Analysis of Fermi LAT data

Likelihood tutorial

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Overview of activities

Day 1

- Introduction, overview
- Obtaining and exploring LAT data
- Inspecting the data: count map

Day 2

- **Basics of modeling**
- Likelihood analysis of a blazar
- Create a SED
- Produce a light curve

R. Nemmen, Fermi LAT hands-on

Structure of this talk

see jupiter notebook

- **Basic theory of likelihood analysis**

- Likelihood fit → Characterize spectra of a source

- obtain spectral energy distribution (SED)

- build a light curve

Fundamental questions of science

statistics

Model fitting: given this model, what parameters best fit my data?

Model selection: given two potential models, which better describes my data?

Model fitting

given this model, what parameters best fit my data?
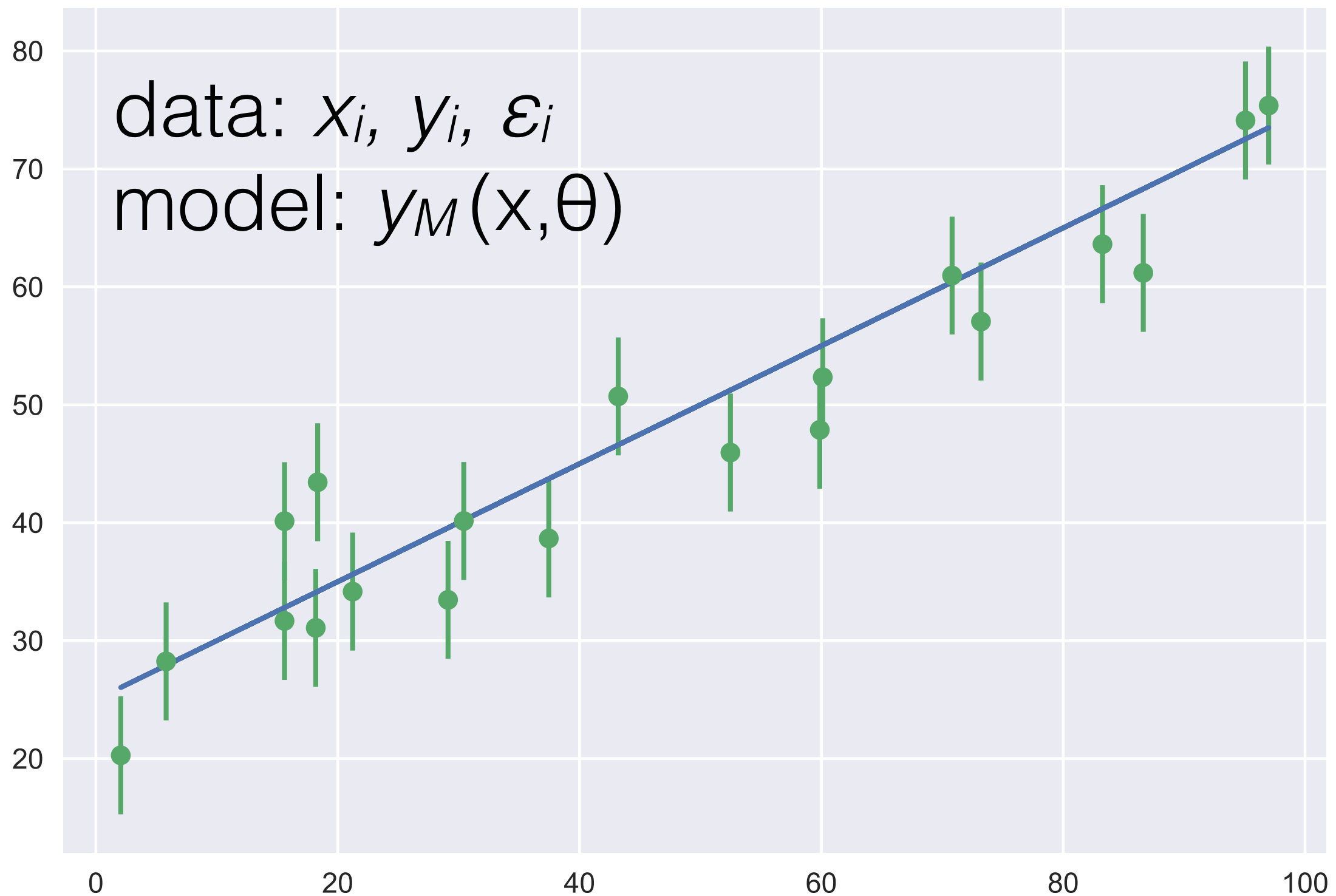
Maximum likelihood approach

