Principles of Earthquake Forecasting
Short-Term Prediction
Application to Vrancea

apoma Lab

Magurele-Bucharest, 2005

Special day:

Yesterday $M = 3$, Vrancea (one in $5 - 6$ days)
(Institute for Earth's Physics Daily Report)

Prediction: Today an $M > 4.8$ (that can be felt in Bucharest), most likely

Probability ~ 2**%**

Theory validated on the spot!

What means 2% a probability?

Live 50 times the same situation, then you have almost surely one such event!

This means about one $M > 4.8$ surely in one year (50 times $5 - 6$ days), in the next day following one of $M > 3$!

Summary

1 Principles of Earthquake Forecasting

2 Regular Earthquakes. Mean Recurrence Time. Long-Term Forecasting

3 Gutenberg-Richter Magnitude Distribution

4 Statistical Analysis

5 Mean Recurrence Time

Principles of Earthquake Forecasting

-Statistical approach

$$P(M, t, \mathbf{r}, ...) = d^3N/dMdtd\mathbf{r}$$

-A priori knowledge (conditioned probabilities, Bayesian theory)

-Analysis of a statistically significant data set

-Prediction: "what happened will happens again"

-"Shaking" map (effects rate, Mercalli intensity, peak ground acceleration)

$$I(t, \mathbf{r}) = \int dMd\mathbf{r}' I(M, \mathbf{r} - \mathbf{r}')P(M, t, \mathbf{r}')$$

Regular Earthquakes. Mean Recurrence Time. Long-Term Forecasting

(apoLab, 2004-2005)

-Mean recurrence time t_r

-Probability $\sim 1/t_r^2$

-Accumulating seismic energy $t_r \sim E^{1/r}$; geometric exponent $r = 1/3$ (point-like focus)

$r = 1/2$ (two-dimensional fault)

-Gutenberg-Richter $\ln(E/E_0) = bM \quad (b = 3.5)$

Gutenberg-Richter Magnitude Distribution

$$P(M) = \beta e^{-\beta M} \ , \ \ \beta = br$$

-well documented

$$log\ distr \quad \ln(N/T) = \ln(\beta \Delta M/t_0) - \beta M$$

$$exced\ rate \quad \ln(N_{ex}/T) = -\ln(t_0) - \beta M$$

-seismicity rate $1/t_0 = N_0/T$

Statistical Analysis

-Overall, worldwide data (Bullen, 1963) ($5.8 < M < 7.3,\ \ \Delta M = 0.1$)

$$\beta = 1.38\ ,\ (r = 0.39\ ,\ b = 3.5),\ 1/t_0 = 10^{5.5}\ per\ year$$

-Point-like focus model: $\beta = 1.17\ ,\ (r = 1/3\ ,\ b = 3.5)$

-California: $\beta = 2.3,\ r = 0.66,\ 1/t_0 = 10^{7.5}\ per\ year$

-Vrancea (**apoLab, 2005**): $\beta = 1.89\ ,\ (r = 0.54\ ,\ fault),\ 1/t_0 = 10^{4.21}\ per\ year$

