3ML

The Multi-Mission Maximum Likelihood framework

Multi-Mission Maximum Likelihood analysis with 3ML

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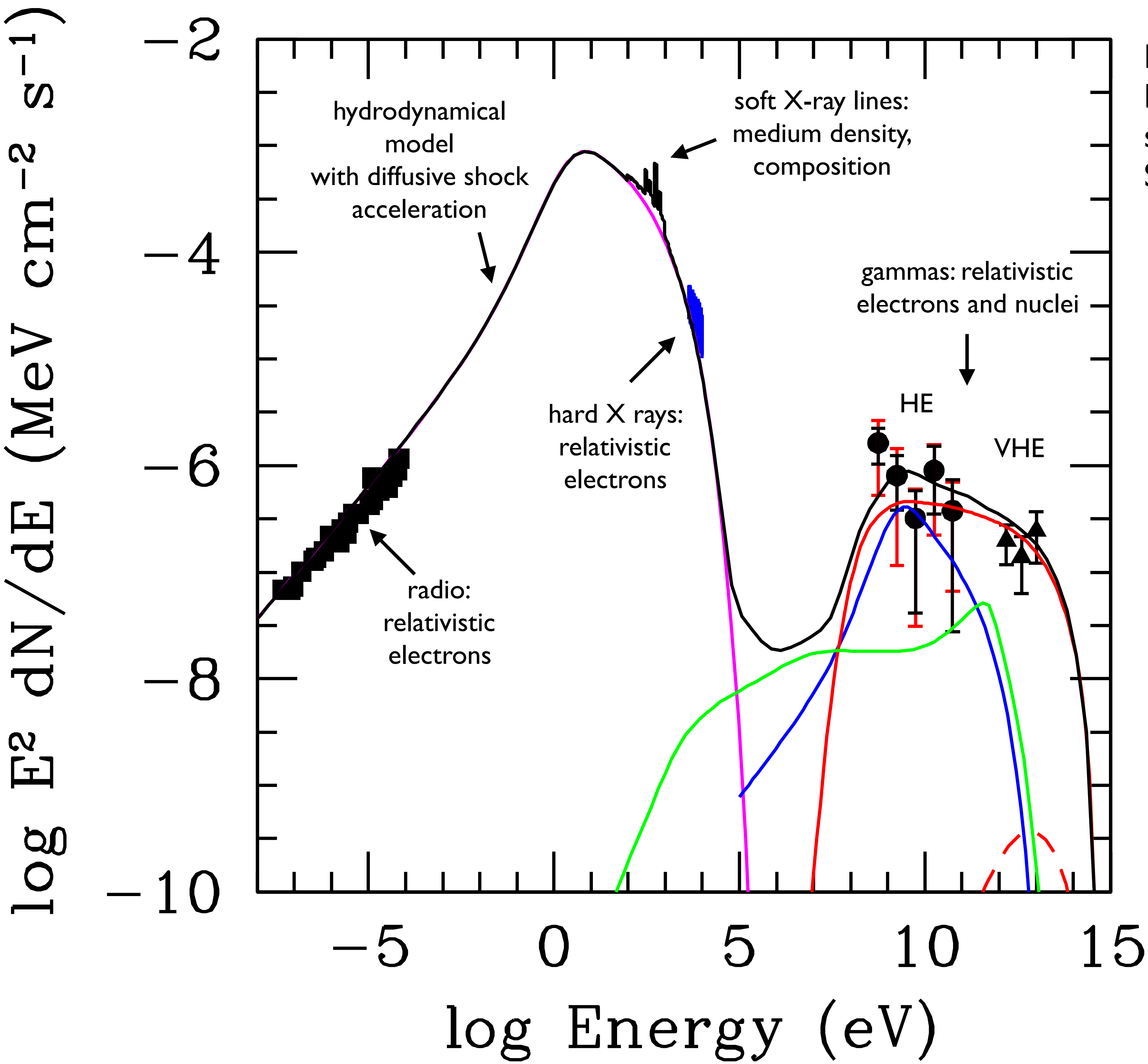
Python for gamma-ray astronomy

MPI-K, 16 November 2015

Why multi-mission studies?



