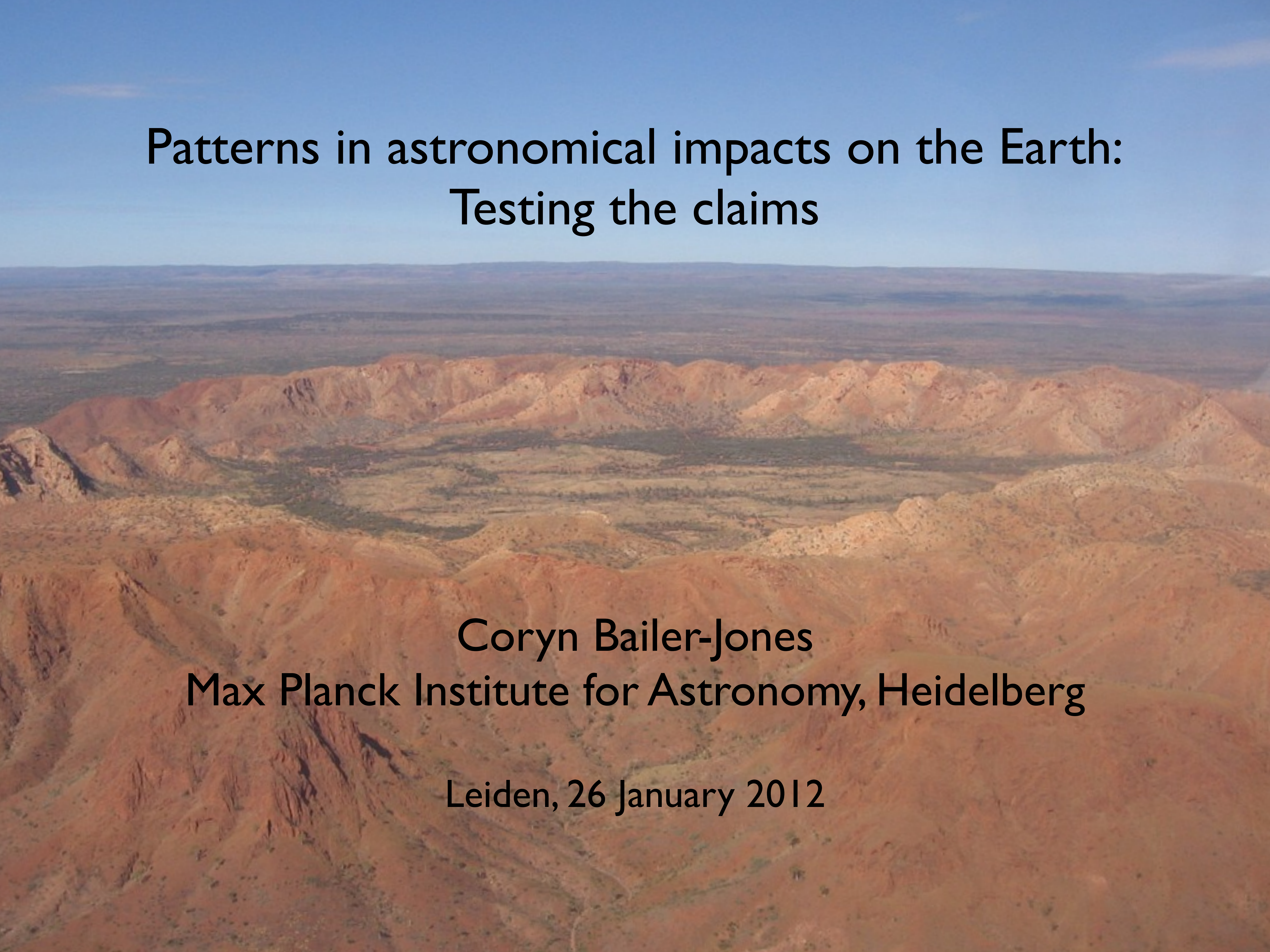

Patterns in astronomical impacts on the Earth: Testing the claims

Coryn Bailer-Jones
Max Planck Institute for Astronomy, Heidelberg

Leiden, 26 January 2012

Outline

- Geological record: climate, biodiversity, impact craters
- Modelling time series
- Simulations
- Application of the model to the cratering record
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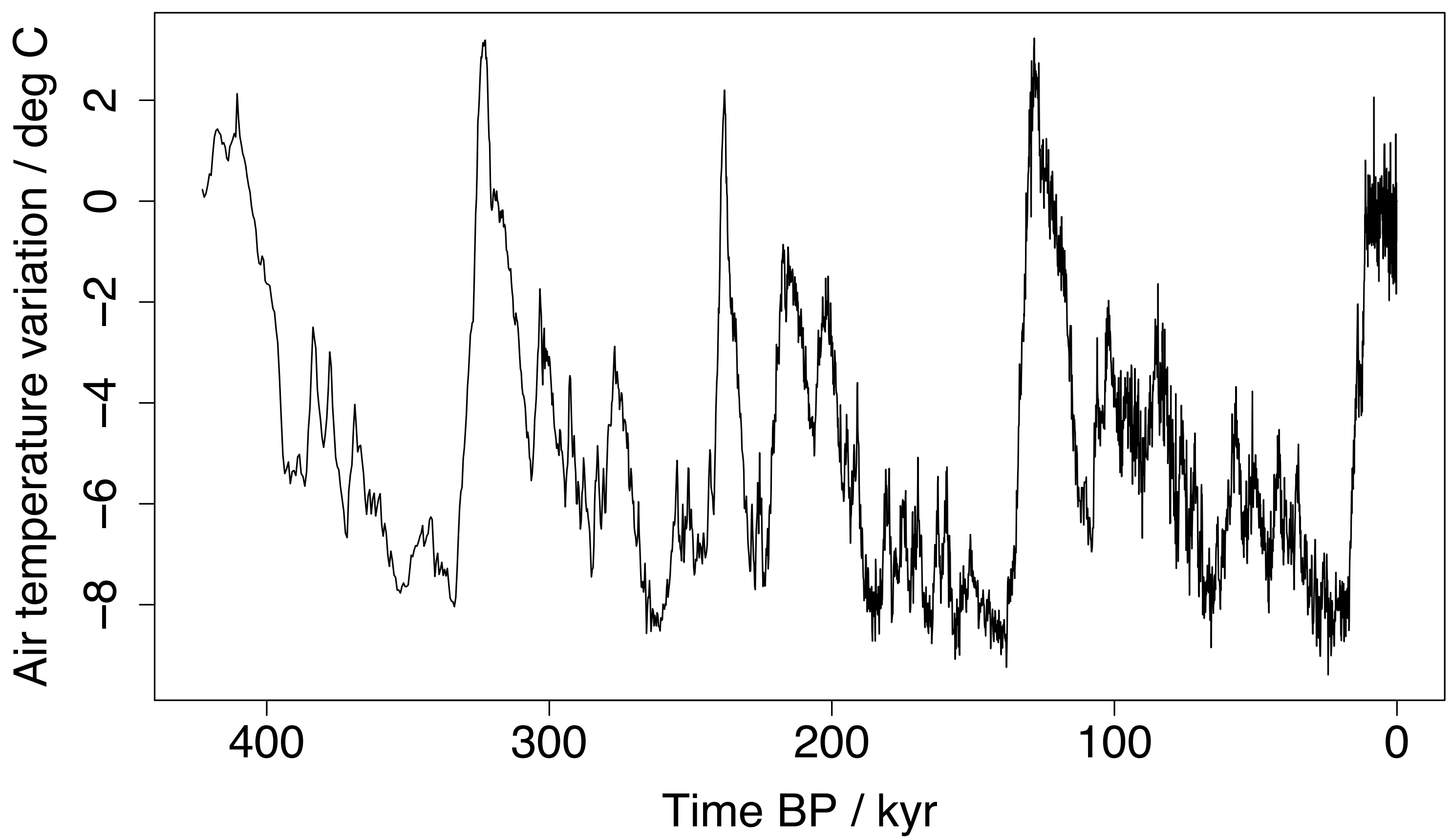
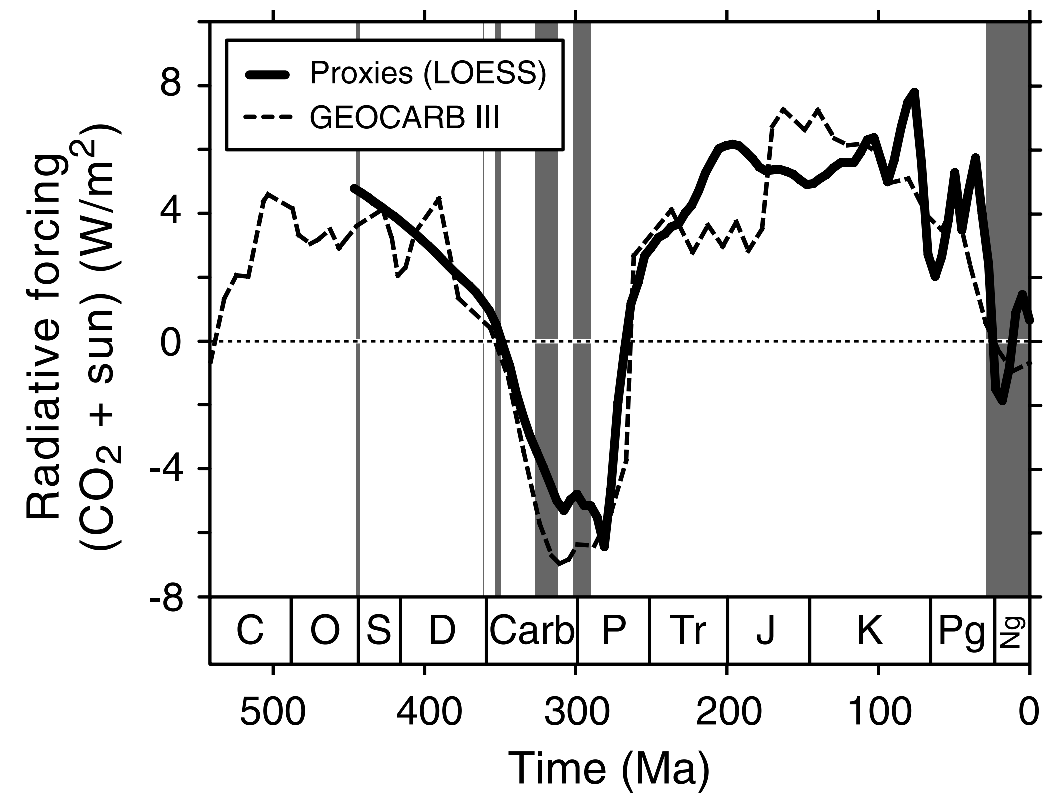
Geological record: climate



Petit et al. (1999)

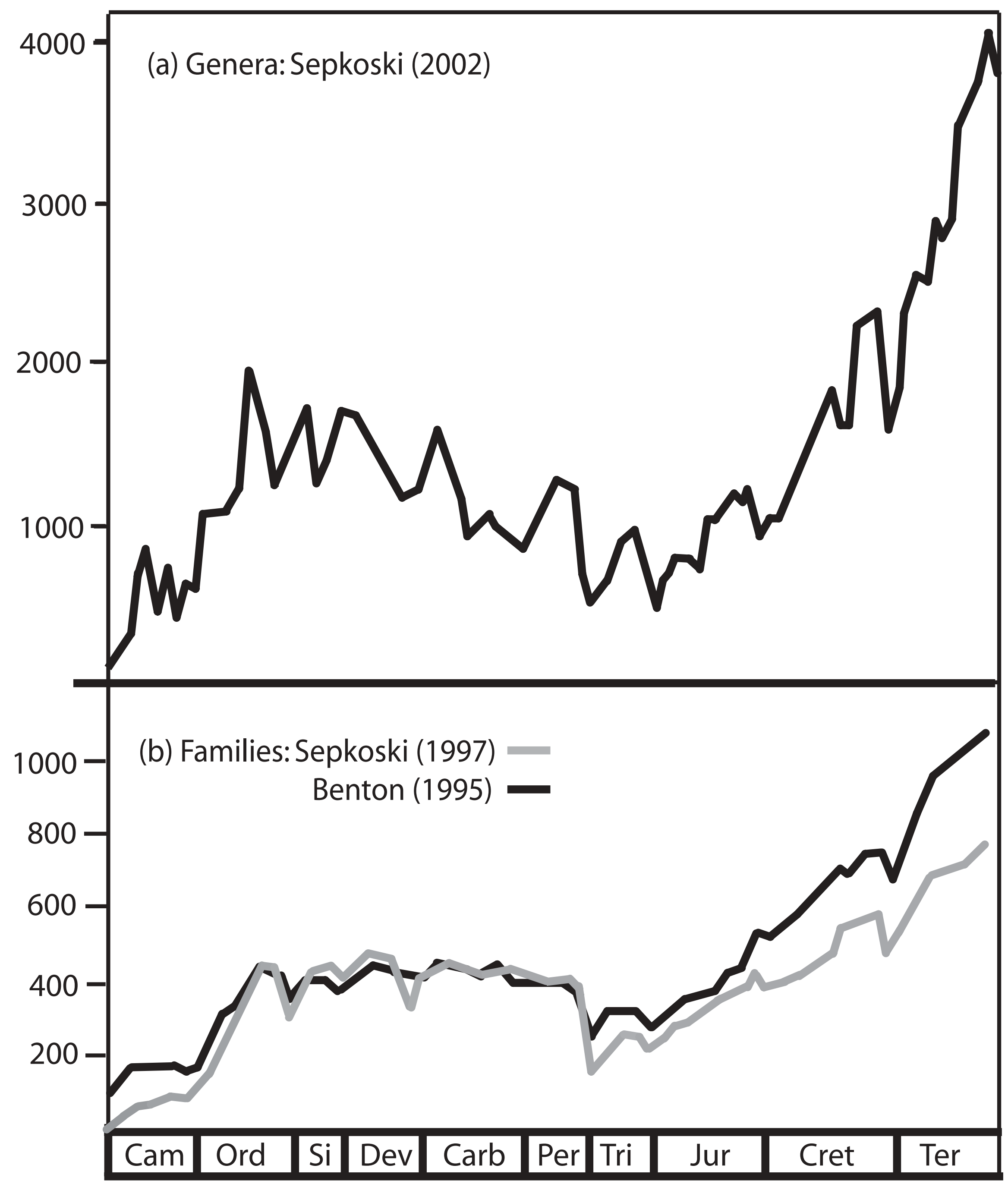


Royer (2006)

- 20-400 kyr periodicity (*Milankovitch cycles*)
  - variation in eccentricity of Earth's orbit
  - also precession and variations in obliquity

variations on 10-100 Myr timescales

Geological record: biodiversity



Smith (2007)