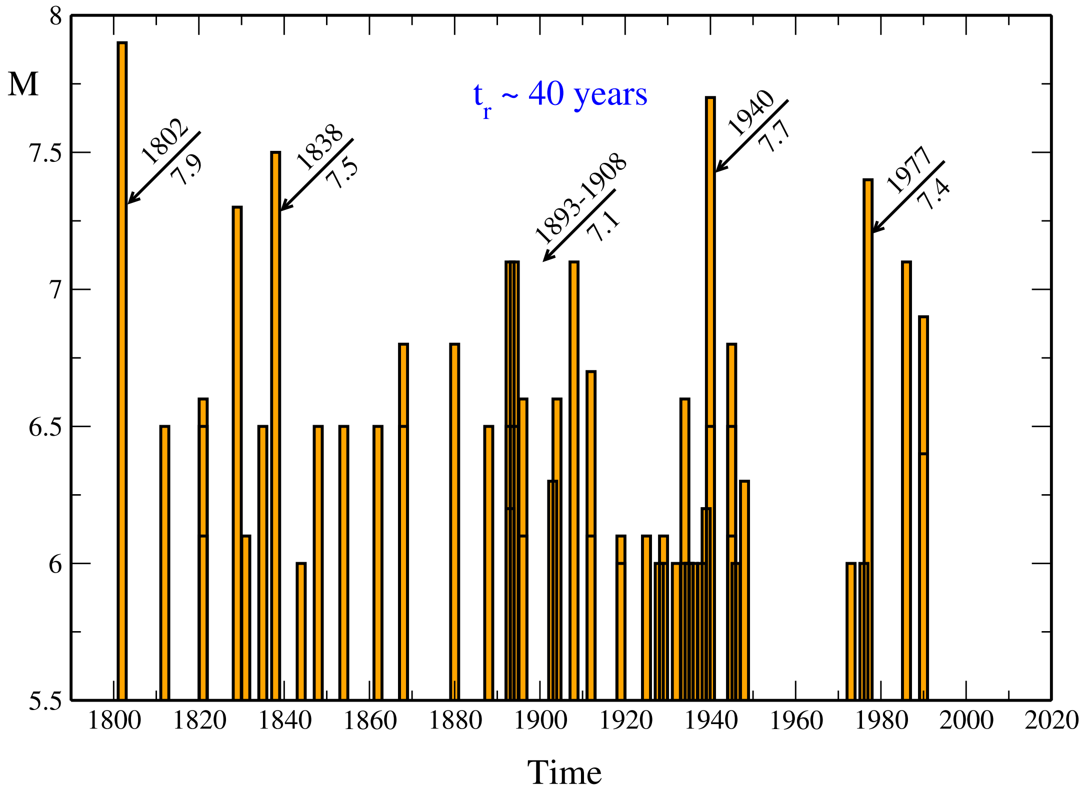
Mean Recurrence Time

$$t_r = (t_0/\beta\Delta M)e^{\beta M} \;\; , \;\; t_{ex} = t_0 e^{\beta M}$$

-Vrancea: $t_r = 34.9$ years $(M > 7)$

-Statistical character, randomness, Poisson assumption $p(t) = t_r e^{-t/t_r}$

-Deviation $(\bar{t^2})^{1/2} - t_r = 0.41 t_r$; $\quad t_r = 34.9 \pm 14.3$ years; little practical use



Vrancea earthquakes with (moment) magnitude $M > 6$ in the last two centuries (Romanian Earthquakes Catalogue, 2005)

Summary

1 Accompanying Seismic Activity. Omori's Law

2 Short-Term Seismic Activity is More Complex

3 California Short-Term Prediction Model

Accompanying Seismic Activity. Omori's Law

(apoLab, 2005)

-Omori's law $dn/d\tau \sim 1/\tau$, aftershocks, or foreshocks

-originating in the self-replication of a generating exponential $\sim e^{-\alpha\tau} = e^{-2\tau/t_r}$

-abrupt fall, long tail

-similar for $m = M_0 - M$; $\sim e^{-\beta m}$; $\bar{m} = 0$, $(\bar{m^2})^{1/2} = \sqrt{2}/\beta = 1.2$ ($\beta = 1.17$); Bath's law

-similar for $1/E$; $dE/d\tau \sim 1/\tau^2$ (emp evidence) ($E \sim 1/\tau$, released energy)

Short-Term Seismic Activity is More Complex

-Omori's law - a particular short-term pattern

$$M = M_0 - \alpha\tau/\beta \ \ (\alpha(M_0))$$

-Scarcity of data (poor statistics), little practical use

-Disentangling accompanying events from the regular ones (especially for long time)

-Any aftershock or foreshock: a "main" shock in turn; multi-branch activity

-M and t independent statistical variables

California Short-Term Prediction Model

$$P(M,t,r) = const \cdot e^{-\beta M} \cdot \frac{1}{t+t_c} \cdot \frac{1}{(r+r_c)^2}$$

-cutoff t_c, cutoff r_c;   ($t \sim r$; area variables$\rightarrow$ $1/r^2$); isotropy; spatial grid 5 km

-time-descending sequences, over a few months, within $M \pm 0.5$

-fit; ongoing sequence; prediction; null hypothesis (former half predicts the later half)

