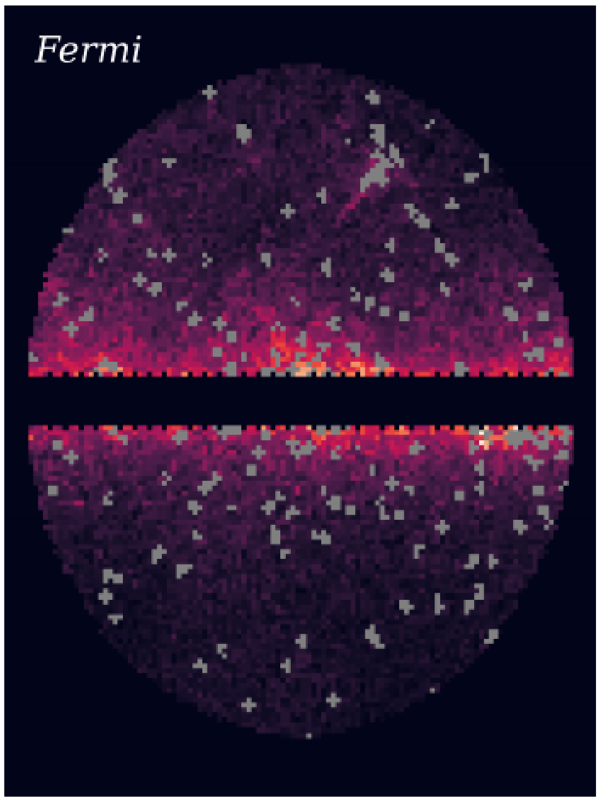
$$\mathrm{Softmax}(\mathbf{x})_n = \frac{e^{x_n}}{\sum_{m=1}^{M} e^{x_m}}$$

enforces that flux fractions

- lie in (0, 1)
- sum up to 1

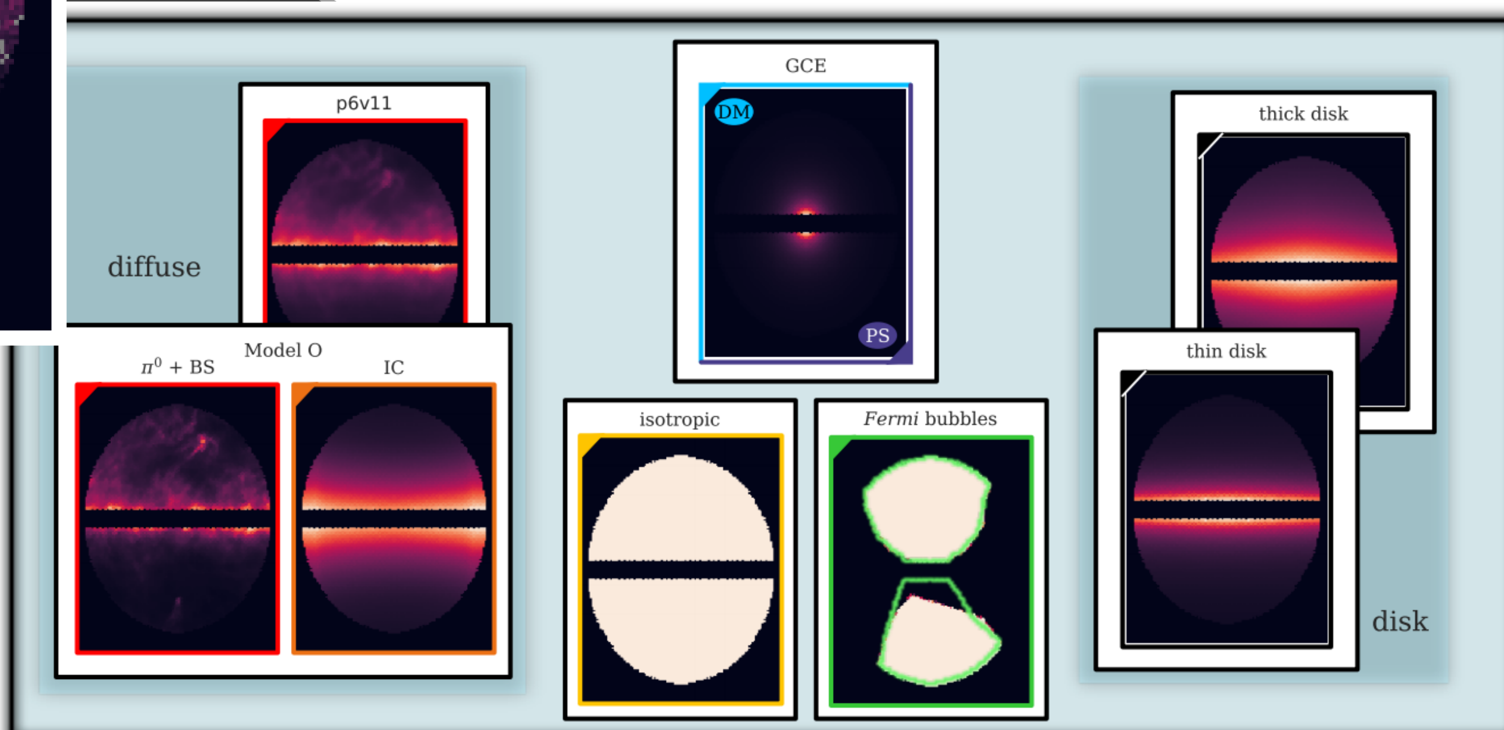
Based on **DeepSphere** framework: HEALPix sphere is modelled as a graph — Perraudin et al. 2019, Defferrard et al. 2020