Example:
MWL spectrum of Tycho supernova remnant
Slane et al. ApJ 783, 33 (2014)

more data

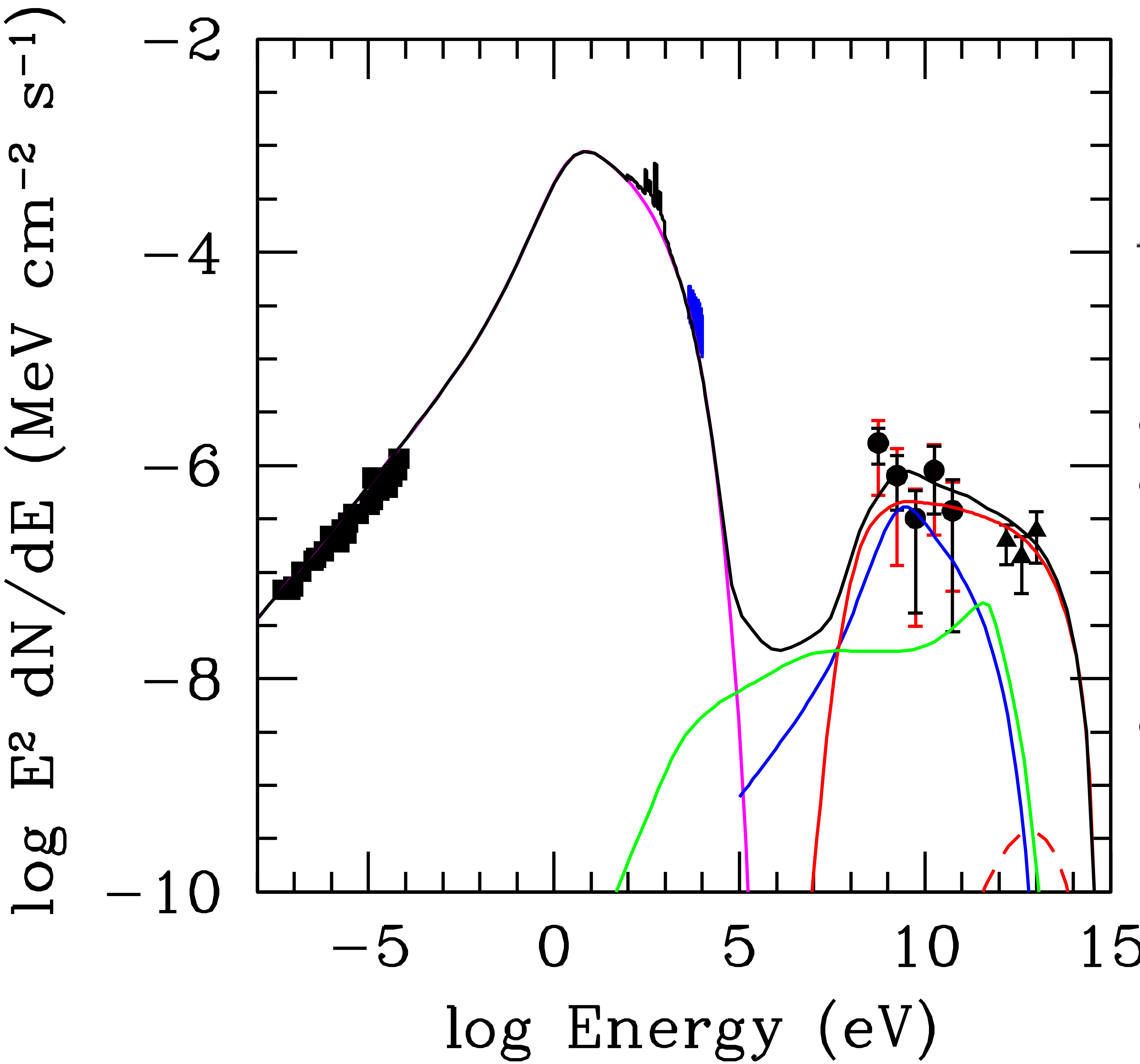
↓

more constraints on models

↓

more physics!

