SOCIETÀ ITALIANA DI FISICA - 107° CONGRESSO NAZIONALE

Sezione 4 – Geofisica e fisica dell'ambiente

SEDUTA – Geodinamica, Tettono-fisica, Sismologia

Epidemic-like description for foreshock hypothesis

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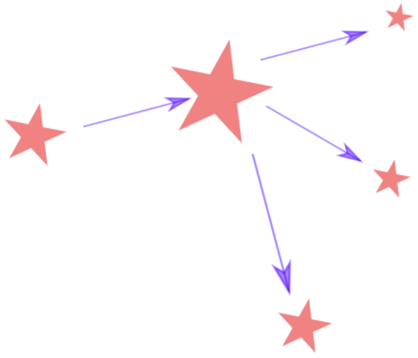
13-17 settembre 2021

Foreshock hypotesis

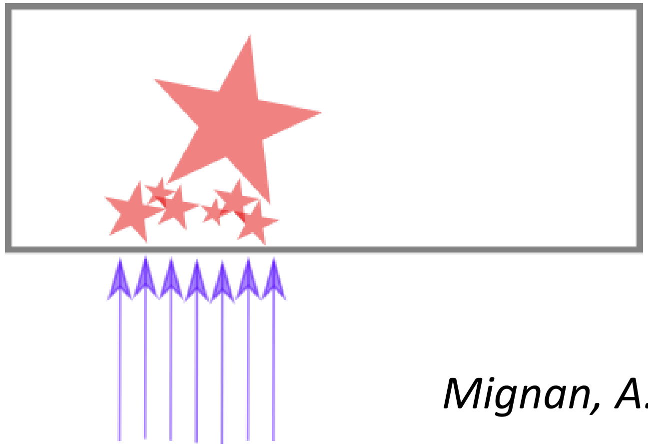
Bottom-up triggering

Earthquake triggering. A background event can trigger aftershocks, which in turn can trigger their own aftershocks. **If we assume that the magnitude of a descendant can be larger that the triggering one**, we can have a foreshock.



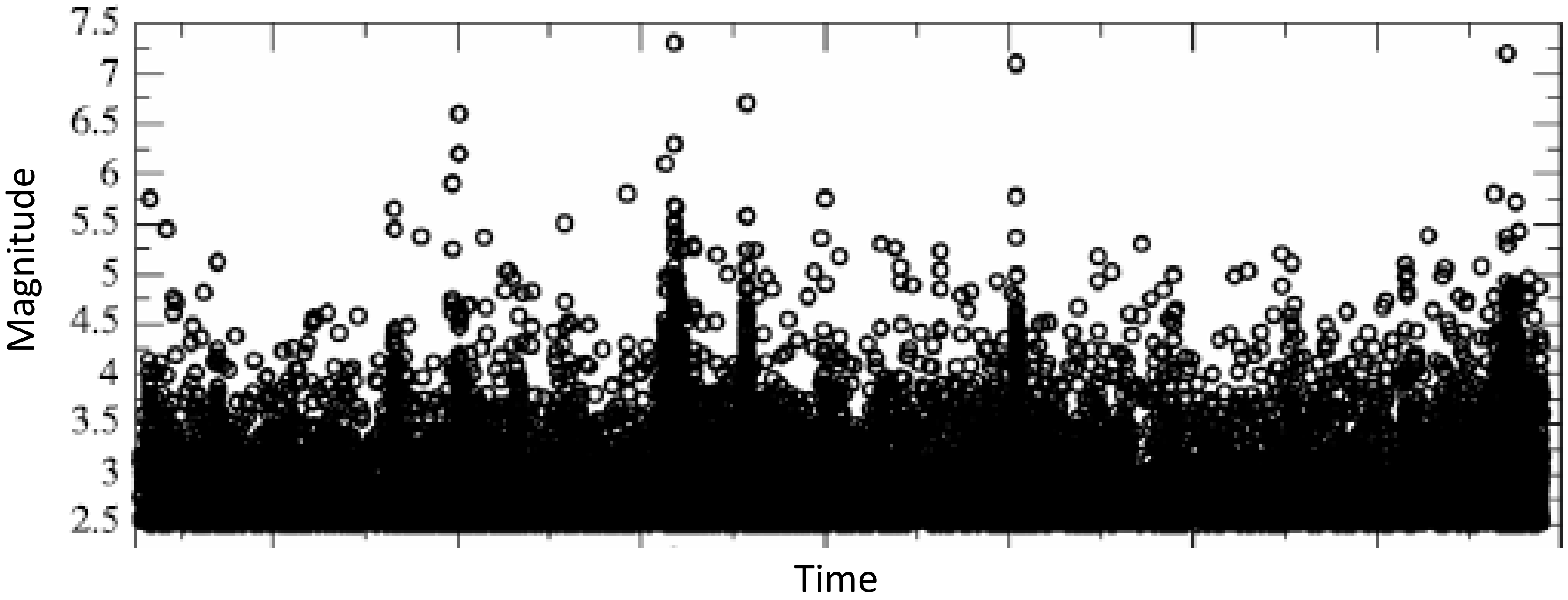
Top-down loading

Tectonic preparatory process. Foreshocks are events due to the stress accumulation caused by aseismic slip which anticipates the mainshock occurrence.