Frequentist

$$P(data \mid scientific\ model)$$

$$P(D \mid \theta)$$

likelihood

How to write the likelihood function for the problem below?

data: x_i, y_i, ε_i

model: $y_M(x, \theta)$

Probability for a single measurement

$$P_i = \frac{1}{\sqrt{2\pi\epsilon_i^2}} e^{-\frac{(y_i - y_M)^2}{2\epsilon_i^2}}$$

Likelihood:

$$\mathcal{L} = \sum_i P_i = \sum_i \frac{1}{\sqrt{2\pi\epsilon_i^2}} e^{-\frac{(y_i - y_M)^2}{2\epsilon_i^2}}$$

Log-likelihood:

$$\log \mathcal{L} = -\frac{1}{2} \sum_{i=1}^{N} \left\{ \log(2\pi\varepsilon_i^2) + \frac{[y_i - y_M(x_i; \theta)]^2}{\varepsilon_i^2} \right\}$$

What about Fermi LAT data?

Likelihood for Poisson distribution

$$\mathcal{L} = \prod_i P_i = \prod_i \frac{m_i^{n_i} e^{-m_i}}{n_i!}$$

Binned likelihood

$$\mathcal{L} = \prod_i e^{-m_i} \prod_i \frac{m_i^{n_i}}{n_i!} = e^{-N_{\mathrm{pred}}} \prod_i \frac{m_i^{n_i}}{n_i!}$$

For bin sizes infinitesimally small, n_i=1

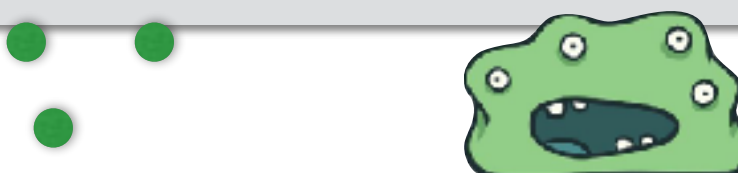$$\mathcal{L} = e^{-N_{\mathrm{pred}}} \prod_i m_i$$

Log-likelihood

$$\log \mathcal{L} = \sum_i \log m_i - N_{\mathrm{pred}}$$

We need to maximize this likelihood function numerically

$$\log \mathcal{L} = \sum_i \log m_i - N_{\mathrm{pred}}$$

total predicted number of counts

$$\int_{\mathrm{ROI}} \left(\text{instrument response function} \right) \left(\text{source model} \right) dE \, d\mathbf{p} \, dt$$

source model = point sources + diffuse sources + other stuff

Model selection

given two potential models, which better describes my data?

Is there a source in a given position of the sky?

maximum likelihood: model without an additional source (the "null hypothesis")

maximum likelihood: model with additional source

$$TS = -2\log\left(\frac{\mathcal{L}_{\mathrm{max},0}}{\mathcal{L}_{\mathrm{max},1}}\right)$$

Rule of thumb:

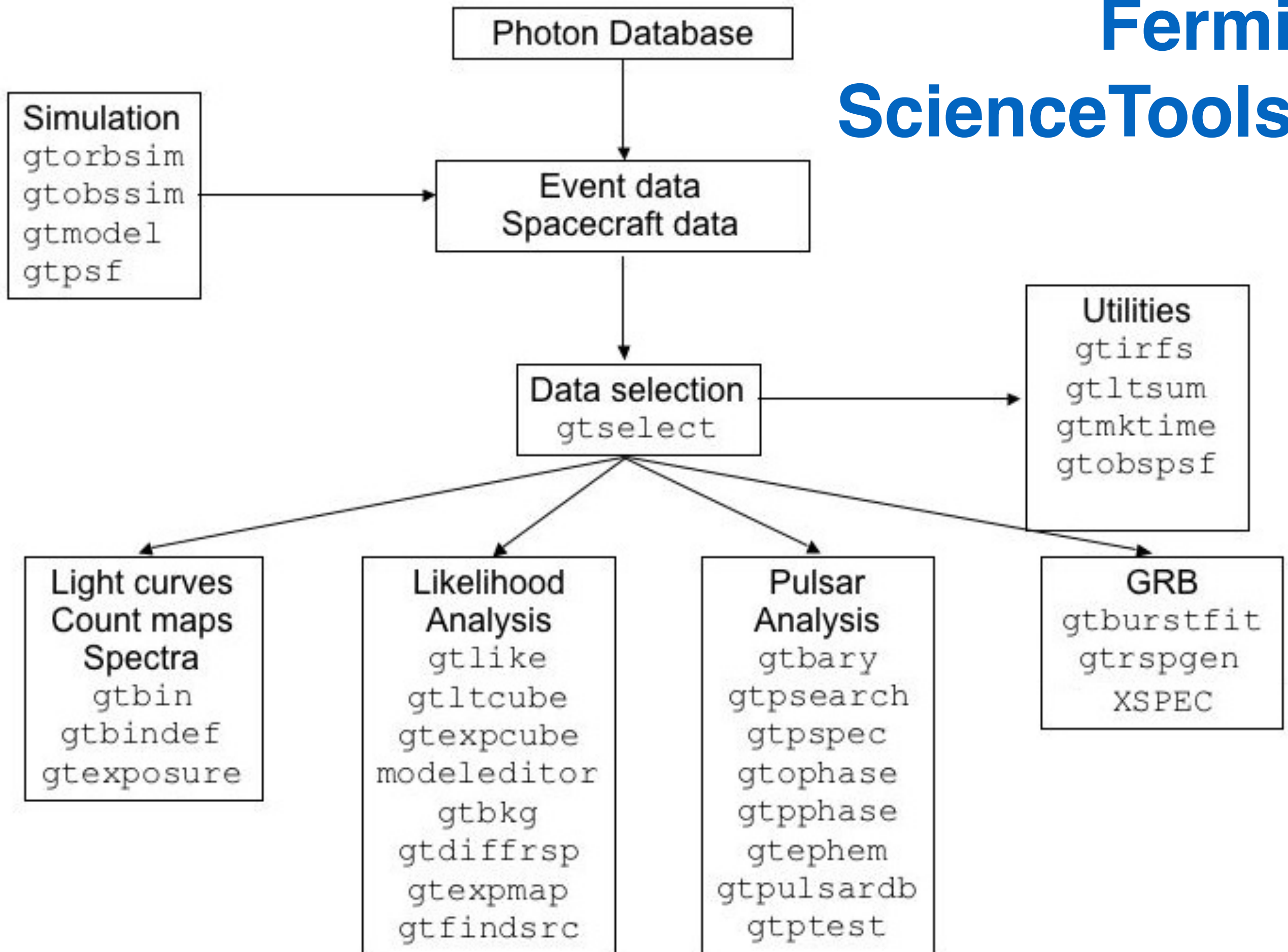TS = 100 $\Rightarrow$ $\approx 10\sigma$
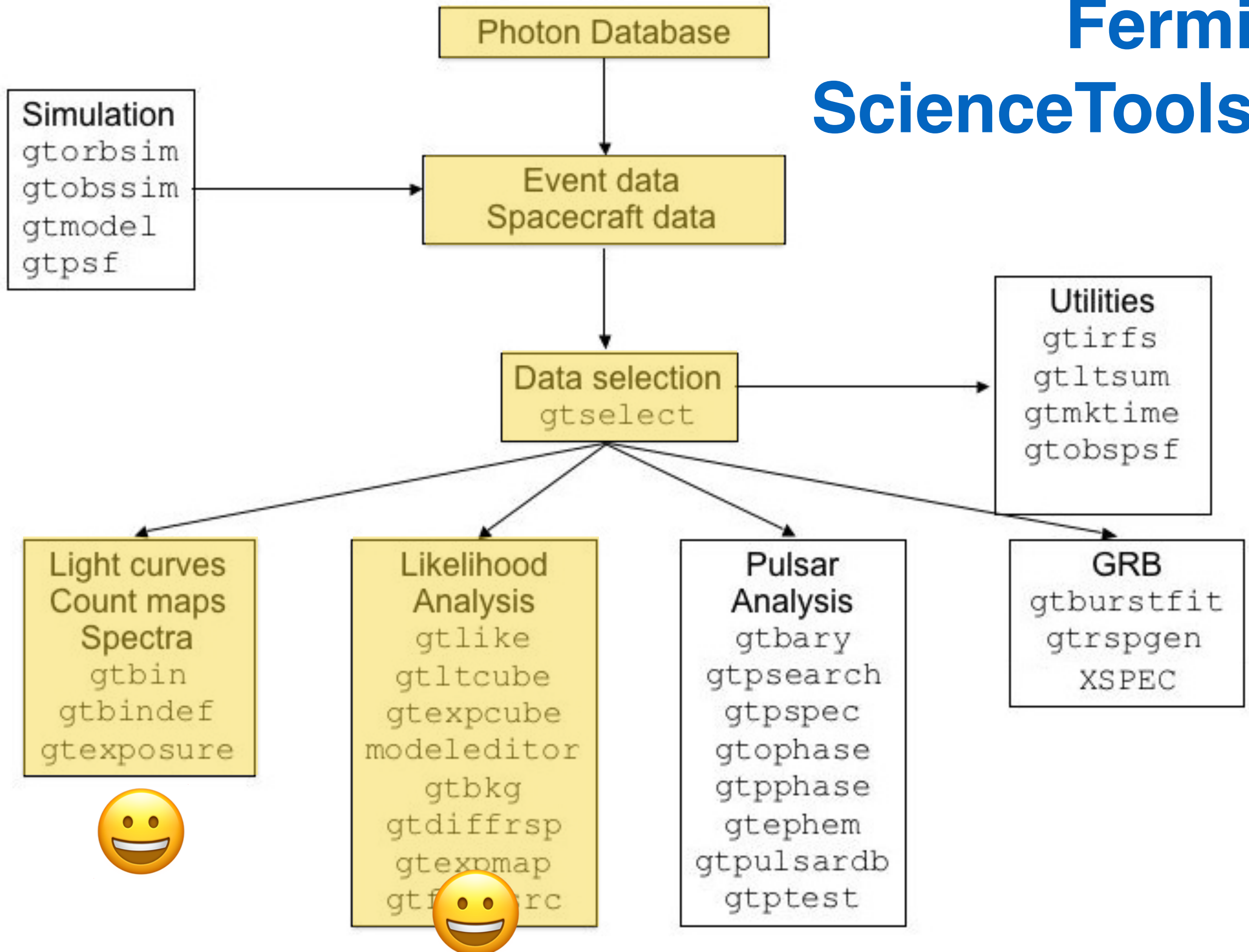
TS = 25 $\Rightarrow$ $\approx 5\sigma$