-real-time "shaking" map

Summary

1 Vrancea Focus (Fault)

2 Vrancea Earthquakes

3 Next-Earthquake Probability $P(t)$, $P(M,t)$

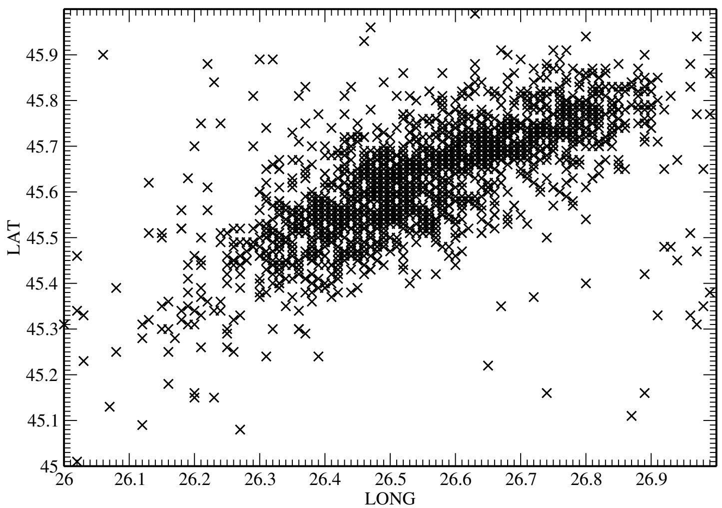
4 Time-Magnitude Distribution for the Next-Earthquake $P(t/M_0)$

$P(M,t/M_0)$

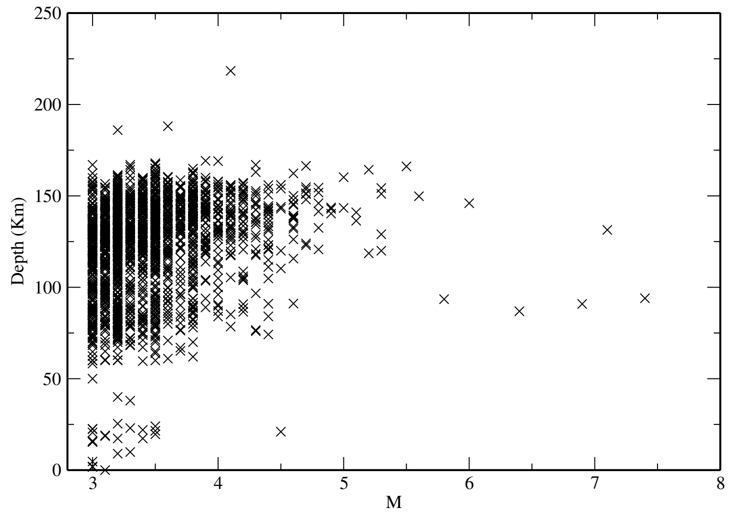
5 Next-Earthquake Time-Magnitude Distribution for Threshold Magnitude $M = 4.7$

6 Conclusions

Vrancea Focus (Fault)



Geographical distribution of 1999 Vrancea earthquakes with (moment) magnitude $M > 3$ recorded between 1974 and 2004 (30 years) within $45^{\circ} - 46^{\circ}$N latitude and $26^{\circ} - 27^{\circ}$E longitude (Romanian Earthquake Catalogue)



Depth distribution of 1999 Vrancea earthquakes with (moment) magnitude $M > 3$ recorded between 1974 and 2004 (30 years) within $45^\circ - 46^\circ$N latitude and $26^\circ - 27^\circ$E longitude (Romanian Earthquake Catalogue)