The SED approach



idealised case

$$F(E) = E \cdot \frac{N}{\Delta t\, A}$$

- narrow energy bins
- counts integrated in PSF-like region, background subtracted
- measured energy ~ real energy

Deriving a SED: the real deal

- Complications:
  - limited counting statistics require large-ish bins
  - energy variable PSF and backgrounds
  - energy dispersion

flux normalisation spectral model instrument response background model

$$N = \int \mathrm{d}t\,\mathrm{d}E\,\mathrm{d}\Omega\ [k \cdot S(\vec{p'}, E'|\vec{\alpha}) \otimes \mathrm{IRF}(\vec{p'}, E'|\vec{p}, E; t) + \mathrm{BG}]$$

from fit in specific energy bin from broadband fit

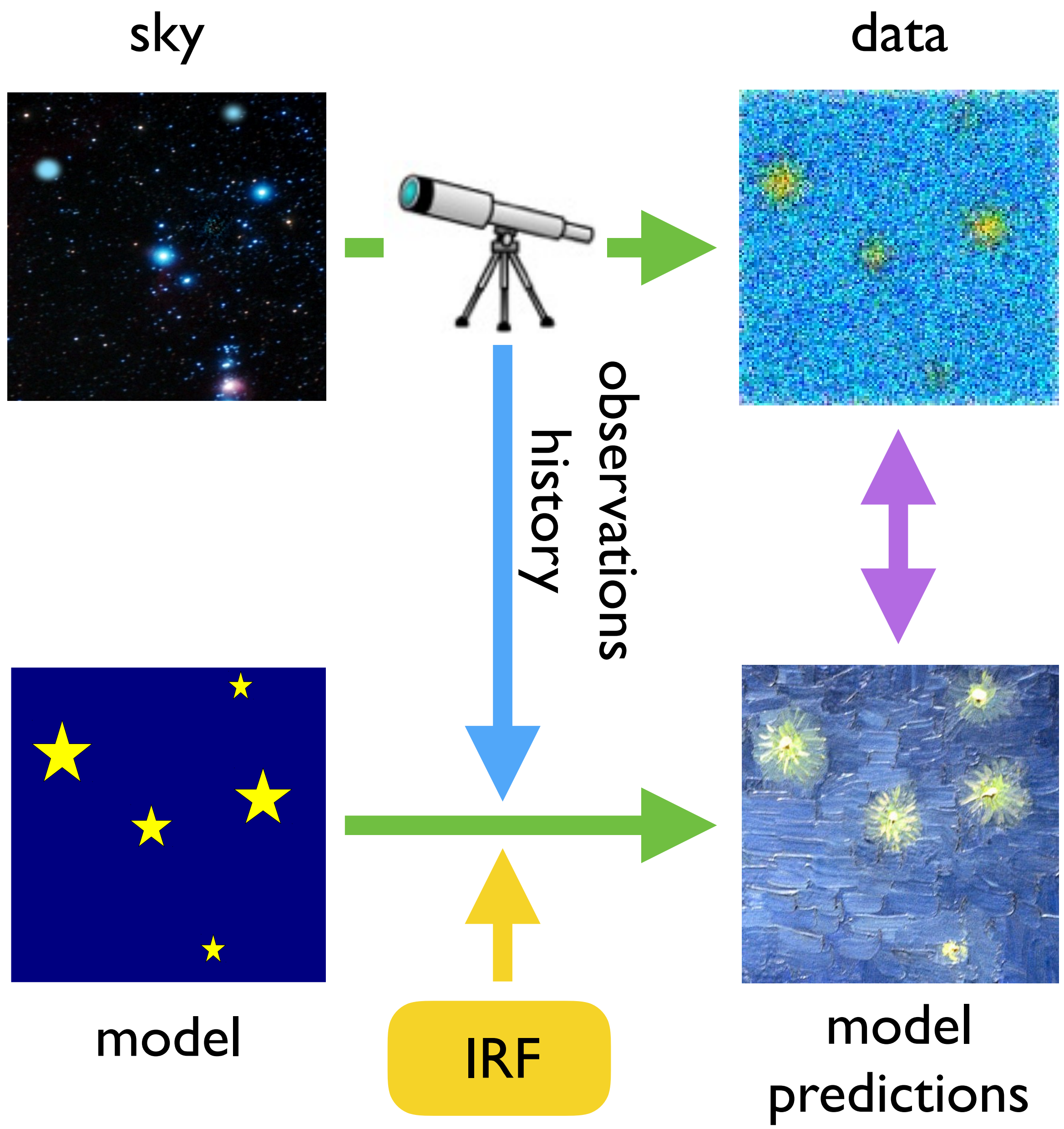
$$F(\langle E \rangle_{12}) = \tilde{k}_{12} \int_{E1}^{E2} \int_{\Delta\Omega} \mathrm{d}E\,\mathrm{d}\Omega \quad E S(\vec{p}, E|\tilde{\vec{\alpha}})$$