Hands-on activity

Steps for modeling of *Fermi* LAT data

1 Define your source model
2 Select data + ROI cuts gtselect
3 Select good time intervals (GTI) gtmktime
4 Bin data, create a count map gtbin
5 Compute useful quantities: live time cube, binned exposure cube gtltcube, gtexpcube2
6 Maximize likelihood numerically, get initial estimate of parameters gtlike
7 Optimize fit: improve parameter estimate

Fermi ScienceTools

Photon Database

Simulation
gtorbsim
gtobssim
gtmodel
gtpsf

Event data
Spacecraft data

Data selection
gtselect

Utilities
gtirfs
gtltsum
gtmktime
gtobspsf

Light curves
Count maps
Spectra
gtbin
gtbindef
gtexposure

Likelihood
Analysis
gtlike
gtltcube
gtexpcube
modeleditor
gtbkg
gtdiffrsp
gtexpmap
gtfindsrc

Pulsar
Analysis
gtbary
gtpsearch
gtpspec
gtophase
gtpphase
gtephem
gtpulsardb
gtptest

GRB
gtburstfit
gtrspgen
XSPEC

Python wrappers make analysis of Fermi data much easier: `Enrico` **and** `fermipy`

We will use Enrico:

http://enrico.readthedocs.io/en/latest/

Tutorial website

https://github.com/rsnemmen/Fermi-LAT-tutorial

Please do not download large files during the tutorial or the WIFI network will *overload*

We will distribute the software and data you need via USB sticks

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🌐	Web	http://rodrigonemmen.com
🐦	Twitter	@nemmen
🐙	Github	rsnemmen
f	Facebook	http://facebook.com/rodrigonemmen
🪣	Bitbucket	nemmen
🐍	Blog	http://astropython.blogspot.com
❋	figshare	http://bit.ly/2fax2cT

Director's cut

(cf separate file)