Vrancea Earthquakes

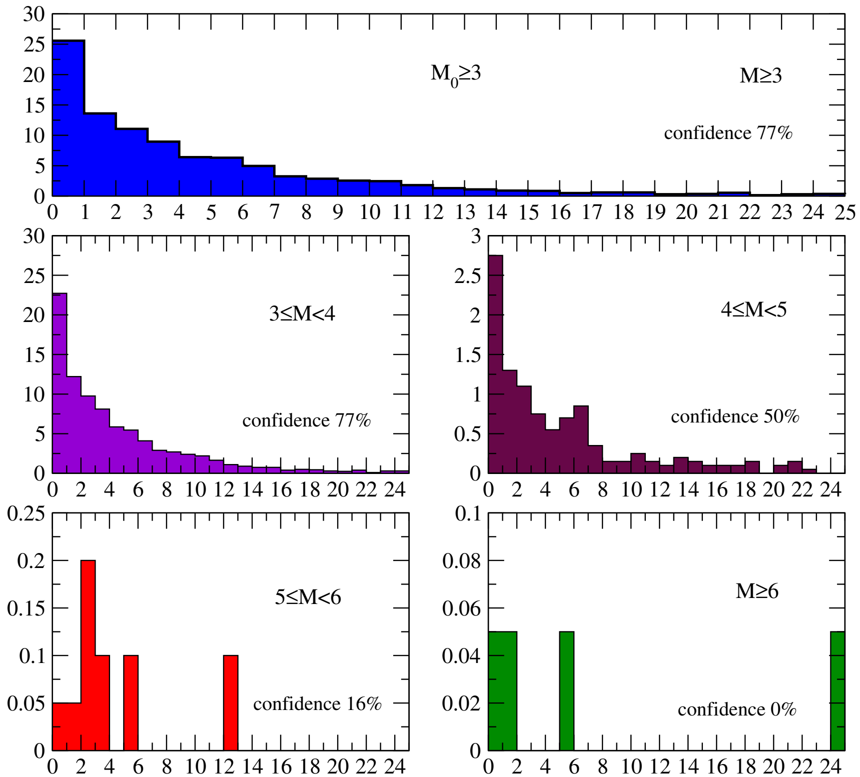
day	N=1998	P(t)%	N(3<M<4)=1769	P(3<M<4,t)%
0	511	25.58	454	22.72
1	272	13.61	244	12.21
2	221	11.06	195	9.76
3	179	8.96	162	8.11
4	128	6.41	117	5.86

N(4<M<5)=211	P(4<M<5,t) %
55	2.75
26	1.30
22	1.10
15	0.75
11	0.55

$N(5<M<6)=13$	$P(5<M<6,t)\%$	$N(6<M<8)=5$	$P(6<M<8,t)\%$
1	0.05	1	0.05
1	0.05	1	0.05
4	0.20	0	0.00
2	0.10	0	0.00
0	0.00	0	0.00

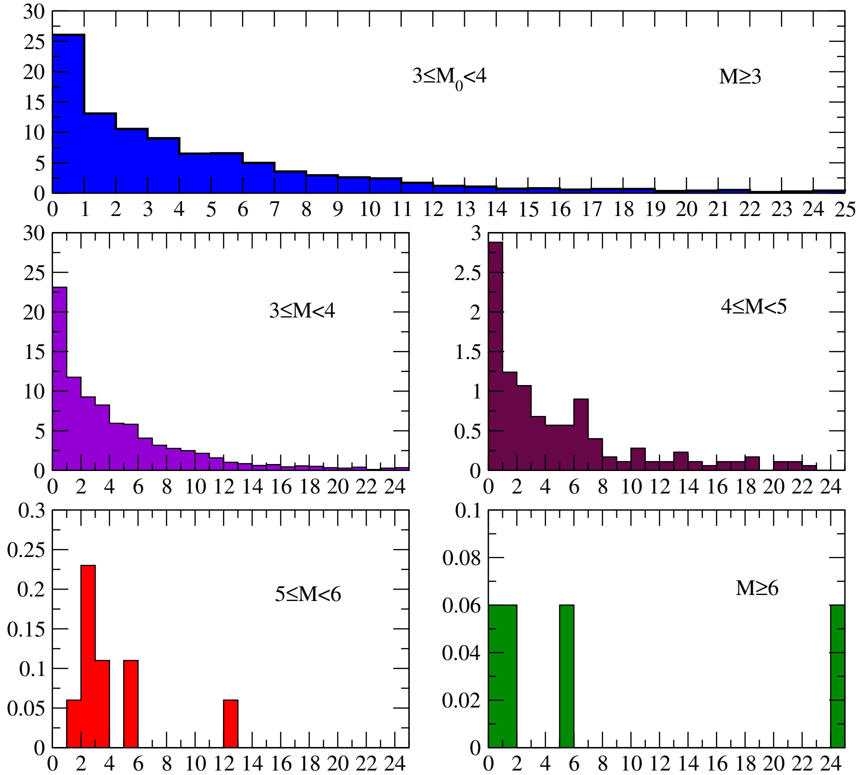
Event distribution for Vrancea next-earthquake (1999 Vrancea earthquakes with (moment) magnitude $M > 3$, recorded between 1974 and 2004 (30 years) within $45^\circ - 46^\circ$N latitude and $26^\circ - 27^\circ$E longitude (Romanian Earthquake Catalogue)