Pitfalls of the SED approach

$$F(\langle E\rangle_{12}) = \tilde{k}_{12}\int_{E1}^{E2}\int_{\Delta\Omega}\mathrm{d}E\,\mathrm{d}\Omega \quad ES(\vec{p},E|\tilde{\vec{\alpha}})$$

- depends on the spectral model chosen and on datasets used to determine the spectral parameters
- consistency of spectral models/parameters in combining different instruments and comparing to model
- impossible to take into account source morphology: spatial information not used/SED points from inconsistent regions
- difficult to incorporate other messengers (neutrinos)

The forward-folding approach



Likelihood:

- estimate model parameters
- compare different models

$$\mathcal{L}(O|M)$$

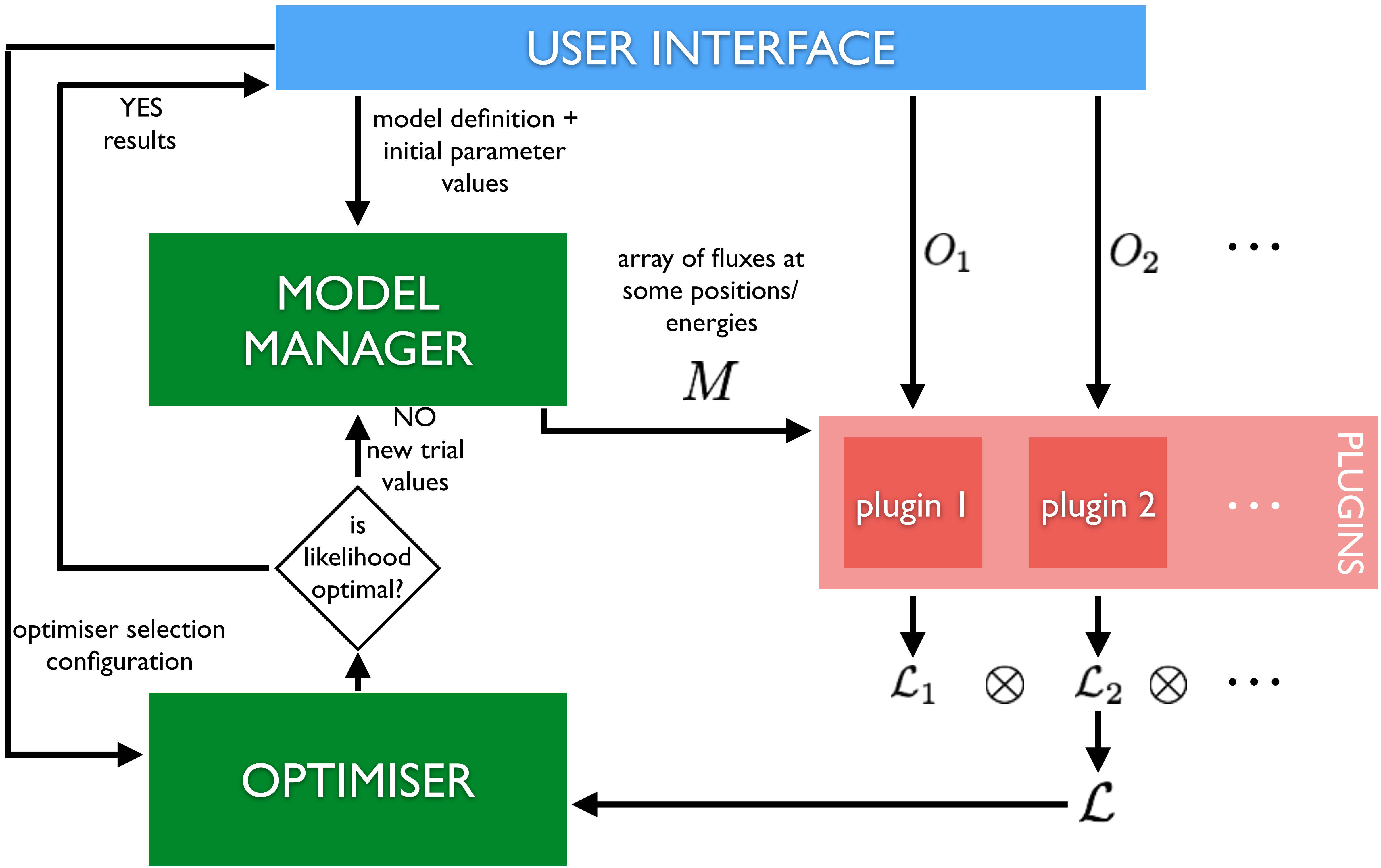
multiple independent observations (instruments)