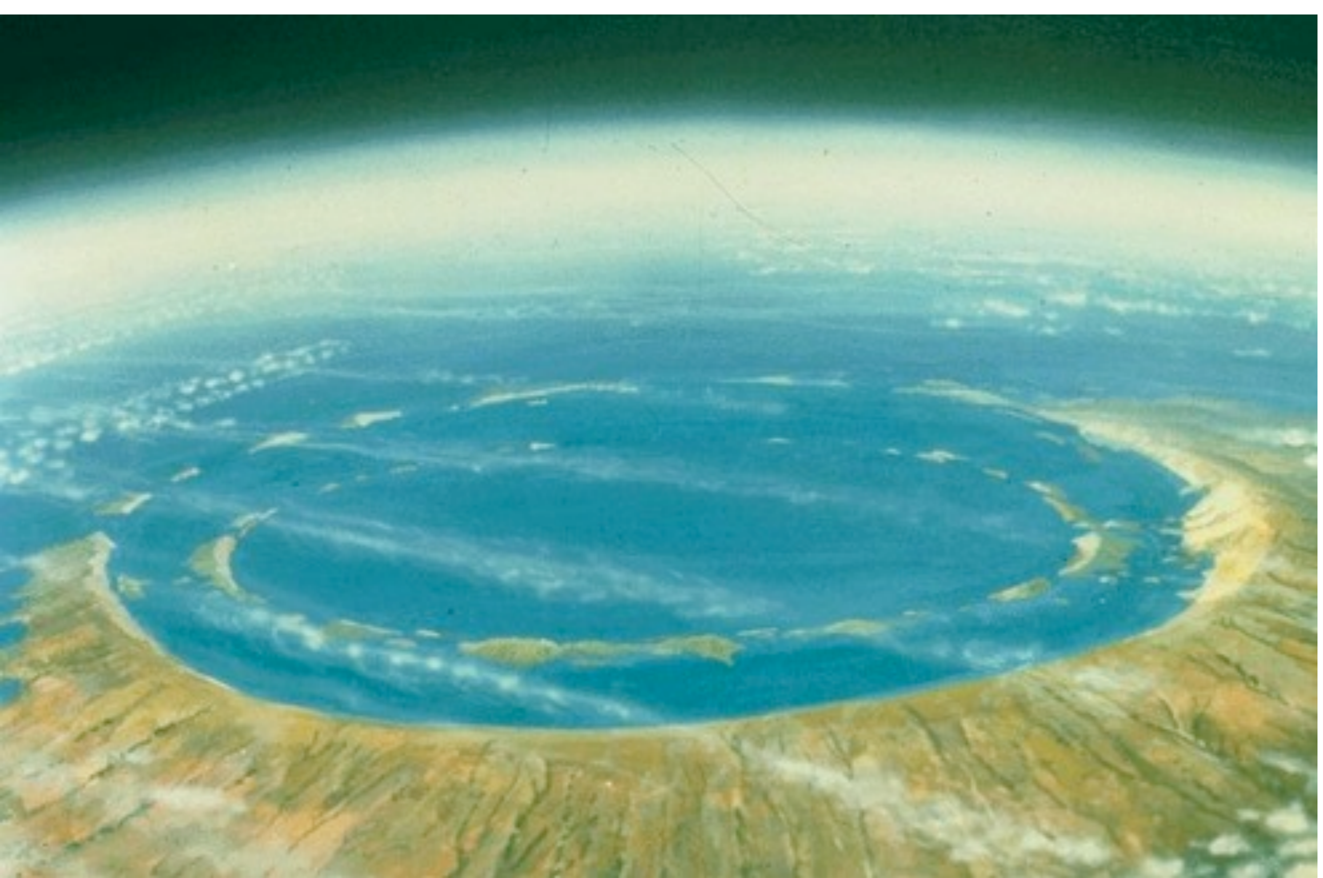
550 Myr BP

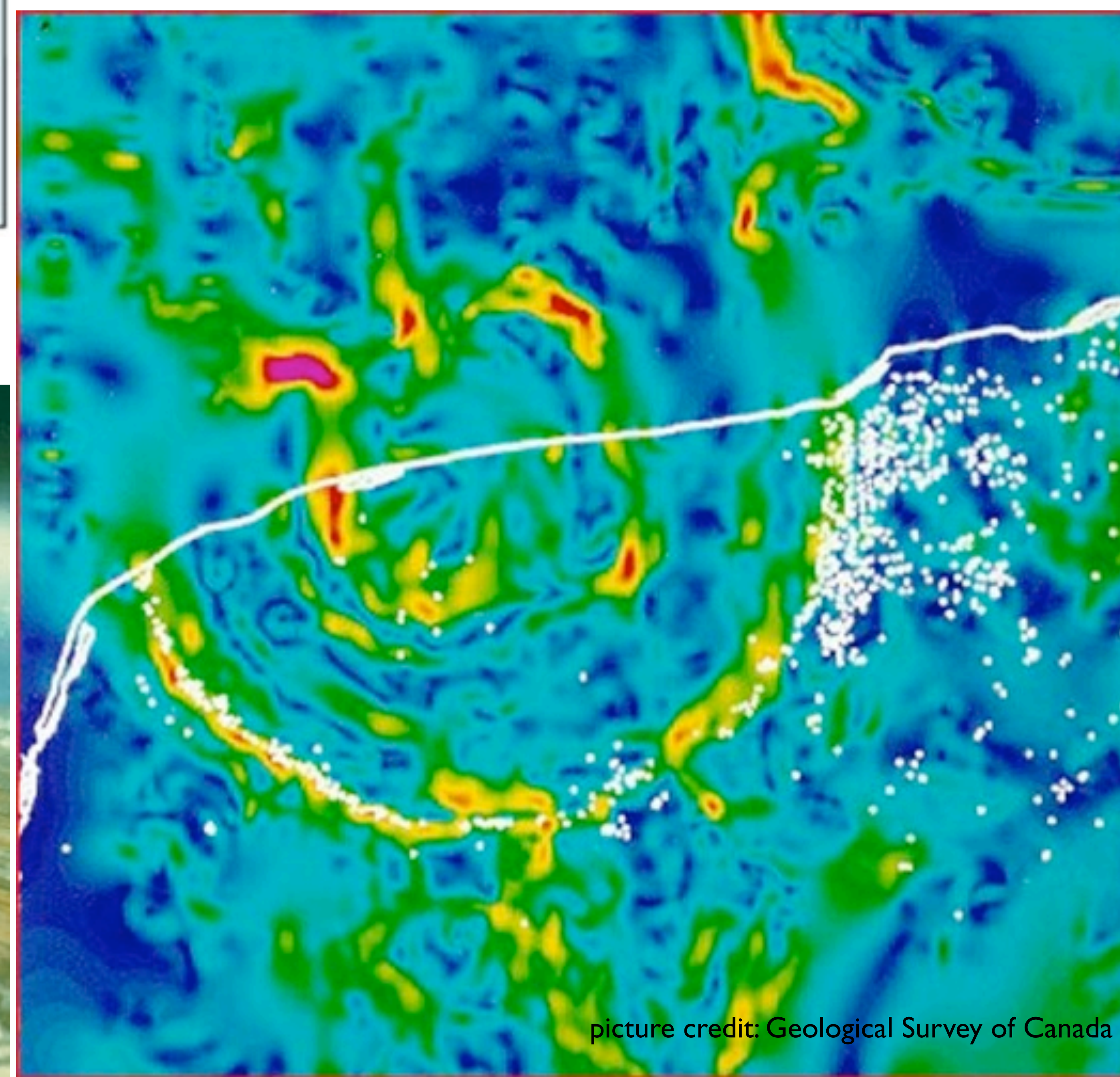
today

Barringer crater, Arizona
diameter = 1.2 km, age = 49 ± 3 kyr

Chicxulub crater, Yucatan
diameter = 170 km
age = 64.98 ± 0.05 Myr

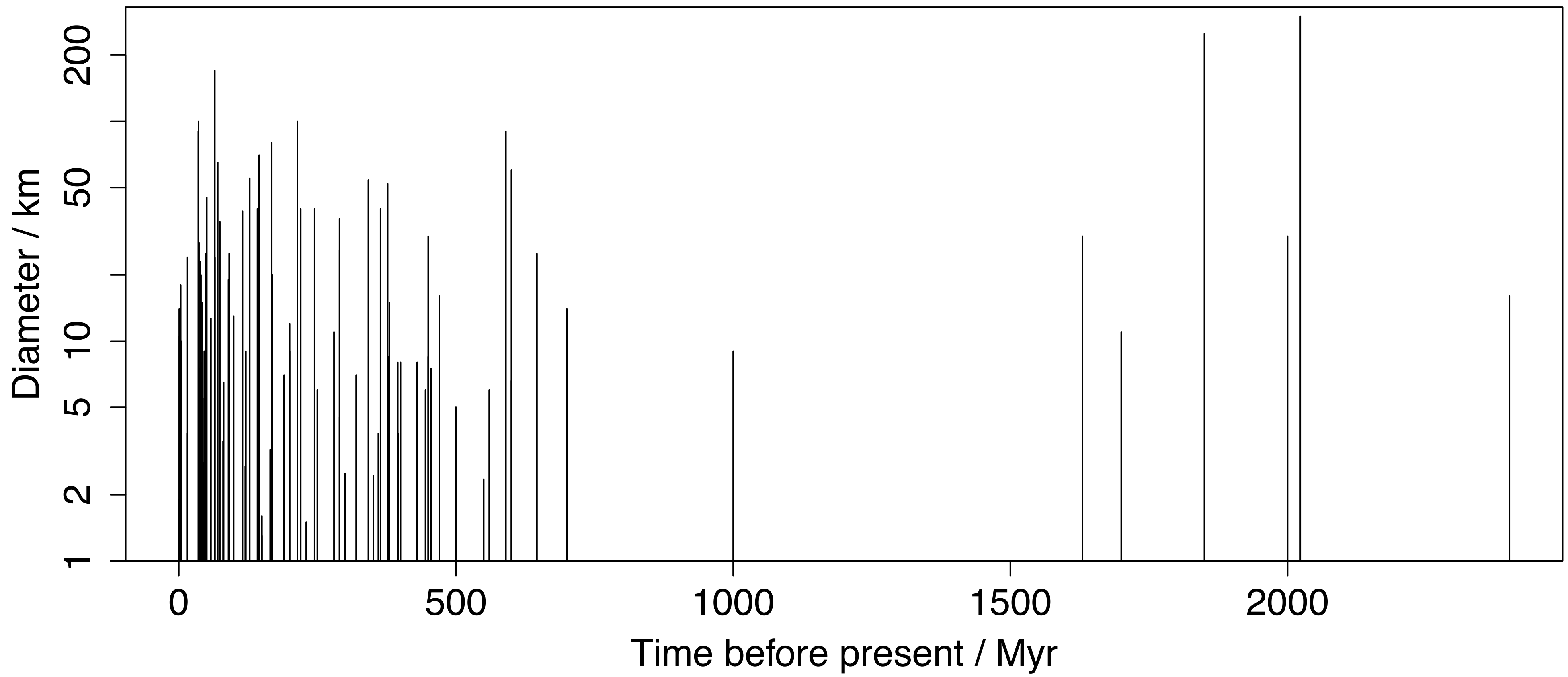
Gravity anomaly map
(red high, blue low)





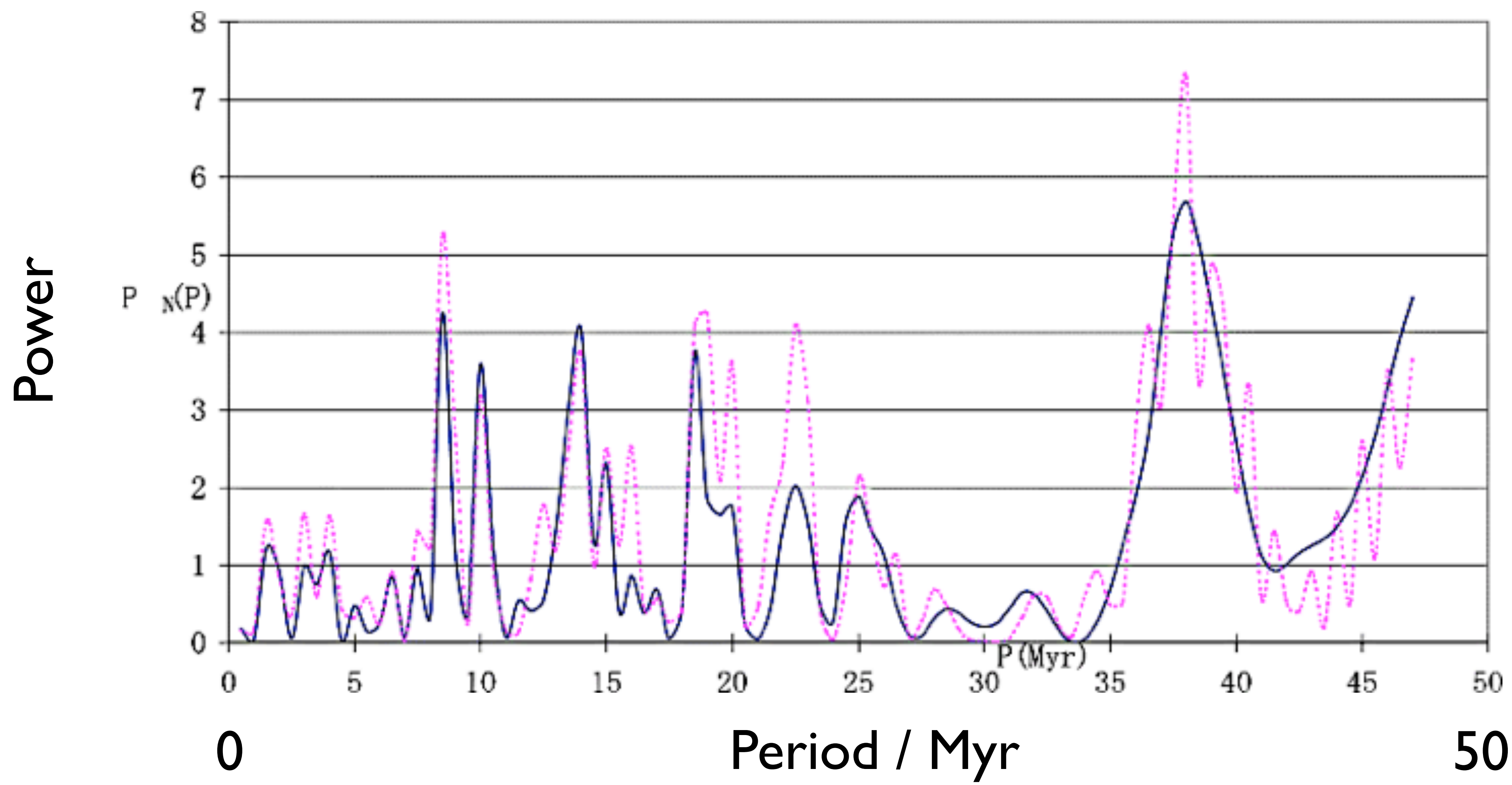
picture credit: Geological Survey of Canada

Geological record: impact cratering



- 180 impact craters (Earth Impact Database, U. New Brunswick)
- 15 m to 300 km diameter
- 63 yr to 2400 Myr old (some with very large uncertainties)