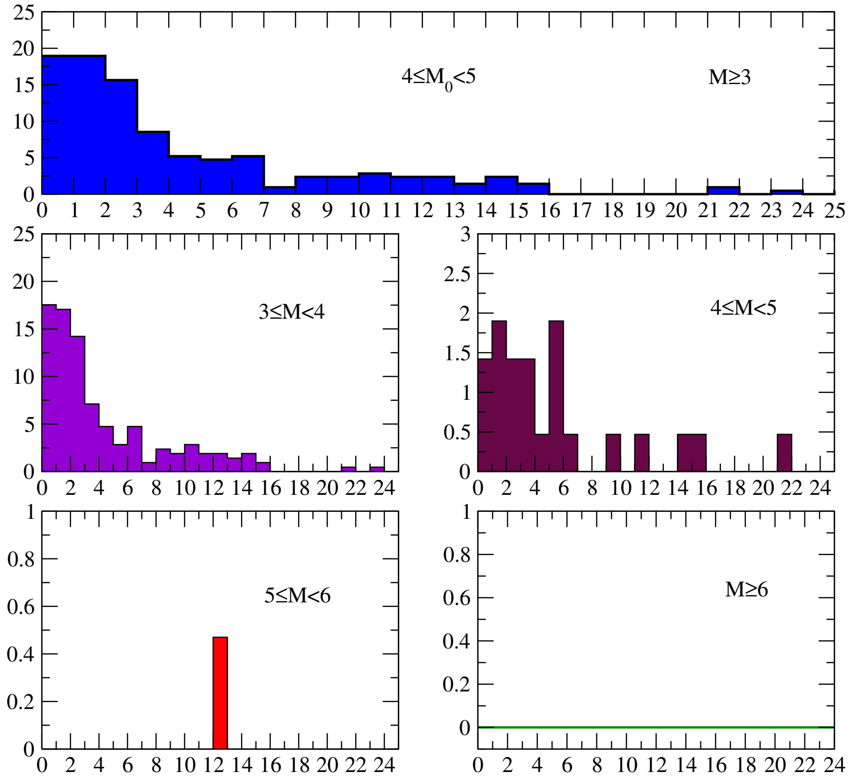
Next-Earthquake Probability $P(t)$, $P(M,t)$



Time-Magnitude Distribution for the Next-Earthquake

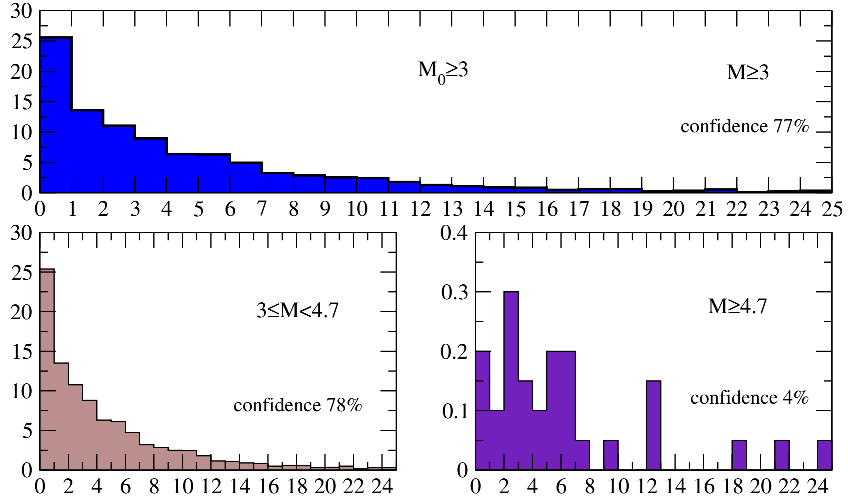
$$P(t/M_0)\ ,\ P(M,t/M_0)$$





4≤M0<5
M≥3
3≤M<4
4≤M<5
5≤M<6
M≥6

Next-Earthquake Time-Magnitude Distribution for Threshold Magnitude $M = 4.7$



Conclusions

-Decrease in time; Omori- type power laws

-Correlation time $\sim 20-25$ days, correlation size $M < 4-5$

-Poor statistics for $M > 5$

-Null hypothesis: first half of data to predict the second half of data; confidence level