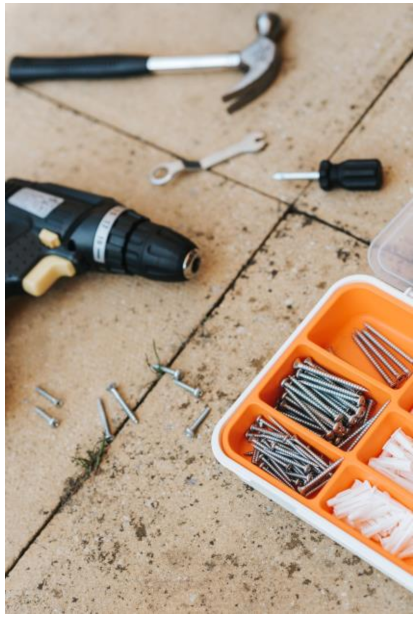


Mignan, A. Sci Rep 4 (2014)

The Epidemic Type Aftershock Sequence (ETAS) is considered the standard model for testing hypoteses associated with earthquake clusters



Fixing the issues of the ETAS model by searching appropriate corrections



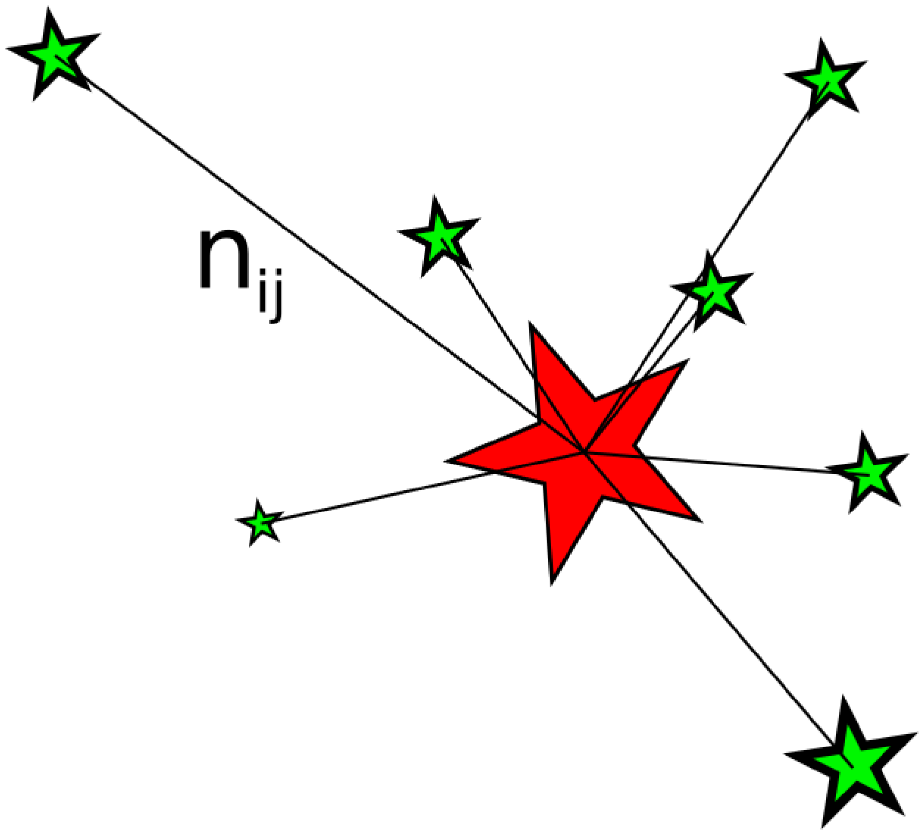
Validate the new model by means of a rigorous statistical test

Aftershock and Foreshock definitions

Baiesi-Paczuski-Zaliapin-Ben-Zion (BPZB)

The i-th event is linked to the previous j-th event with the smallest distance n_{ij} or it is not linked to previous events if $\eta_{ij} > \eta_c, \forall j$.

$$\boldsymbol{\eta_{ij}} = \boldsymbol{\eta_{ij}}[(\boldsymbol{t_i} - \boldsymbol{t_j}), \boldsymbol{d_{ij}}, \boldsymbol{m_j}]$$



Baiesi M. & Paczuski M, Phys. Rev. E (2004)

Measured Quantity

$$n_a(T, R, m_L, m_M) \qquad\qquad n_f(T, R, m_L, m_M)$$

The total number of aftershocks (n_a) and foreshocks (n_f) with magnitude $m \in [m_L, m_L + 0.5)$, with $dt_M < T$ and $dr_M < R$, linked to mainshocks with magnitude $m \in [m_M, m_M + 1)$.