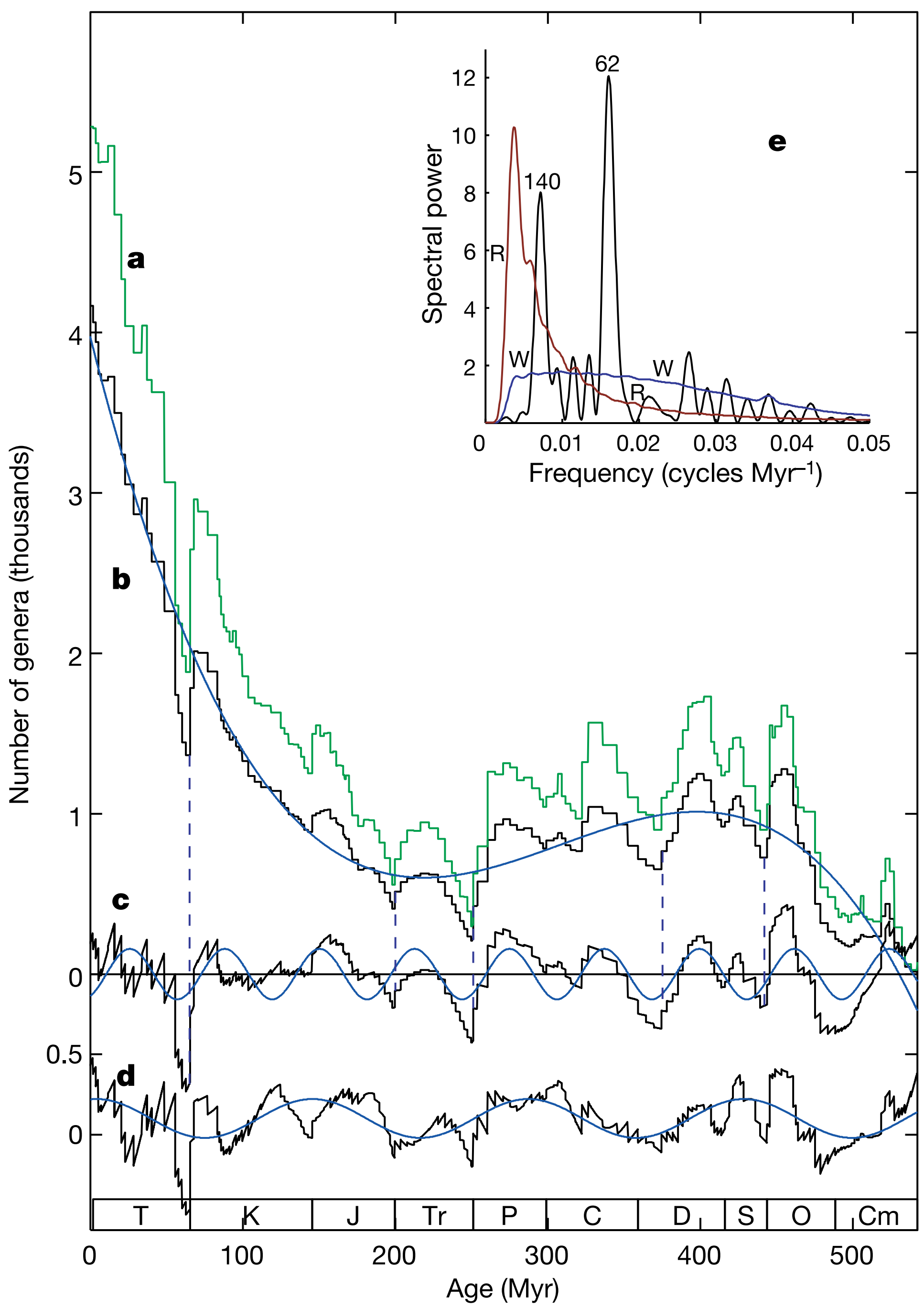
Example claims of periodicity in geological time series



- Periodogram of impact crater dates (Yabushita 2004)
- significant period claimed at 37.5 Myr

Example claims of periodicity in geological time series

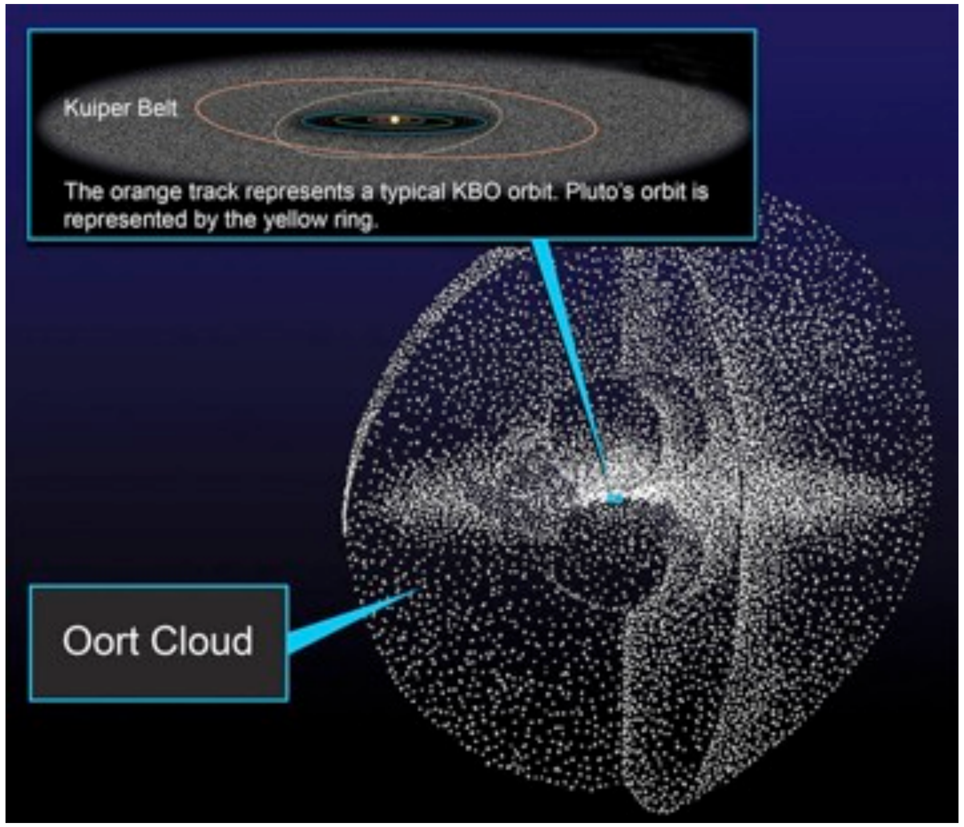
Number of genera



0 Age / Myr 550

- Biodiversity (Rohde & Muller 2005)
- significant period of 62 ± 3 Myr (after detrending) claimed

Suggested astronomical mechanisms



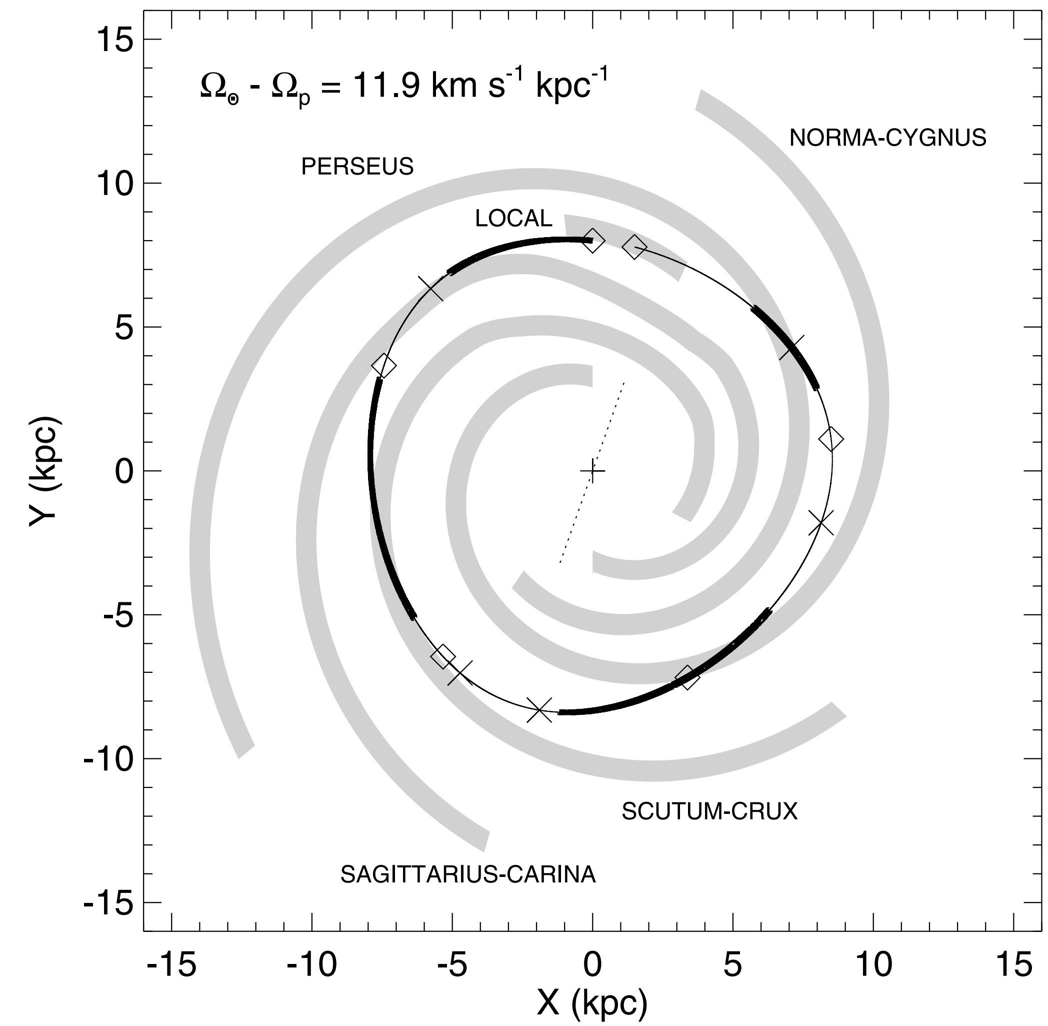
Nearby supernovae
⇒ gamma rays
⇒ biological extinction

Perturbations of Oort cloud by Galactic tide and/or passing stars
⇒ comet impacts

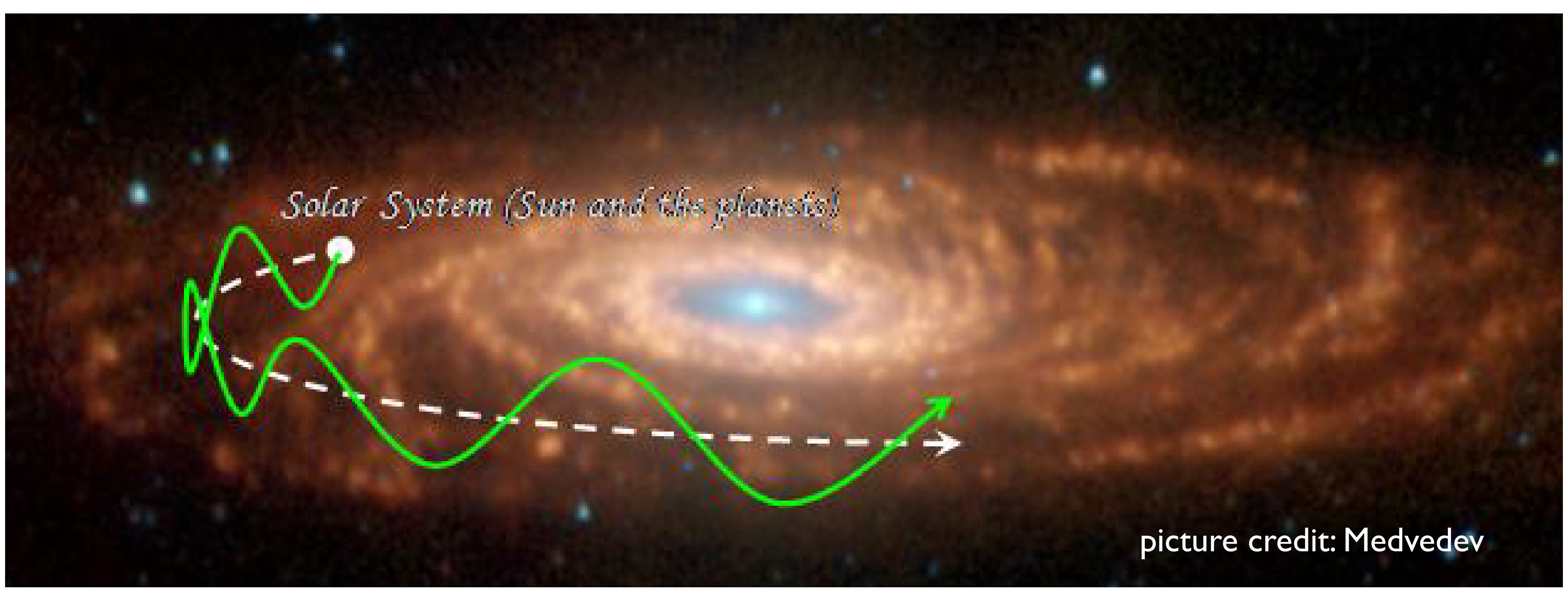
Star forming regions
⇒ cosmic rays
⇒ cloud formation
(highly questionable!)

Suggested causes of the periodicity

- motion of the Sun in the Galaxy
  - vertical oscillation through disk (periods of 50-75 Myr)
  - spiral arm crossing (timescale of 50-100 Myr)



Gies & Helsel (2005)