Modelling the inner Galaxy



- Majority of detected photons: **diffuse Galactic foregrounds** (pion decay + bremsstrahlung, IC)
- Uniform emission from the Fermi bubbles
- Isotropic extragalactic emission
- PSs associated with the Galactic Disk

- We generate the training maps using NPTFit-Sim

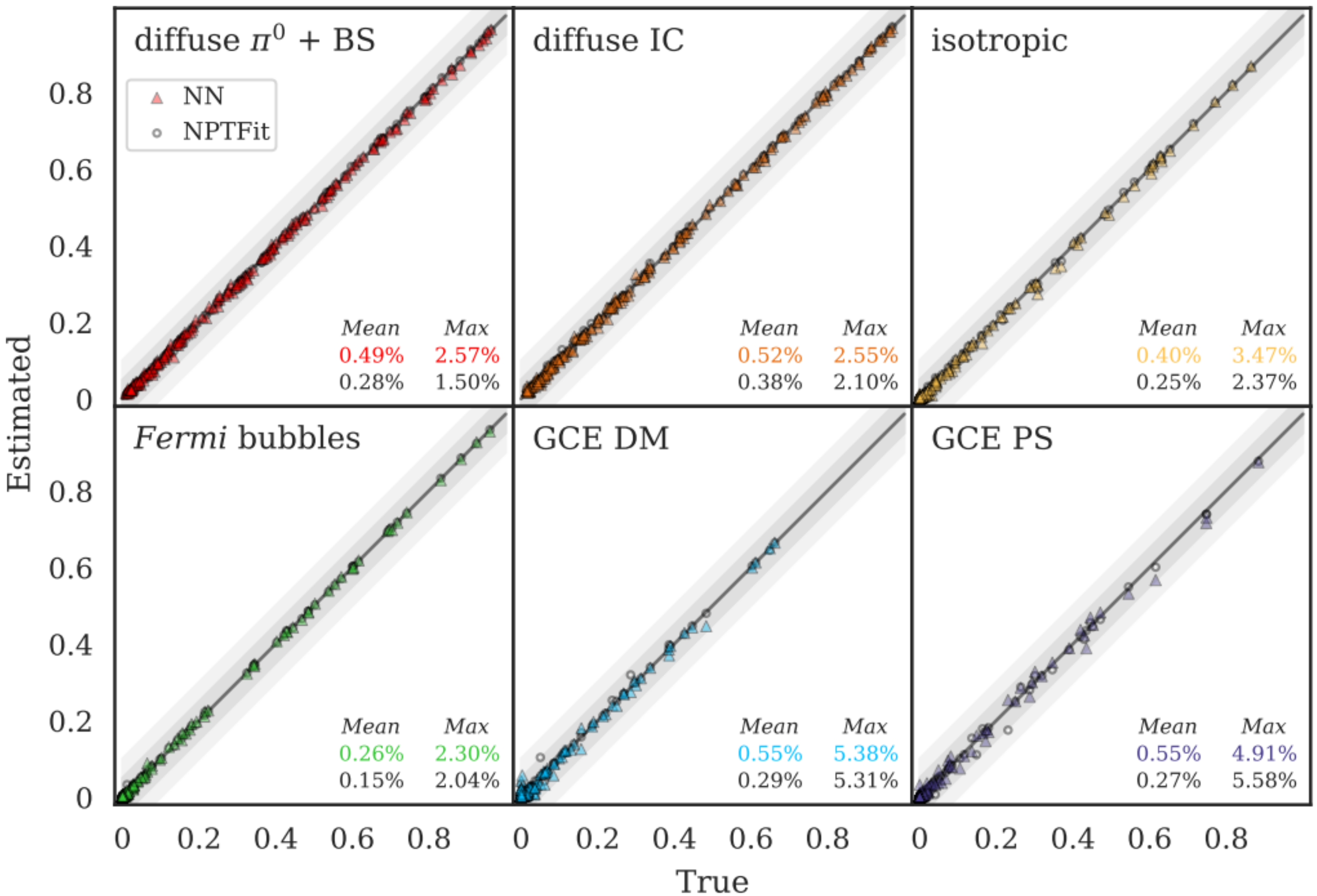


GCE:
generalised NFW profile:

$$\rho(r) \propto \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

Proof-of-concept example

Results on randomly generated maps

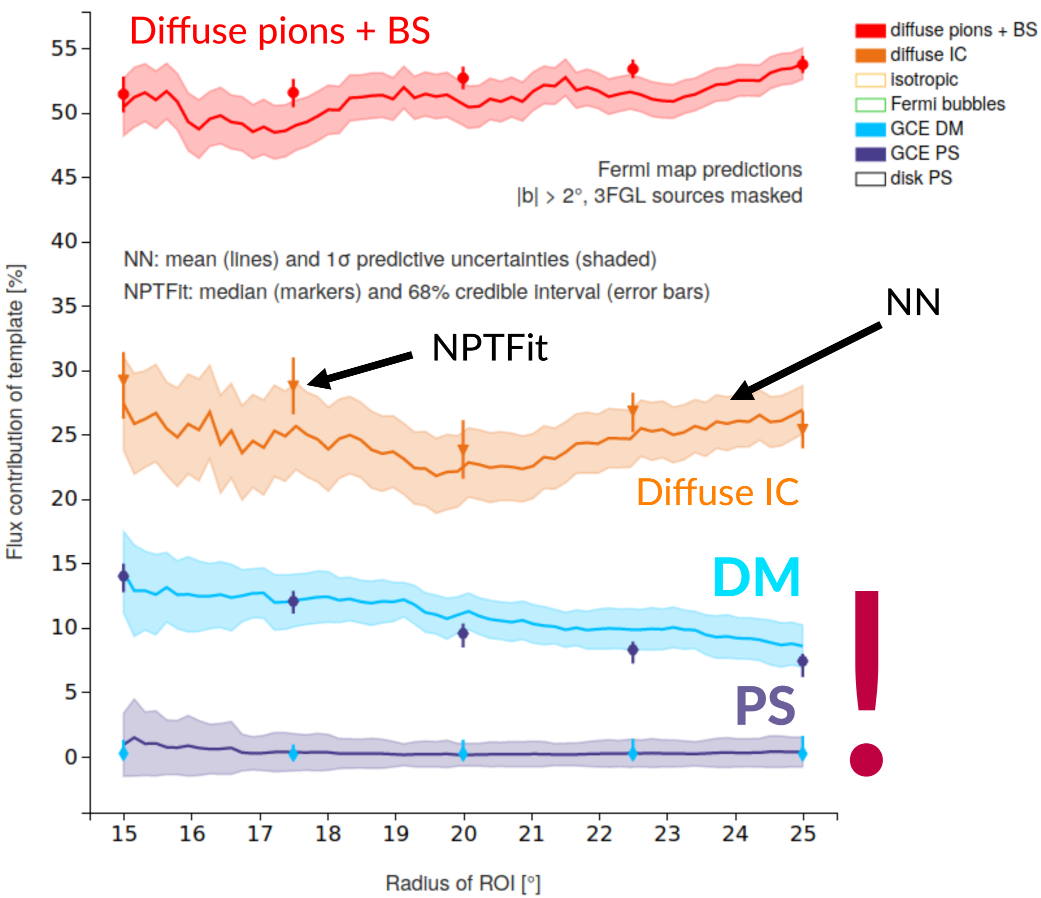


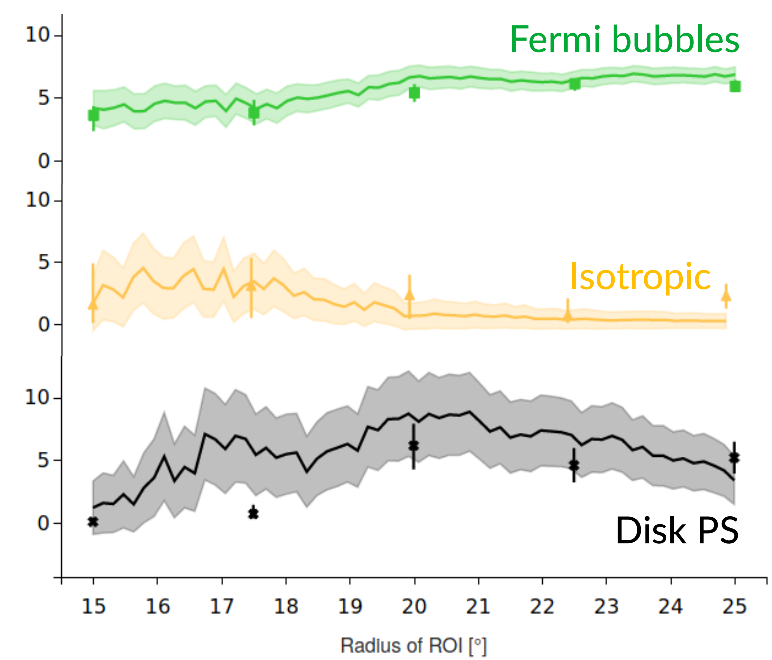
← Maps from the test dataset that NN has not seen during training

- On average, NN accuracy is a bit worse than NPTFit
- *But*: **mean errors** are only **~ 0.5%** (in comparison: GCE contribution is ~ 4 – 10%)
- Maximum errors for GCE templates are very similar for NN and NPTFit

Realistic scenario

*NN results for the **Fermi** map*



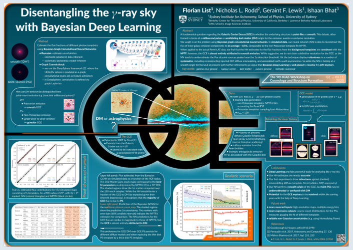


→ NN **identifies a GCE** that decreases monotonically with the ROI radius

→ Almost **100%** of the **GCE** flux is **attributed to DM** arXiv:2006.12504

Paper:

Poster:



Conclusions

- **Deep Learning** provides **powerful tools** for analysing the **γ-ray sky**
- NN estimates are mostly **accurate**
- Our first experiments show **robustness** against **mismodelling**
- Our NN prefers a **smooth origin** of the GCE, but **faint PSs** may be **underestimated** / **confused with DM**
- **Potential** for the **GCE mystery** to be **resolved** within the coming years with the help of Deep Learning