Summary

1 Pair Distribution

2 Scaling Time

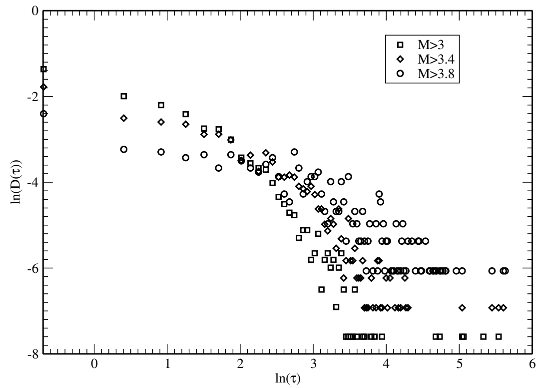
3 Universal Function

4 Prediction for Vrancea $M > 5$

5 Conclusions

Pair Distribution

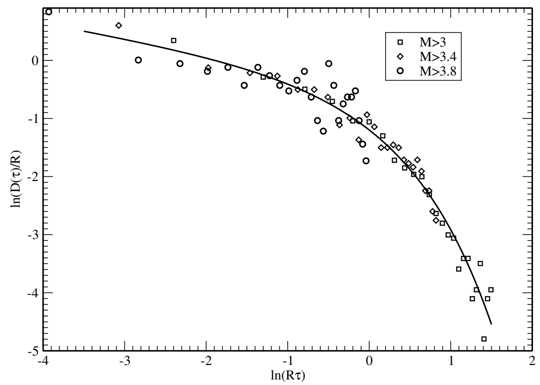
$$D(\tau) = dN/Nd\tau = \frac{1}{N}\sum_i \delta(t_{i+1} - t_i - \tau)$$



Pair distribution vs time (days) for 1999 earthquakes recorded in Vrancea 1974-2004 ($M > 3$)

Scaling Time

$$N = N_{ex} \ , \ R = N_{ex}/T = t_0^{-1} e^{-\beta M_c} \ , \ D(\tau) = Rf(R\tau)$$



Rescaled pair distributions and the fit (solid curve, $r = 0.25$, $B = 1./17$, $C = 0.71$) for 1999 earthquakes recorded in Vrancea between 1974 and 2004 ($M > 3$)

Universal Function

(apoLab 2005)

-$D(\tau) \sim t \sim E^r \sim 1/\tau^r$; $D(\tau) \sim R/(R\tau)^r$: $R\tau \rightarrow 0$; $r = 0.54$, Vrancea

-$R\tau \gg 1$, exponential, uncorrelated, $D(\tau) \sim e^{-R\tau/B}$

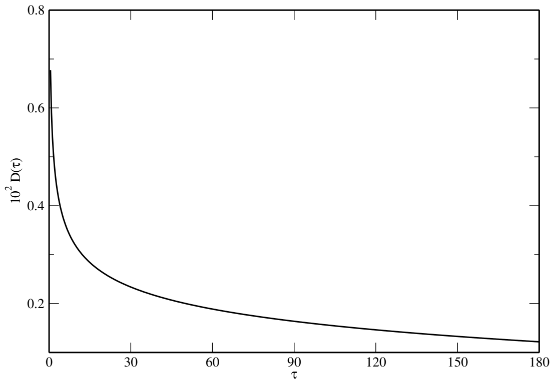
-correction factor $B = R'/R = (1 + e^{bM})^r/e^{brM} \sim 2^r$

-Euler's Gamma class of functions: fitting exponent r

$$D(\tau) = CR \cdot \frac{1}{(R\tau)^r} \cdot e^{-R\tau/B}$$

Prediction for Vrancea $M > 5$

$r = 0.25$, $B = 1.17$, $C = 0.71$ $R = t_0^{-1} e^{-\beta M}$ (fit to recurrence law $\beta = 1.76$, $-\ln t_0 = 8.99$; actually 18 seisms $M > 5$ out of 1999 in 30 years).



Next-earthquake time (days) distribution for Vrancea $M > 5$

For instance, 0.8% to have two $M > 5$ in the same day

Conclusions

-Main feature of earthquakes: seismicity rate $N_{ex}/T = t_0^{-1} e^{-\beta M}$ (their own rhythm)

-Clustering for small τ; inverse-power law (both self-replication and Omori's law and regular seismicity); by accumulating energy spatially and releasing it temporaly!

-Randomness for rare events, Poisson-like