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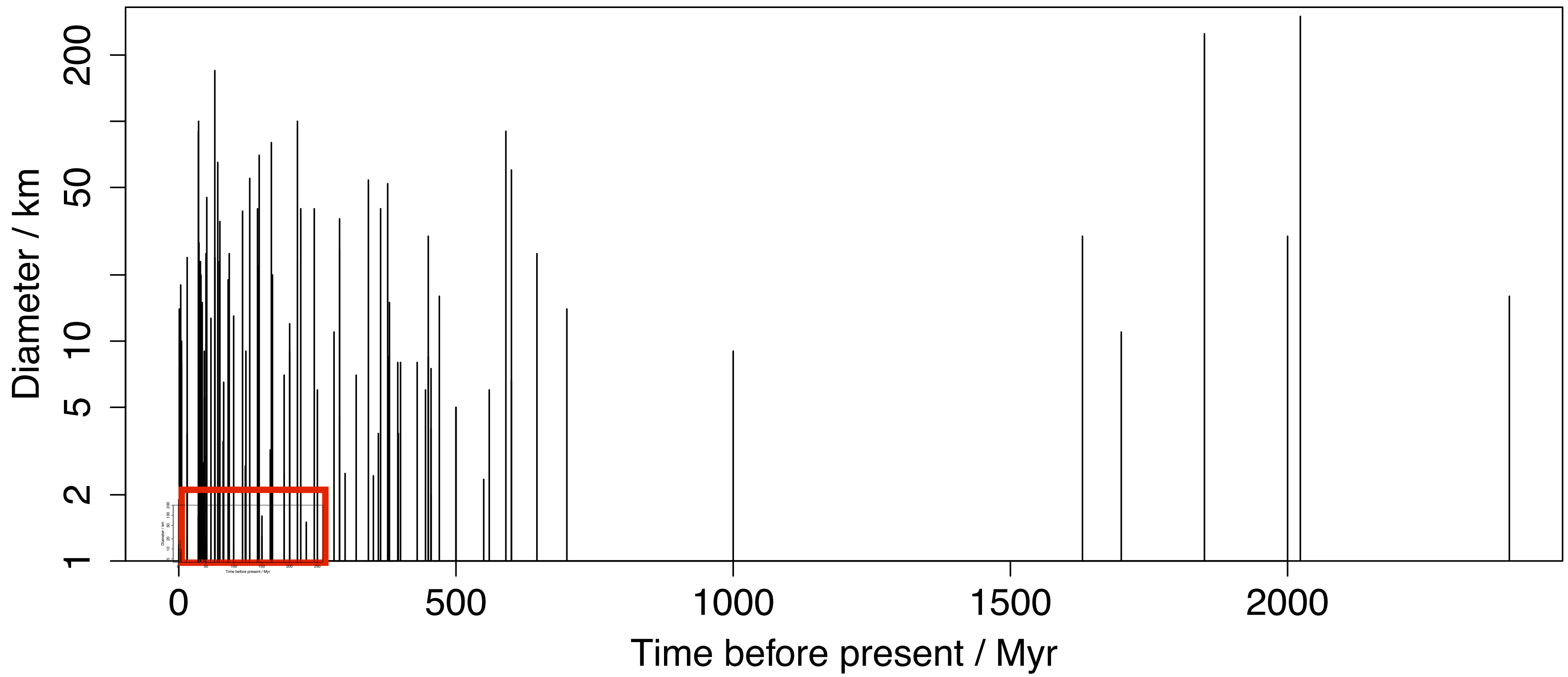
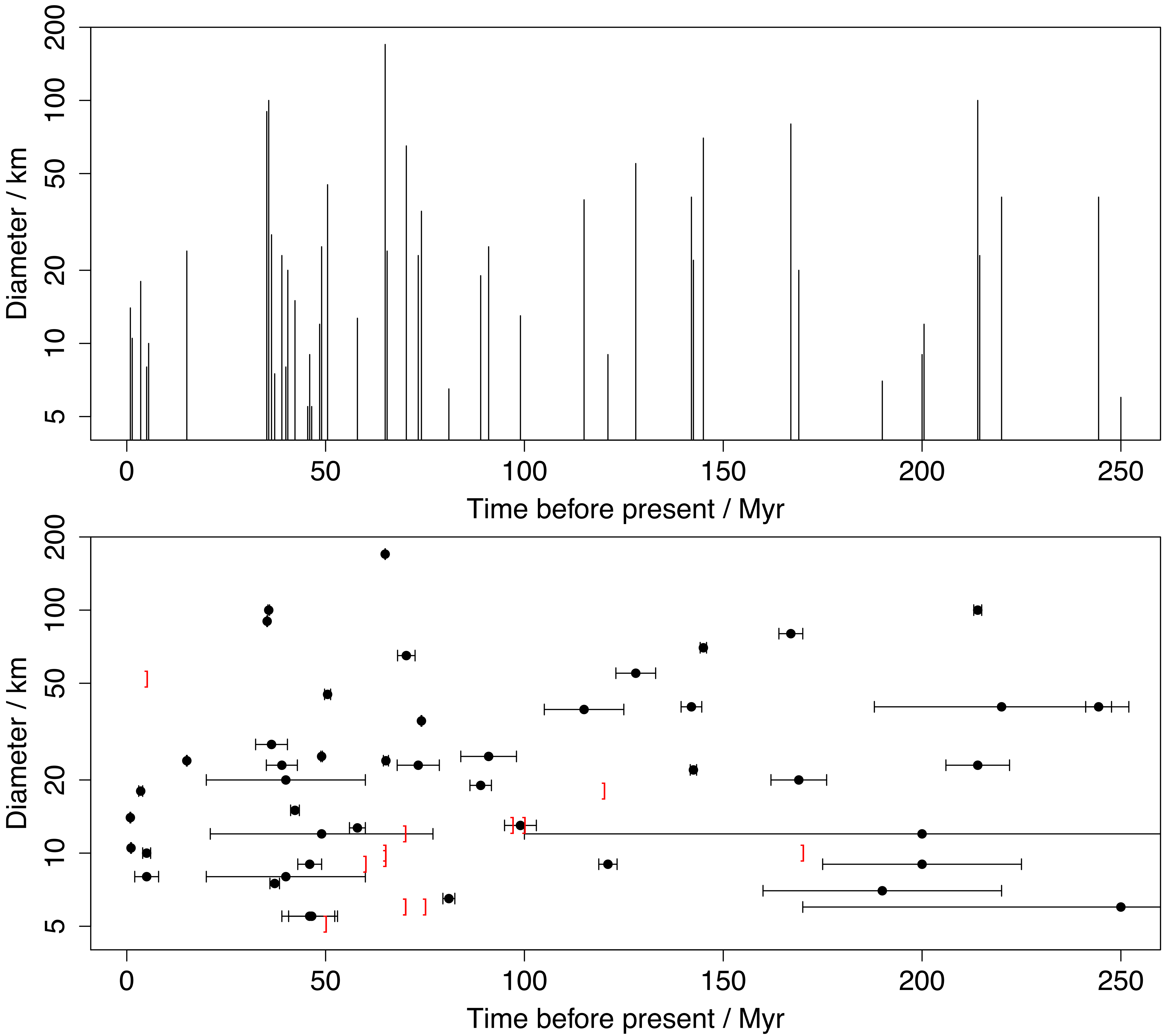
Coryn Bailer-Jones, MPIA

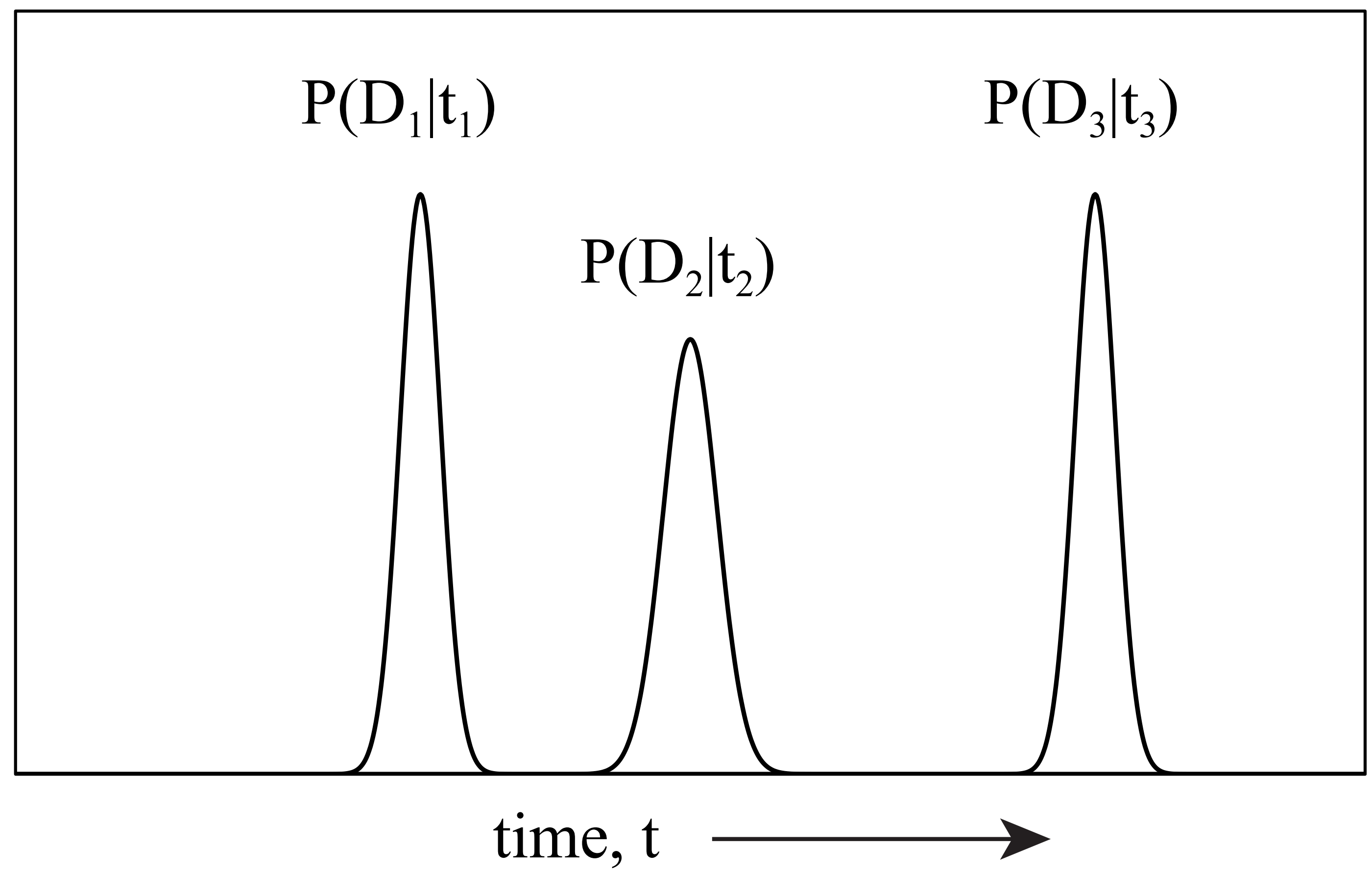
Geological record: impact cratering





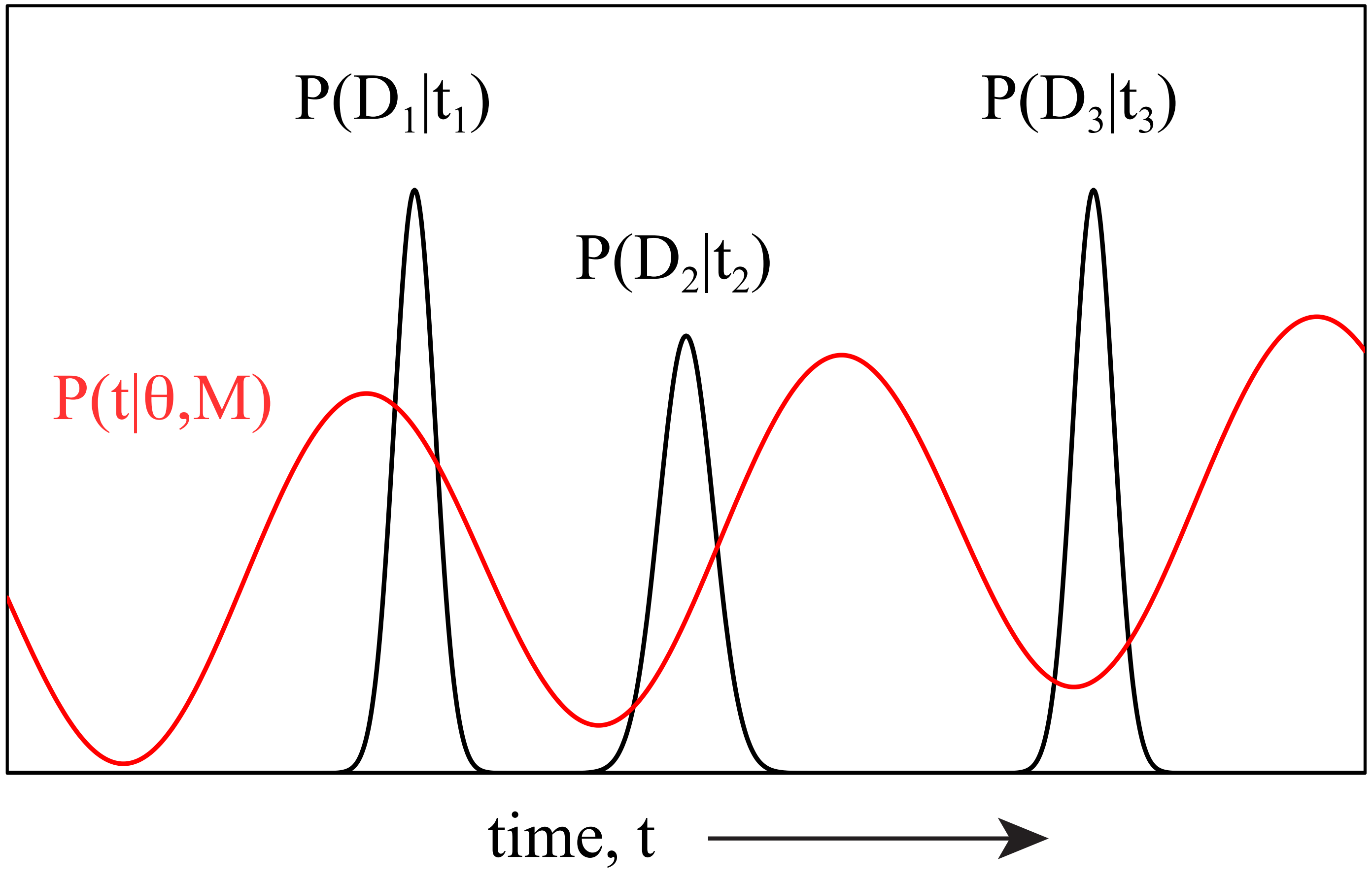
200
100
50
20
10
5
Diameter / km
0
50
100
150
200
250
Time before present / Myr
200
100
50
20
10
5
Diameter / km
0
50
100
150
200
250
Time before present / Myr

Model the events probabilistically



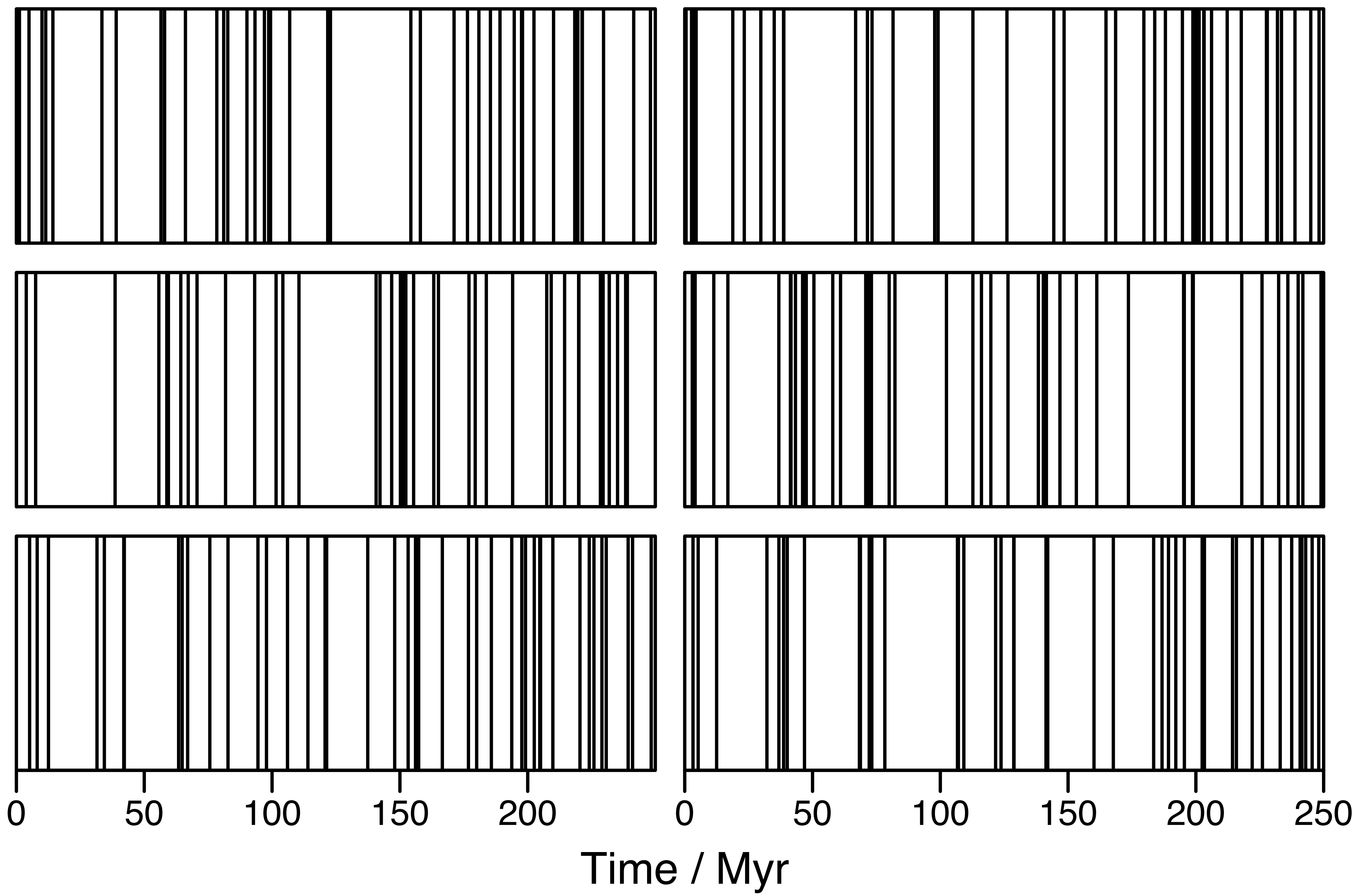
- age measurement, D, is an *estimate* of the true age, t
  - model D as a Gaussian with unknown mean (and standard deviation = measurement error)
- diameter of crater is not used