$$\mathcal{L}(\vec{O}|M) = \mathcal{L}(O_1|M) \times \mathcal{L}(O_2|M) \times \ldots$$

The 3ML project

- lead developer: Giacomo Vianello (Stanford U.); co-developers: J.M. Burgess, R. Lauer, N. Omodei, L. Tibaldo, P. Younk
- python project
  - user friendly
  - relies on open packages (scipy, astropy)
  - very limited C++ code (under the hood)
- website: https://threeml.stanford.edu/
- git repository: https://github.com/giacomov/3ML
- ICRC 2015 proceedings paper: http://arxiv.org/abs/1507.08343

3ML architecture

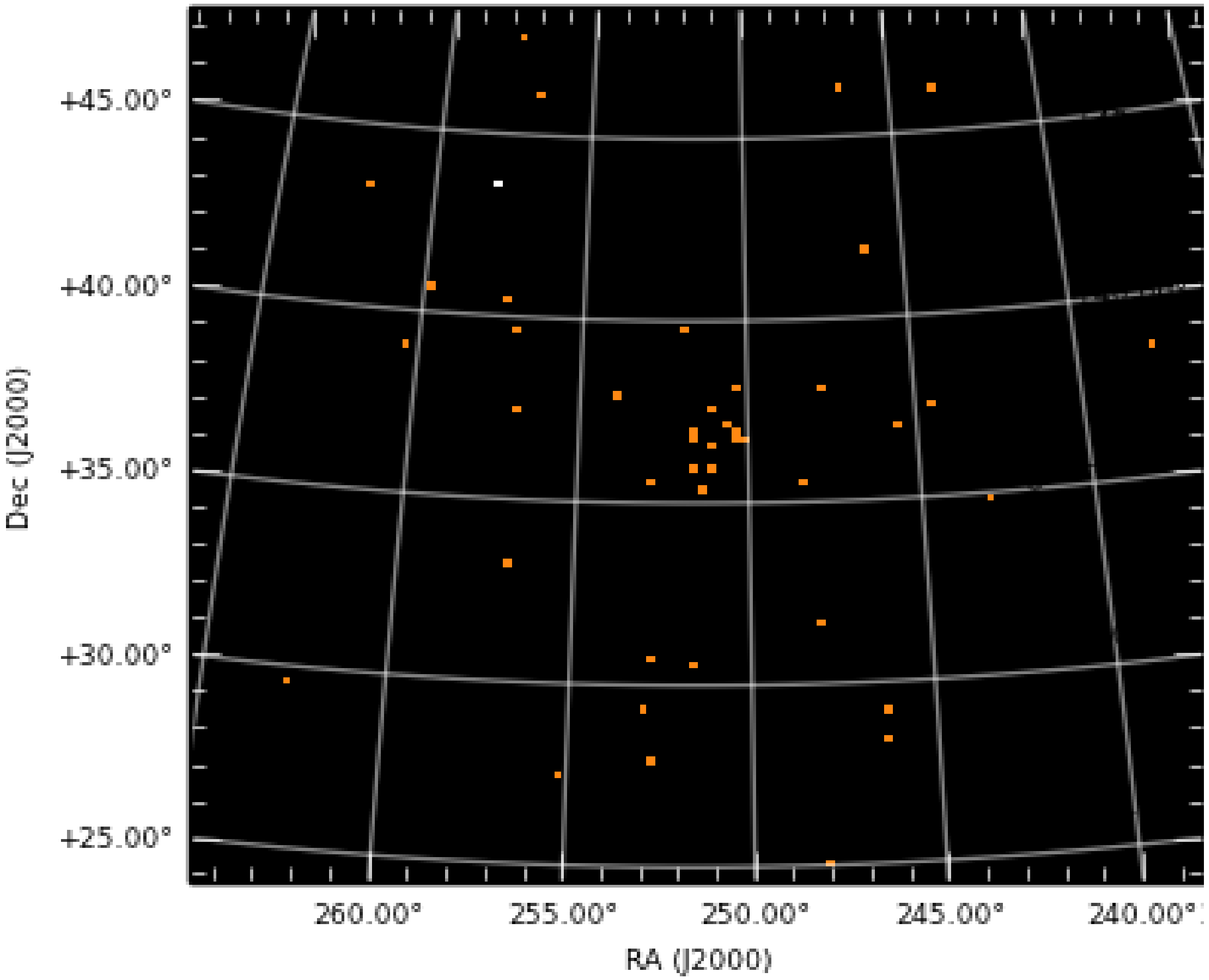


What's special about 3ML? Plugins

- instrument-specific part of the analysis handled through plugins using official/existing software (or at least preserve the existing/official data and instrument response format)
  - no need to re-develop software specific to each instrument
  - no need to export data to a different format
  - flexible: extendable to any instrument (multi-messenger)
- plugins under development
  - working: *Fermi* LAT, *Fermi* GBM, OGIP (*Swift* XRT), HAWC (data/software not public)
  - planned/possible: VERITAS, HESS, GammaLib, anything you want to implement!

Get the most out of each dataset

- software like XSPEC or ISIS retains only spectral information (OGIP format)