Model the time-varying probability of impact



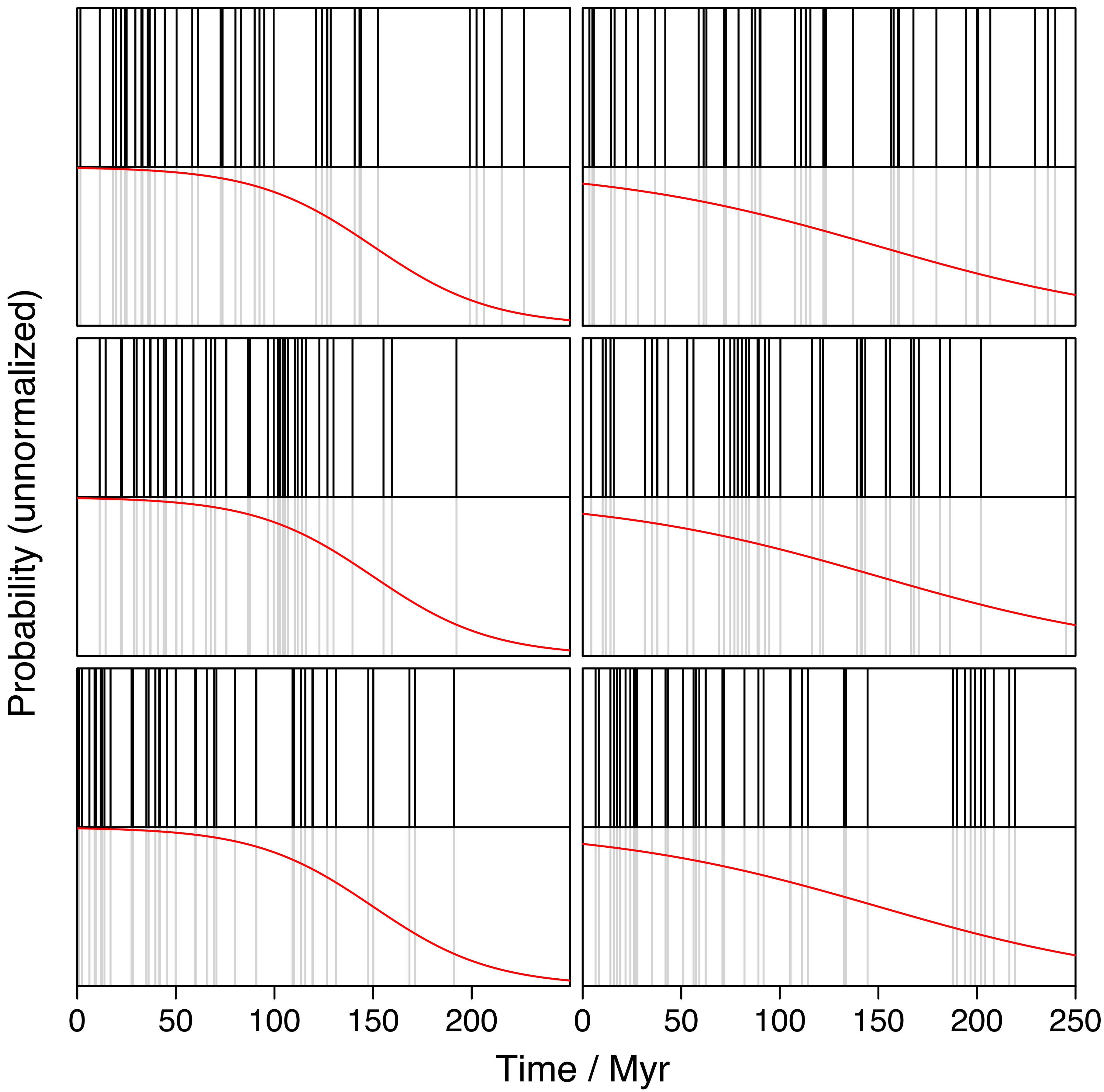
- time series model M with parameters θ
- likelihood for one event: $$P(D_1|\theta, M) = \int_{t_1} P(D_1|t_1)P(t_1|\theta, M)dt$$
- likelihood for all events: $$P(D|\theta, M) = \prod_j \int_{t_j} P(D_j|t_j)P(t_j|\theta, M)dt$$

Simulated time series: uniform model



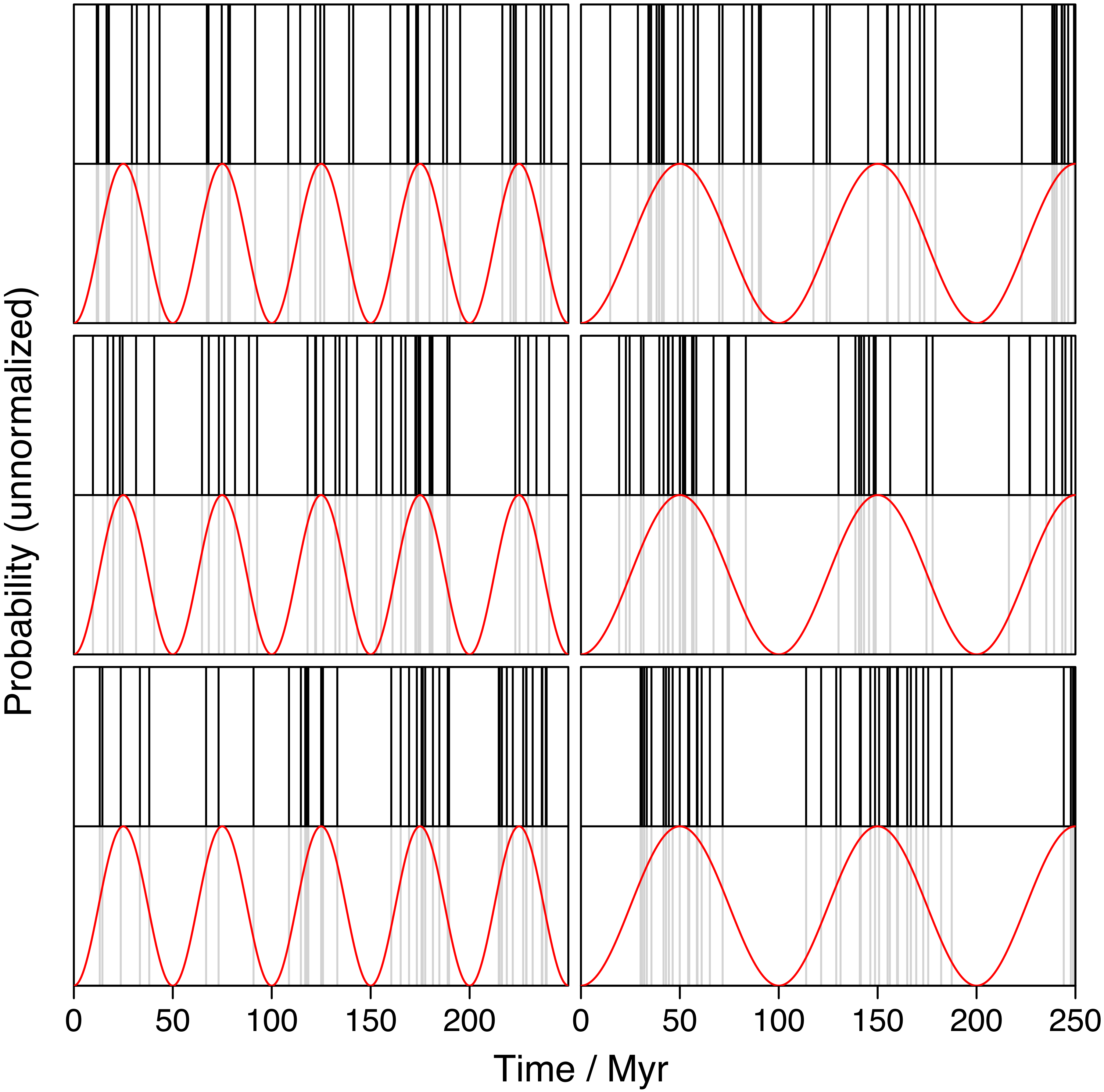
Model parameters: none

Simulated time series: trend model



Sigmoidal function

Model parameters:
slope (lambda)
centre (tzero)



Simulated time series: periodic model

Sinusoidal function

Model parameters:
period
phase

Evidence for a model

- want to know how good model is *overall*
- evidence is likelihood *averaged* over the model parameters
  - formally: the likelihood marginalized over the parameter prior

$$P(D|M) = \int_\theta P(D|\theta, M)P(\theta|M)d\theta$$

- *maximum* likelihood is not appropriate for model assessment
  - because it generally favours the more complex model

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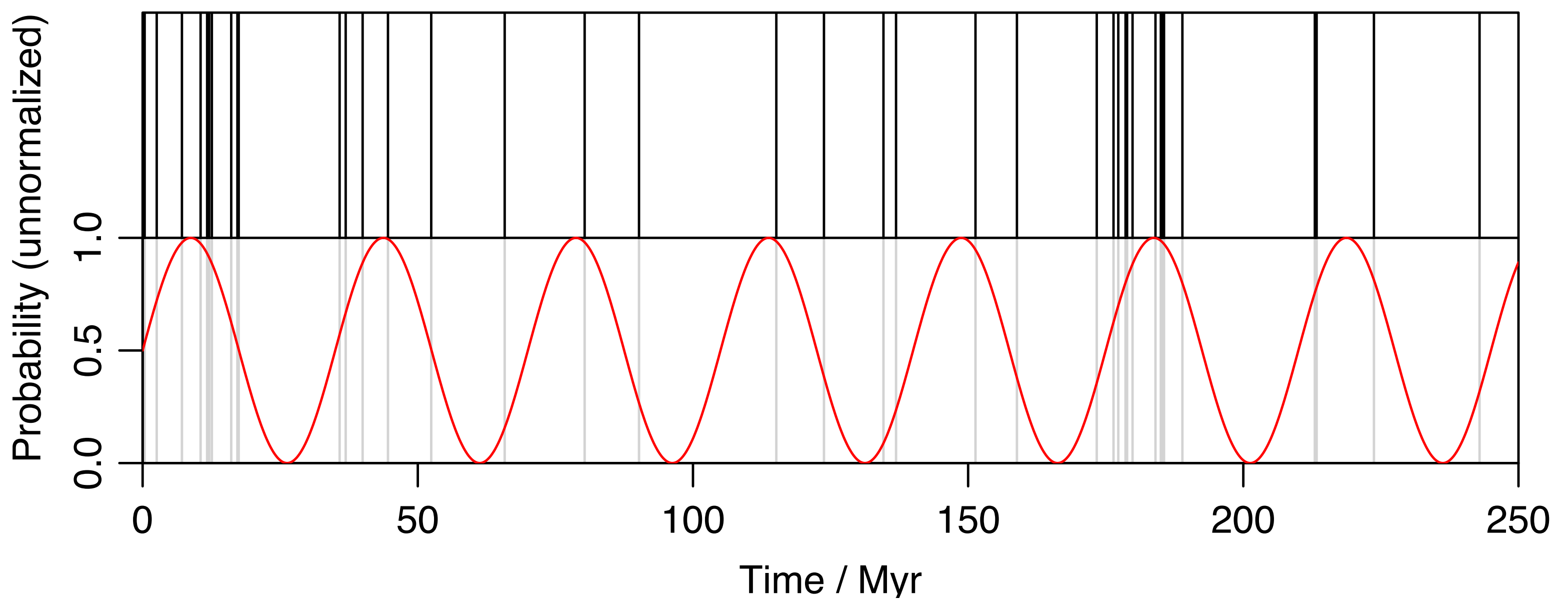
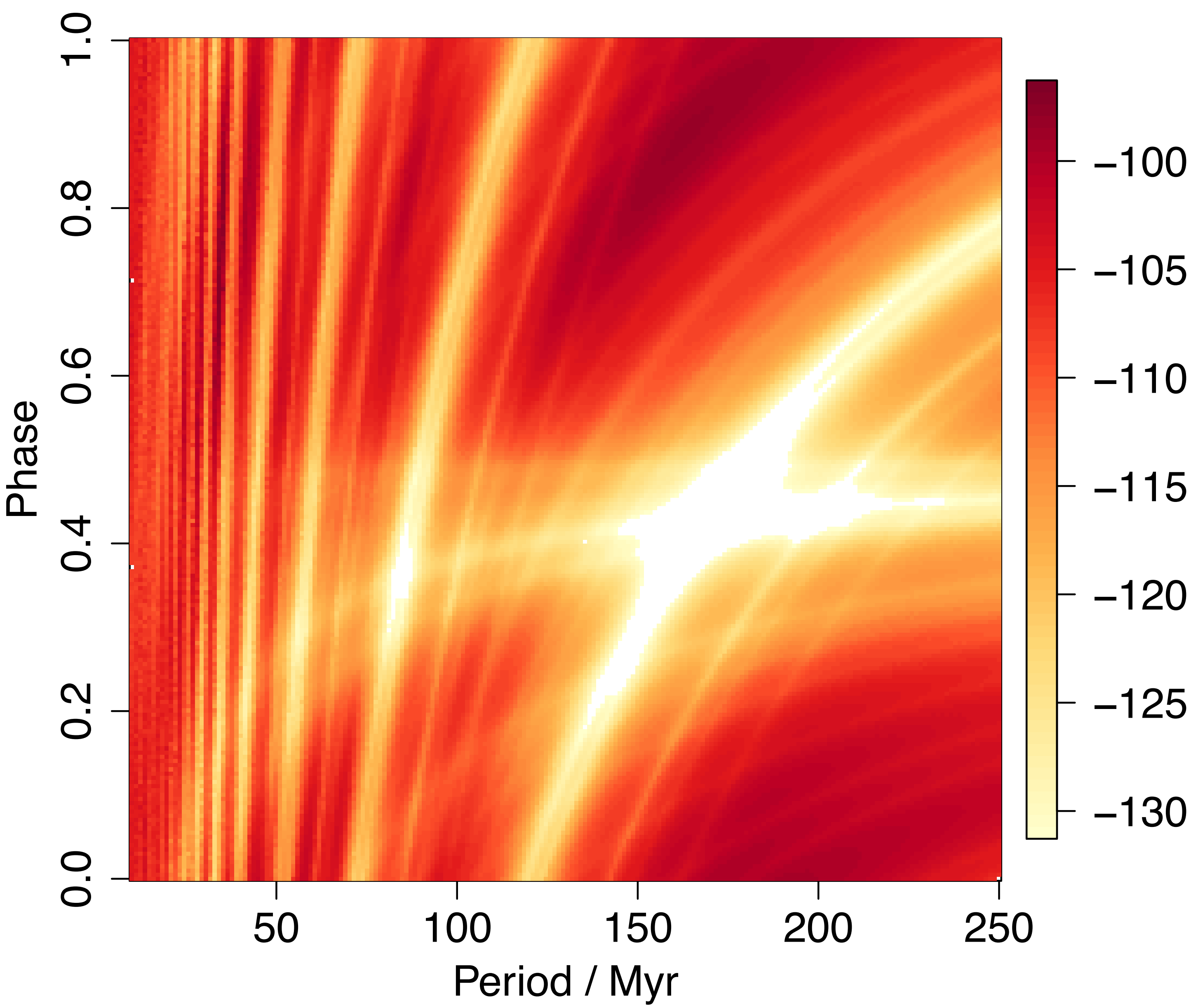


Simulated data set drawn from model with

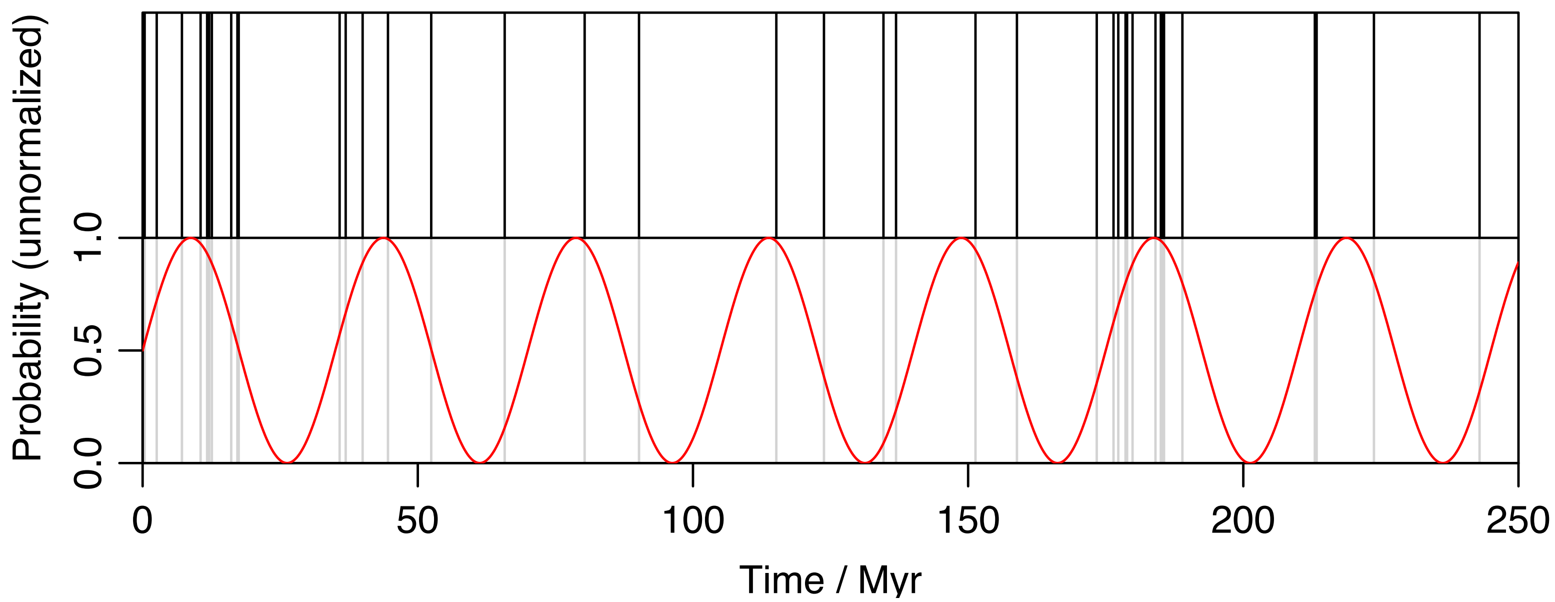
period = 35 Myr
phase = 0.75



log likelihood for the periodic model

Model	**log(Evidence)**
Uniform	-101.05
Periodic10:125	-99.49

Evidence ratio = 36



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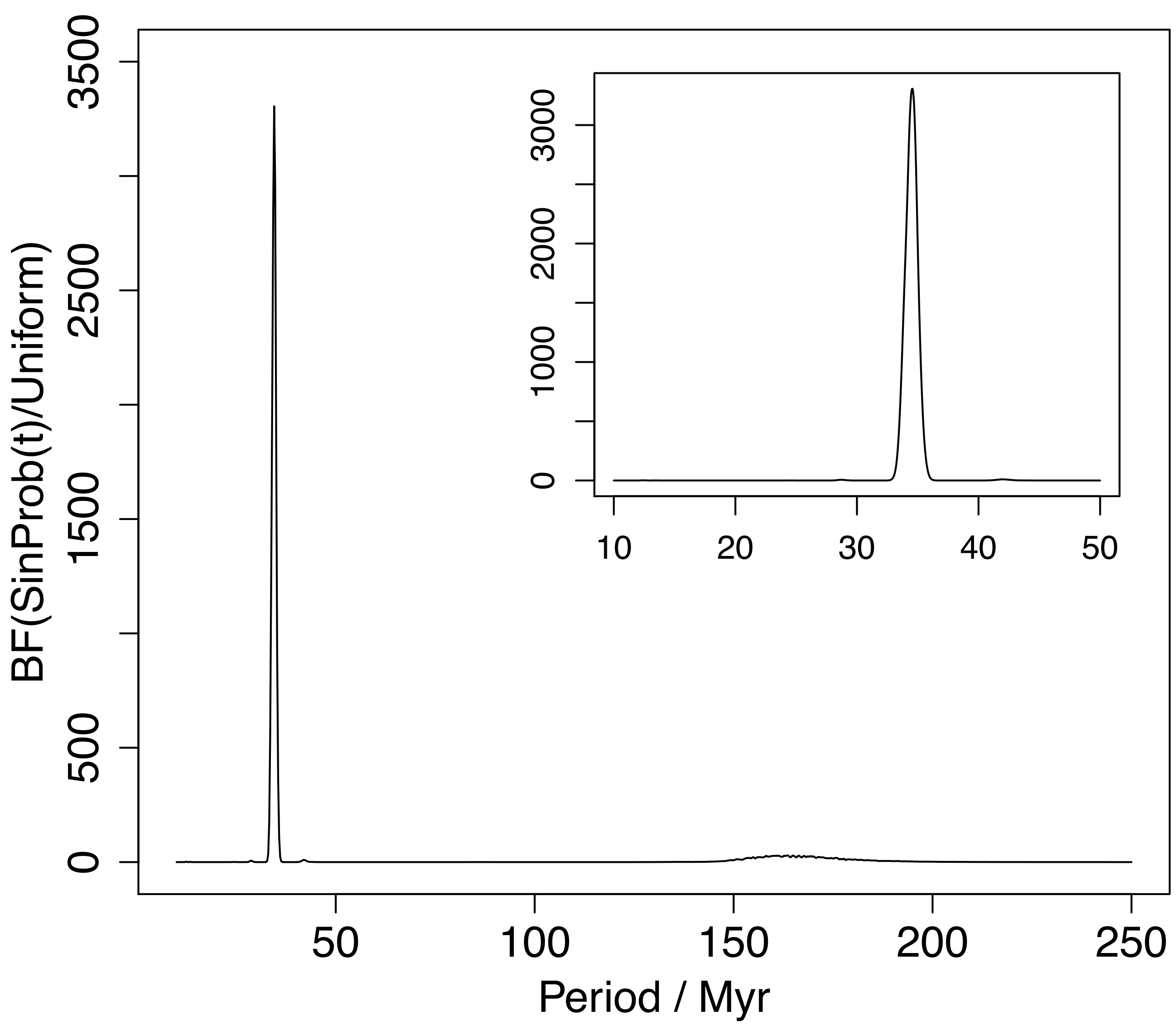
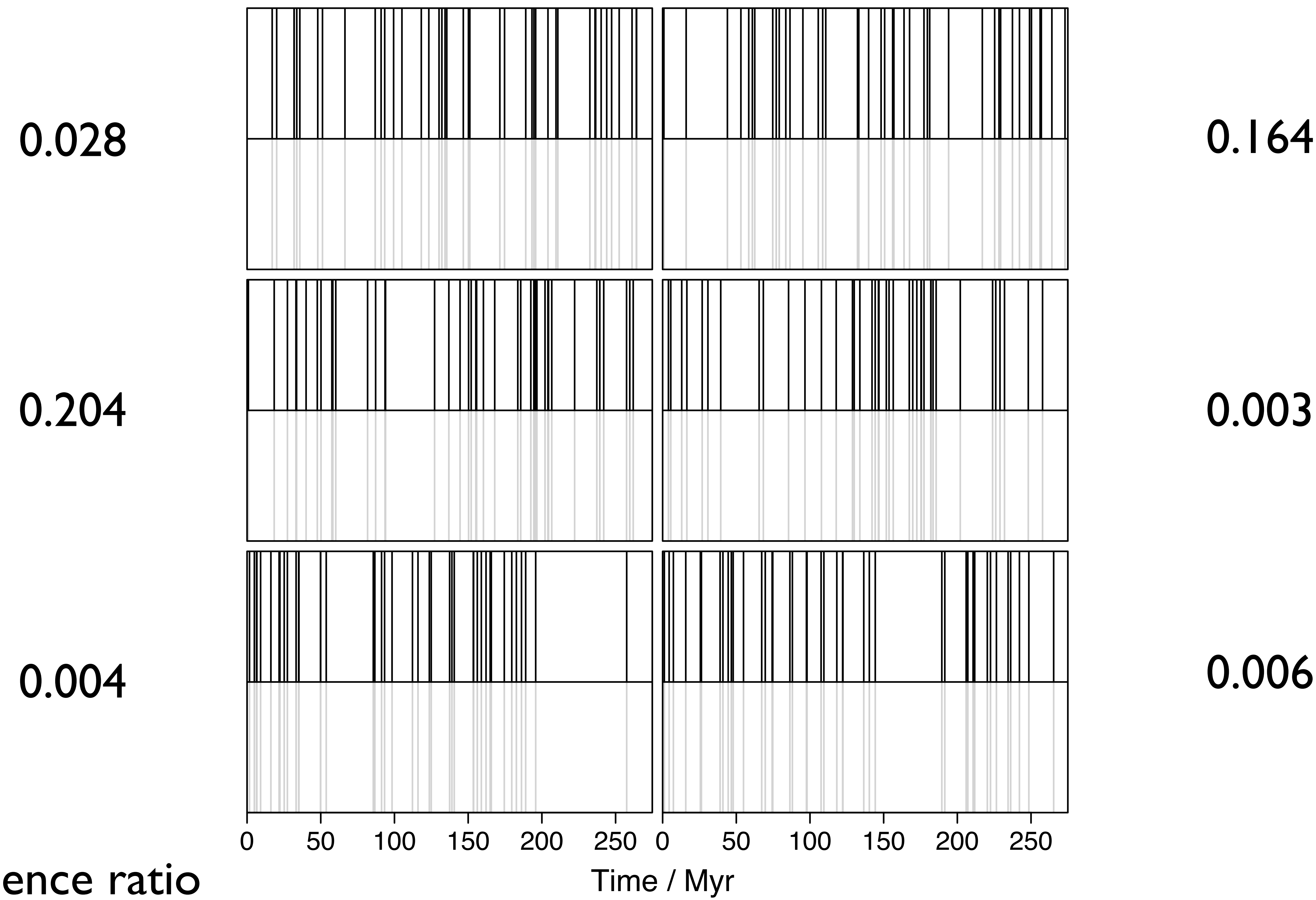


Bayesian periodogram

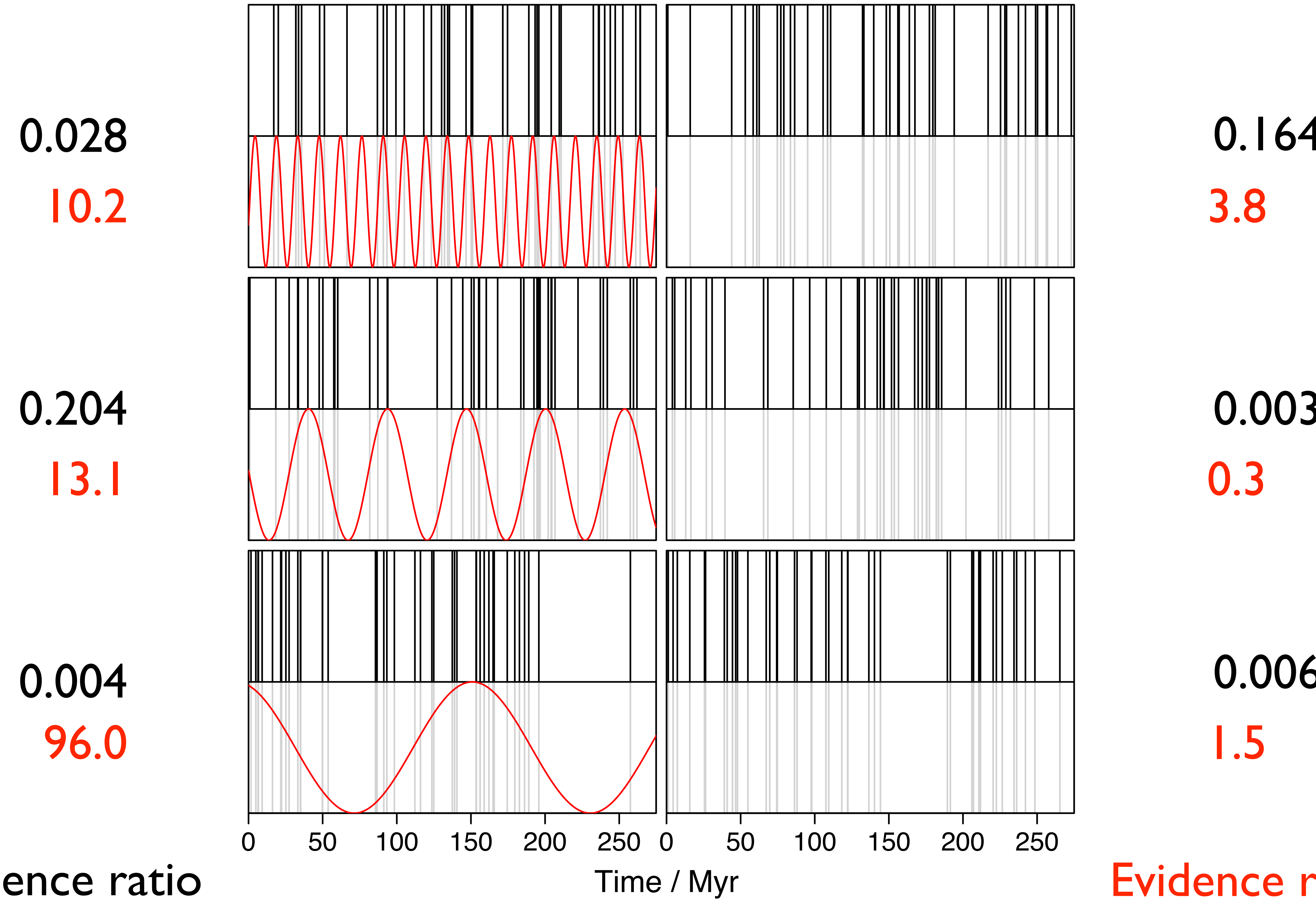
Formed by marginalizing likelihood distribution over phase