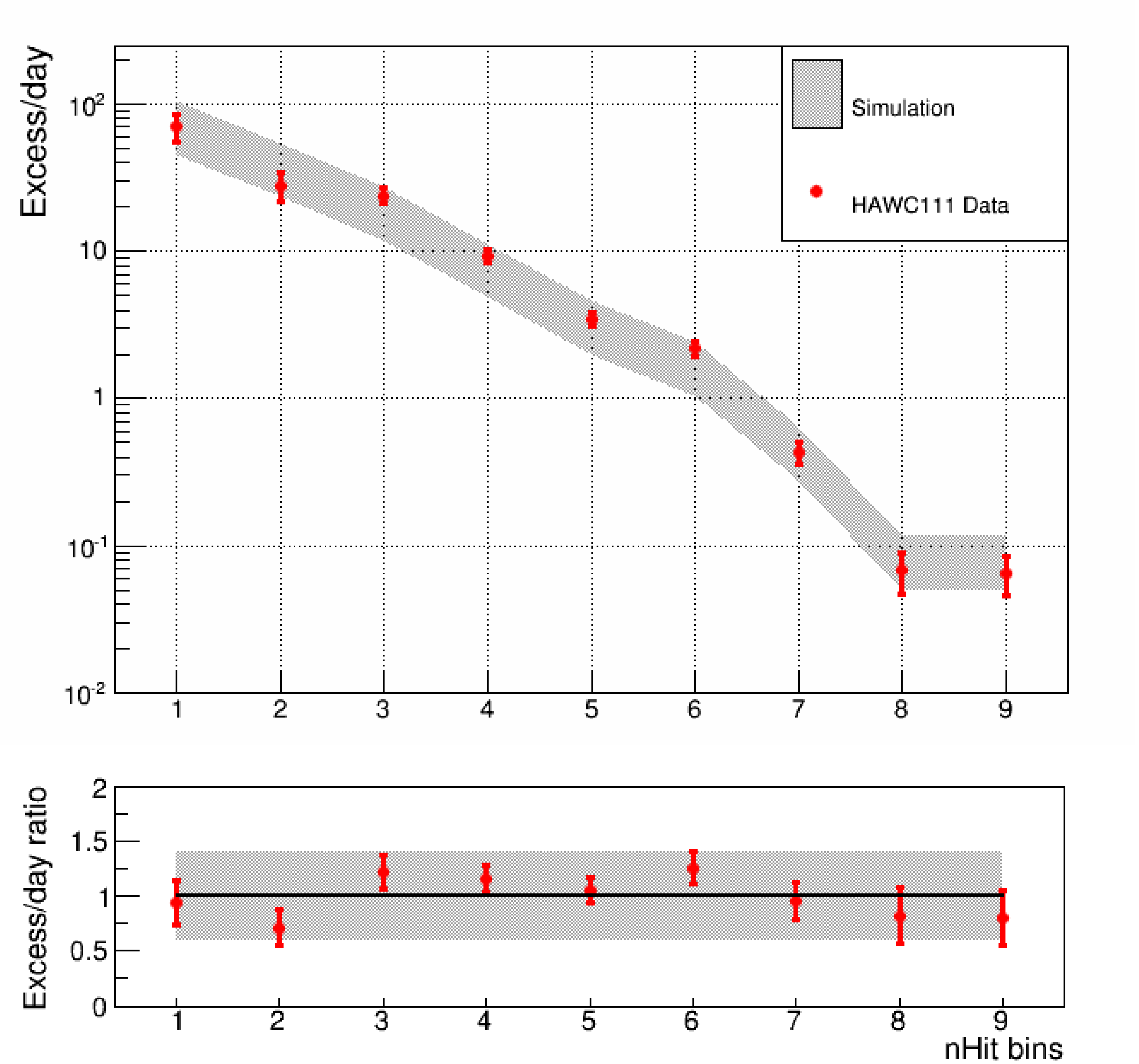
simulation of faint GRB with *Fermi* LAT

- 45 background + 15 signal
- Poisson probability of 60 photons for 45 background expected: 2%, significance ~2σ
- significance from *Fermi* LAT Science Tools (considering spatial information): 7σ

Flexibility

- HAWC does not have (yet) a good energy estimator

- nHit (integrated number of p.e. in a shower)
- not a good energy estimator (strong dependence on core location, zenith angle)
- MC can reliably predict nHit from energy
- 3ML makes possible analyses in nHit space (rather then energy)



nHit "spectrum" of the Crab nebula seen by HAWC
A. J. Smith for the HAWC collaboration, ICRC 2015

Models

- Spectral
  - for the moment several analytical functions and tabulated
  - anything that you can program in python (or fetch from python)
- Spatial
  - several analytical functions
  - FITS maps in WCS coordinates and HEALPix coming soon

Optimisers

- classical likelihood optimisation with Minuit (iMinuit)
- under development: Bayesian sampling of likelihood profile with emcee
- possible to implement other optimisation strategies

Final remarks

- 3ML provides a framework for multi-mission analysis
  - based on forward folding approach: statistically/ methodologically robust
  - based on **plugins** that exploit existing software for each instrument and offer maximum flexibility
  - python based: user friendly and can rely on many community-driven packages
- young project: lots of development required
  - feedback and contributions are welcome
- tutorial will be given on Wed at 11 (unusual room: Multimedia, first floor)