Simulated time series: Uniform model



Evidence ratio
(Periodic10:125 / Uniform)

Simulated time series: Uniform model



Evidence ratio
(Periodic10:125 / Uniform)

Evidence ratio
in periodogram peak

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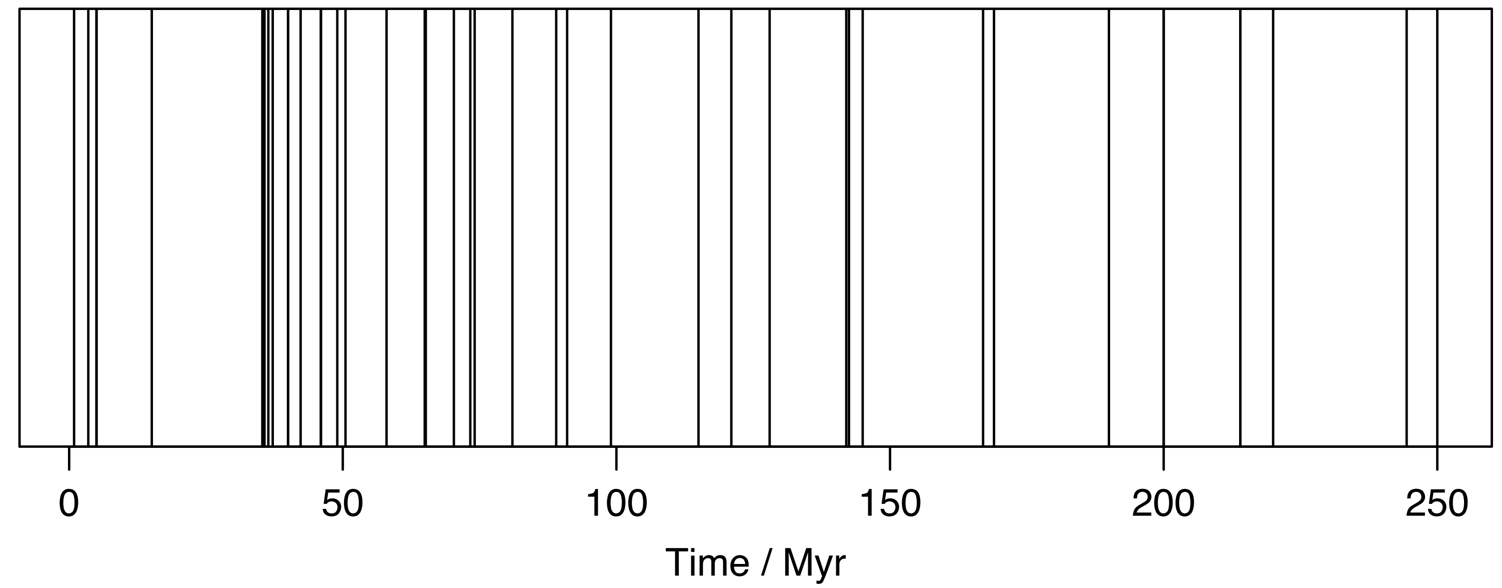
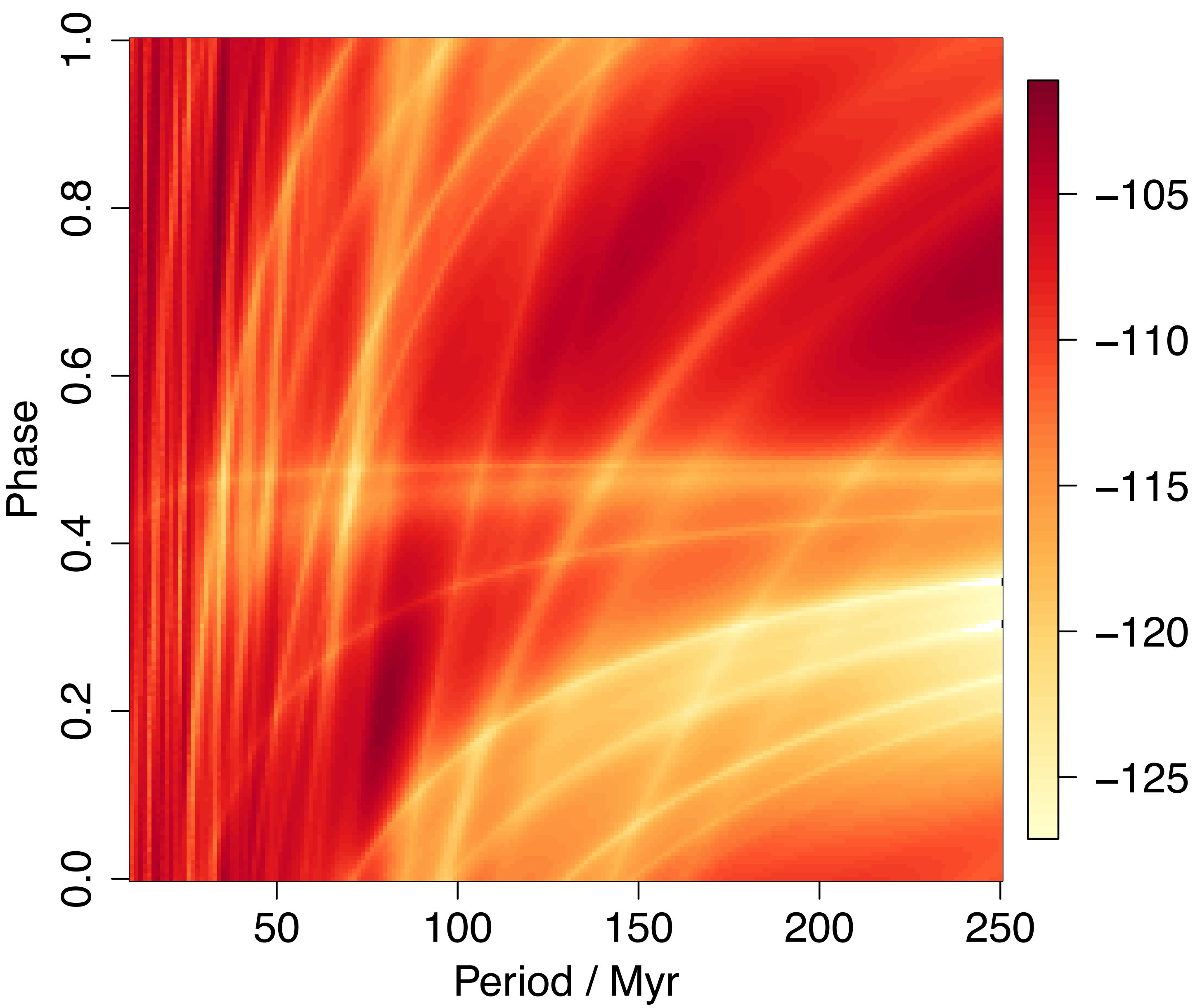
Real cratering data

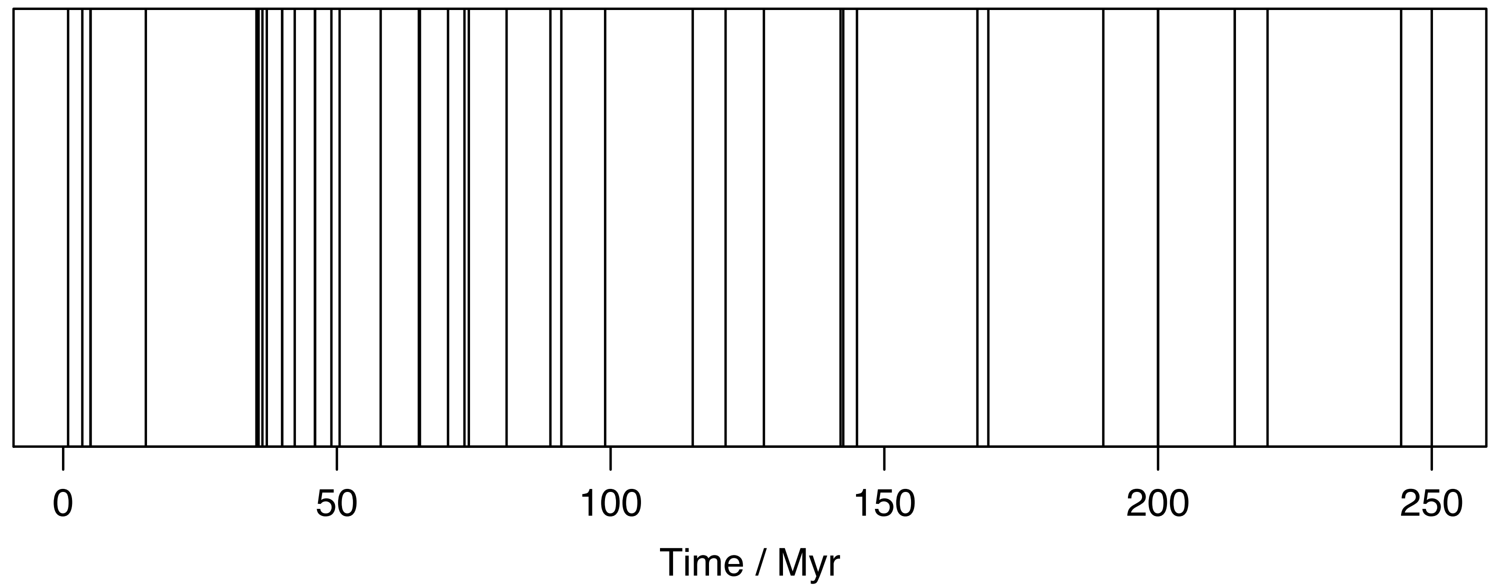




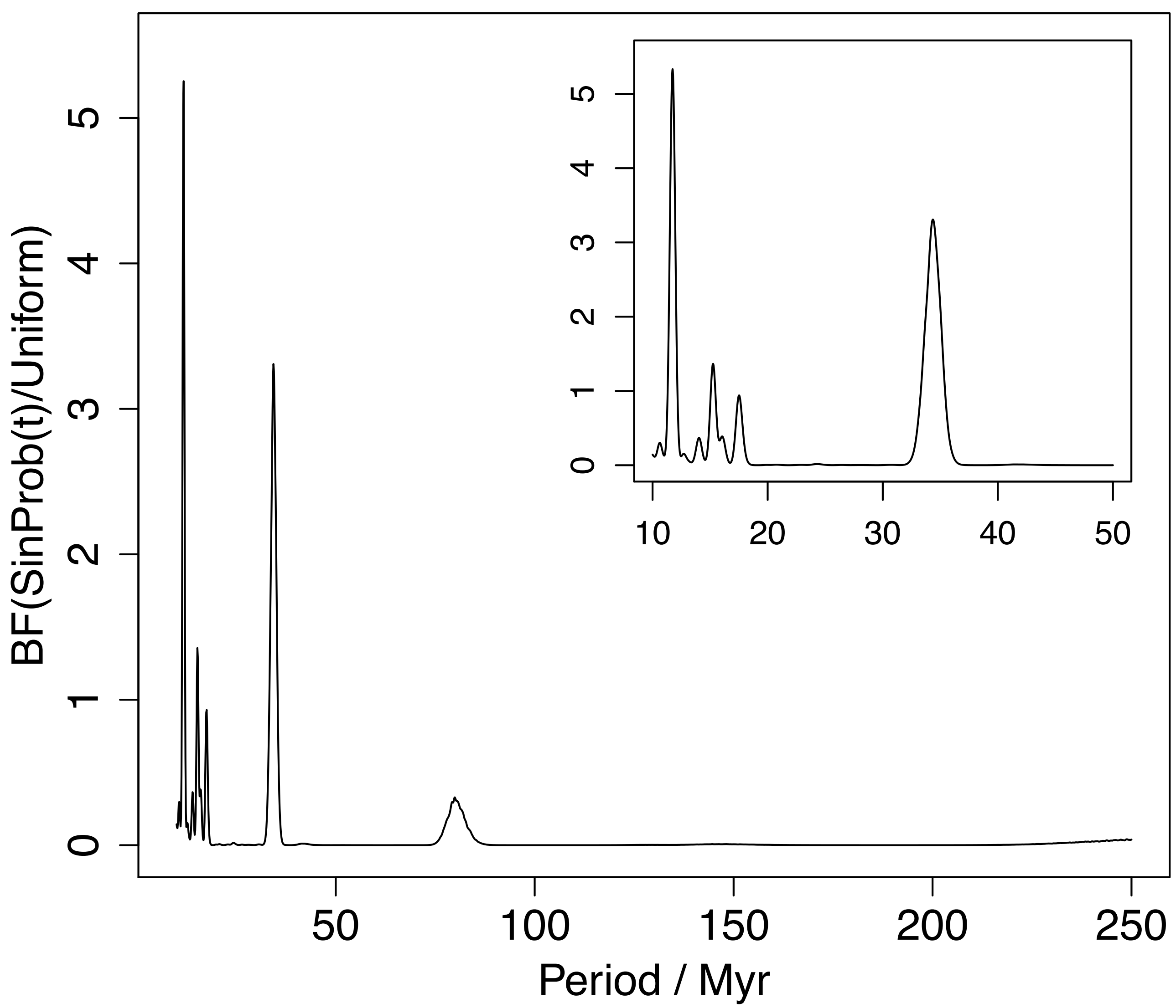
log likelihood for the periodic model

Model	**log(Evidence)**
Uniform	-102.99
Periodic10:125	-103.94

Evidence ratio = 0.11



Real cratering data

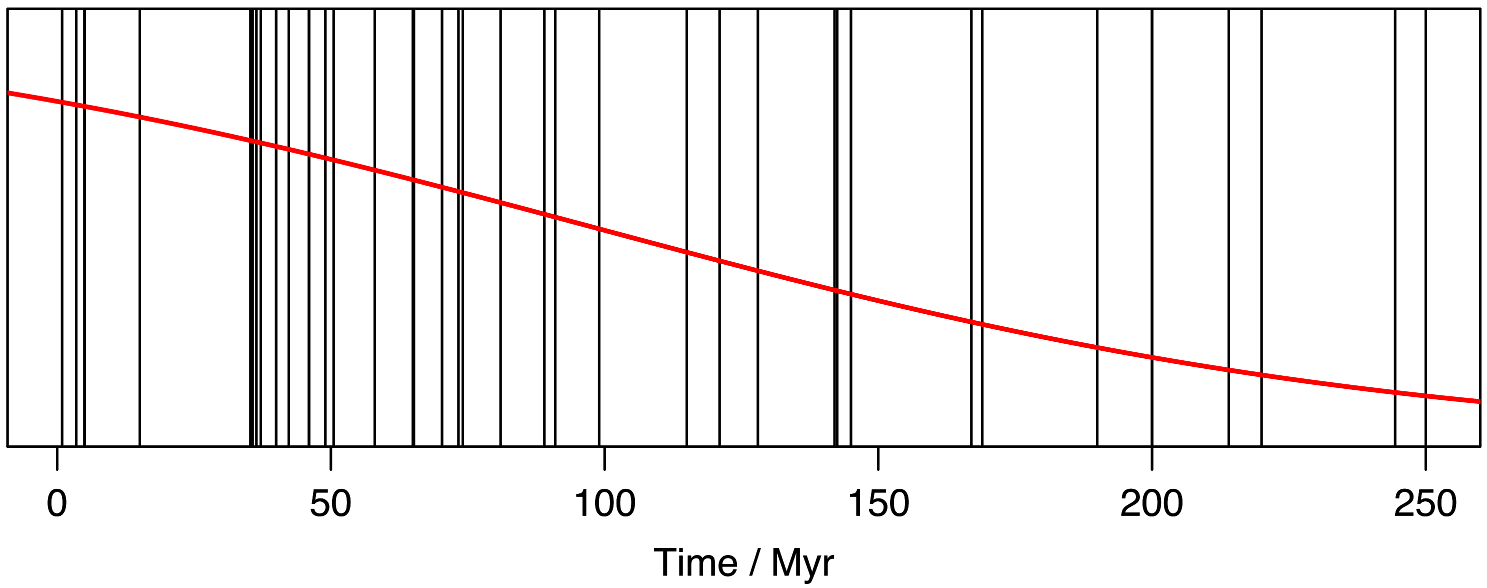


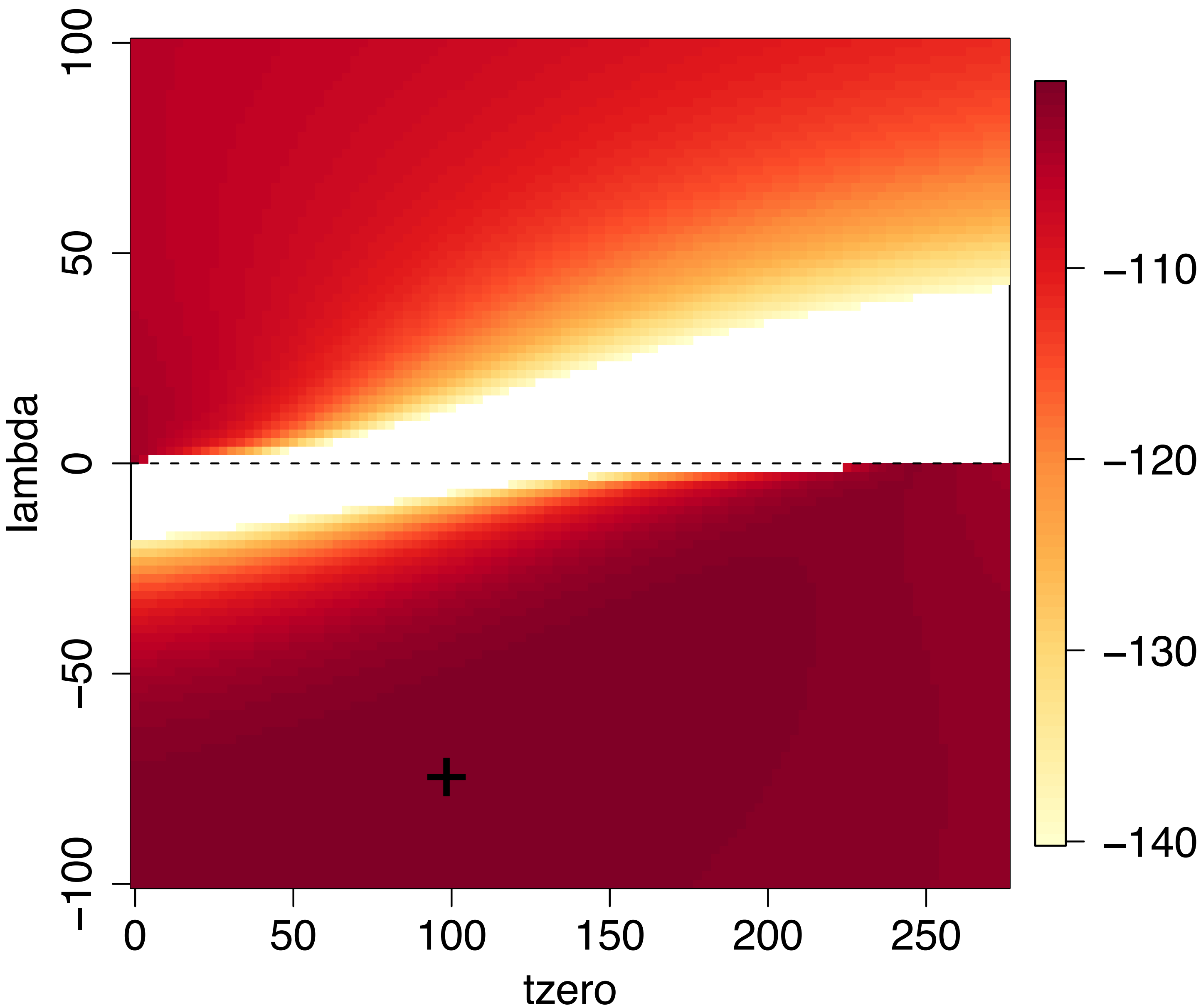
Periodogram for the periodic model

Model	**log(Evidence)**
Uniform	-102.99
Periodic10:125	-103.94

Evidence ratio = 0.11

Real cratering data





log likelihood for the trend (sigmoidal) model

Model	log(Evidence)
Uniform	-102.99
Negative Trend	-100.76

Evidence ratio = 167

Terrestrial impact cratering: conclusions

- no evidence for periodicity in impact crater history over past 250 Myr (d > 5km)
- strong evidence for increase in apparent rate over past 250 Myr
  - predominantly from 150-250 Myr before present
  - even stronger when crater with upper age limits included
  - plausibly a preservation/discovery bias
  - conclusions only refer to models tested!

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Issues with some other studies of astroimpacts

- failure to consider plausible alternative hypotheses
- failure to account for different model complexities
- erroneous concentration on single most probable solutions
- incorrect interpretation of p-values
- Consequence: overestimation of significance of periods

Improving the situation from the astronomical side

- infer the solar environment over the past 500 Myr
  - Galactic potential
  - present solar phase space coordinates
  - Galactic structure (GMCs, spiral arms, ...)
- test the proposed mechanisms, e.g.
  - frequency and effect of nearby SNe
  - time variation in comet/asteroid impact intensity
  - solar and earth orbit variability

Take-home messages

- terrestrial impact cratering
  - no evidence for periods
  - strong evidence for increase in apparent rate. Preservation bias?
- assess a model using the (Bayesian) evidence
  - likelihood *averaged* over parameter (prior distribution)
  - this accounts for the model complexity
  - *maximum* likelihood (e.g. periodogram peaks) not appropriate
- for more see `www.astroimpacts.org`

Extras

Bayesian model comparison

$$P(M_0|D) = \frac{P(D|M_0)P(M_0)}{P(D)}$$

Evidence for model M_0

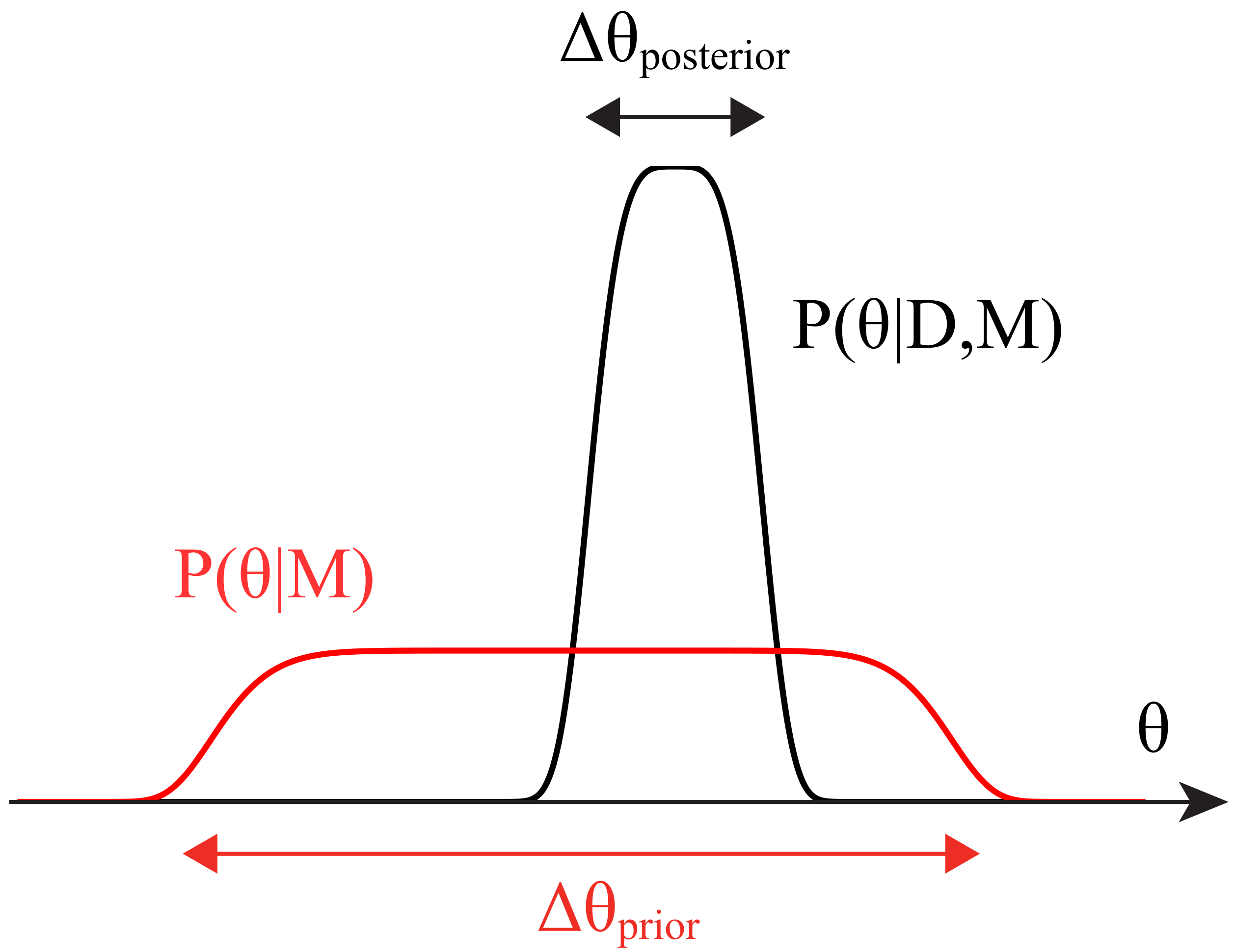
$$= \frac{P(D|M_0)P(M_0)}{\sum_{k=0}^{k=K} P(D|M_k)P(M_k)}$$

$$= \frac{1}{1 + \frac{\sum_{k=1}^{k=K} P(D|M_k)P(M_k)}{P(D|M_0)P(M_0)}}$$

$$= \frac{1}{1 + \frac{P(D|M_1)P(M_1)}{P(D|M_0)P(M_0)}}$$

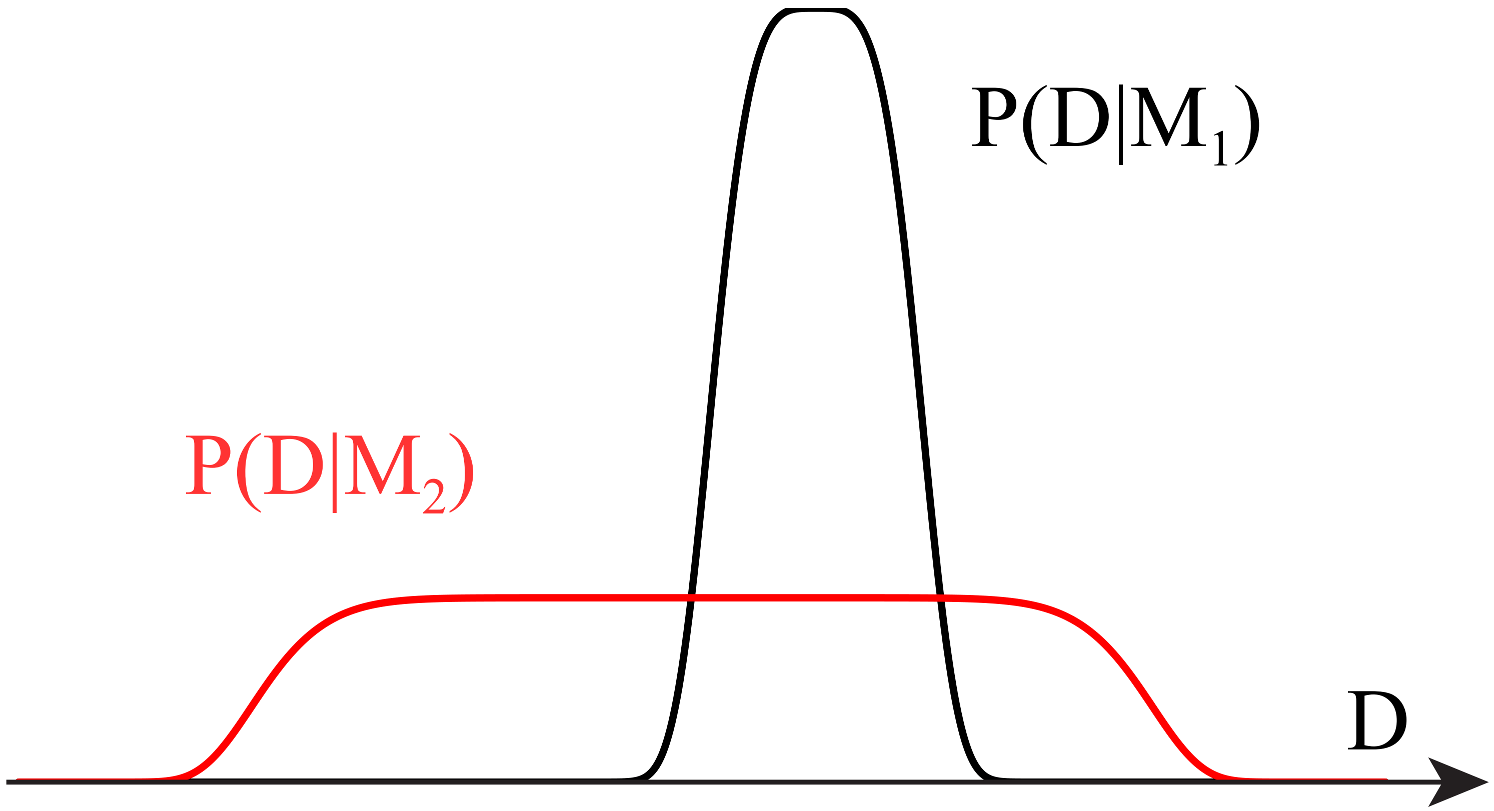
Bayes factor (evidence ratio)

Occam's factor



$$\underbrace{P(D|M)}_{\text{Evidence}} = \underbrace{\mathcal{L}(\hat{\theta})}_{\text{best fit likelihood}} \times \underbrace{\frac{\Delta\theta_{\text{posterior}}}{\Delta\theta_{\text{prior}}}}_{\text{Occam factor}}$$

Evidence and model complexity



Dating craters

- U-238 fission track counting
- cosmogenic nucleides (< 1Myr)
- palaeomagnetism (< 100 Myr)
- biostratigraphy (fossils)
- gas retention age since last rock melt
    - K-40 to Ar-40 radioactive decay ($t_{1/2}$ = 1250Myr)