Time difference between the mainshock and the event considered

Spatial difference between the mainshock and the event considered

ETAS$_{fix}$ Model

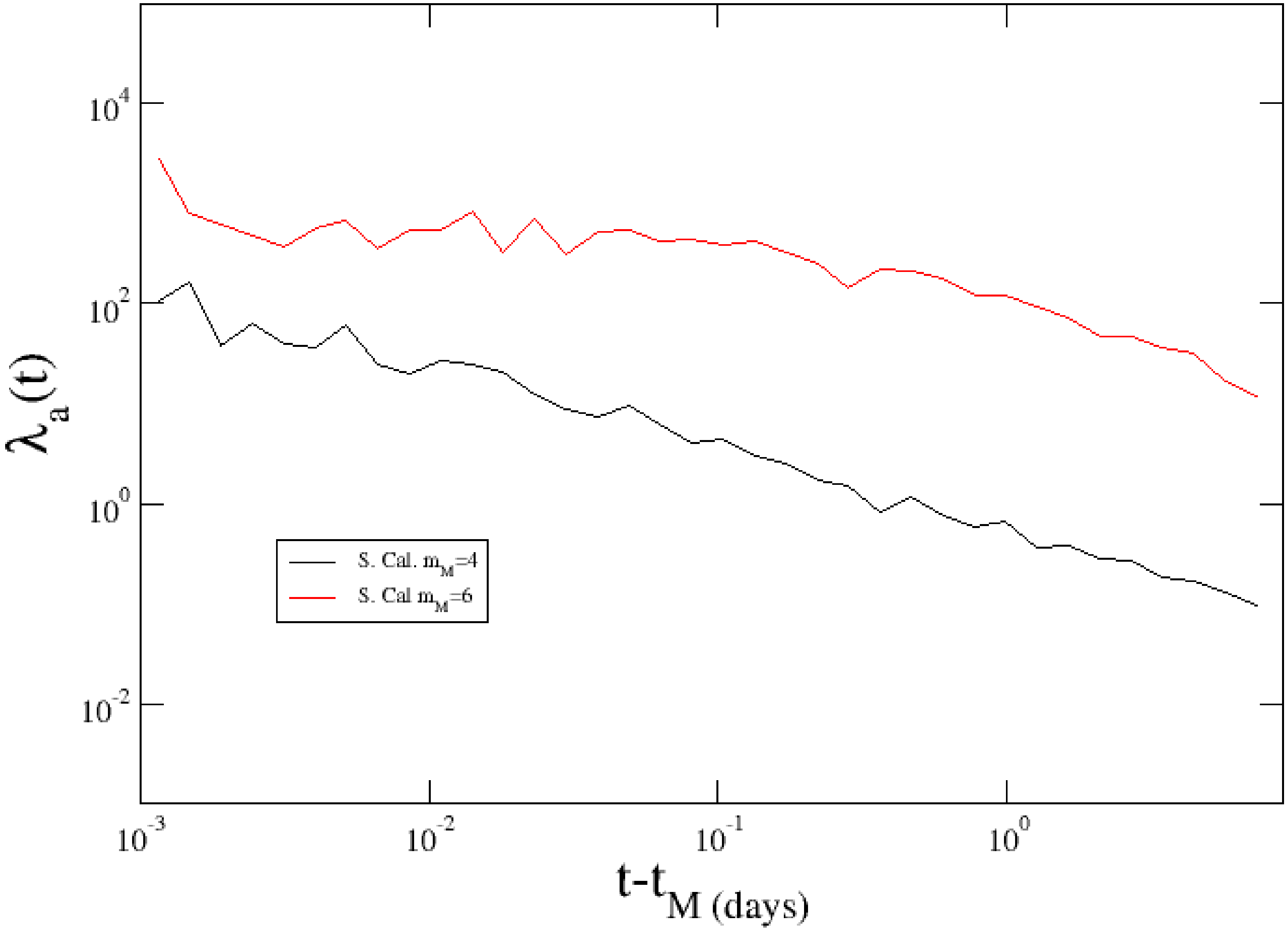
$$\Lambda_{ETAS}(m, x_i, t) = \left[\mu(x_i) + \sum_{j:t_j<t} Q\left(d_{ij}, t - t_i, m_i\right)\right] \frac{1}{b\log(10)} 10^{-b(m-m_0)}$$

$$Q(d_{ij}, t - t_i, m_i) = \frac{K_0(p-1)}{c} \frac{q-1}{\pi d 10^{\gamma(m_j - m_0)}} 10^{\alpha(m_j - m_0)} \left(1 + \frac{t - t_i}{c}\right)^{-p} \left(1 + \frac{d_{ij}^2}{d 10^{\gamma(m_j . m_0)}}\right)^{-q}$$

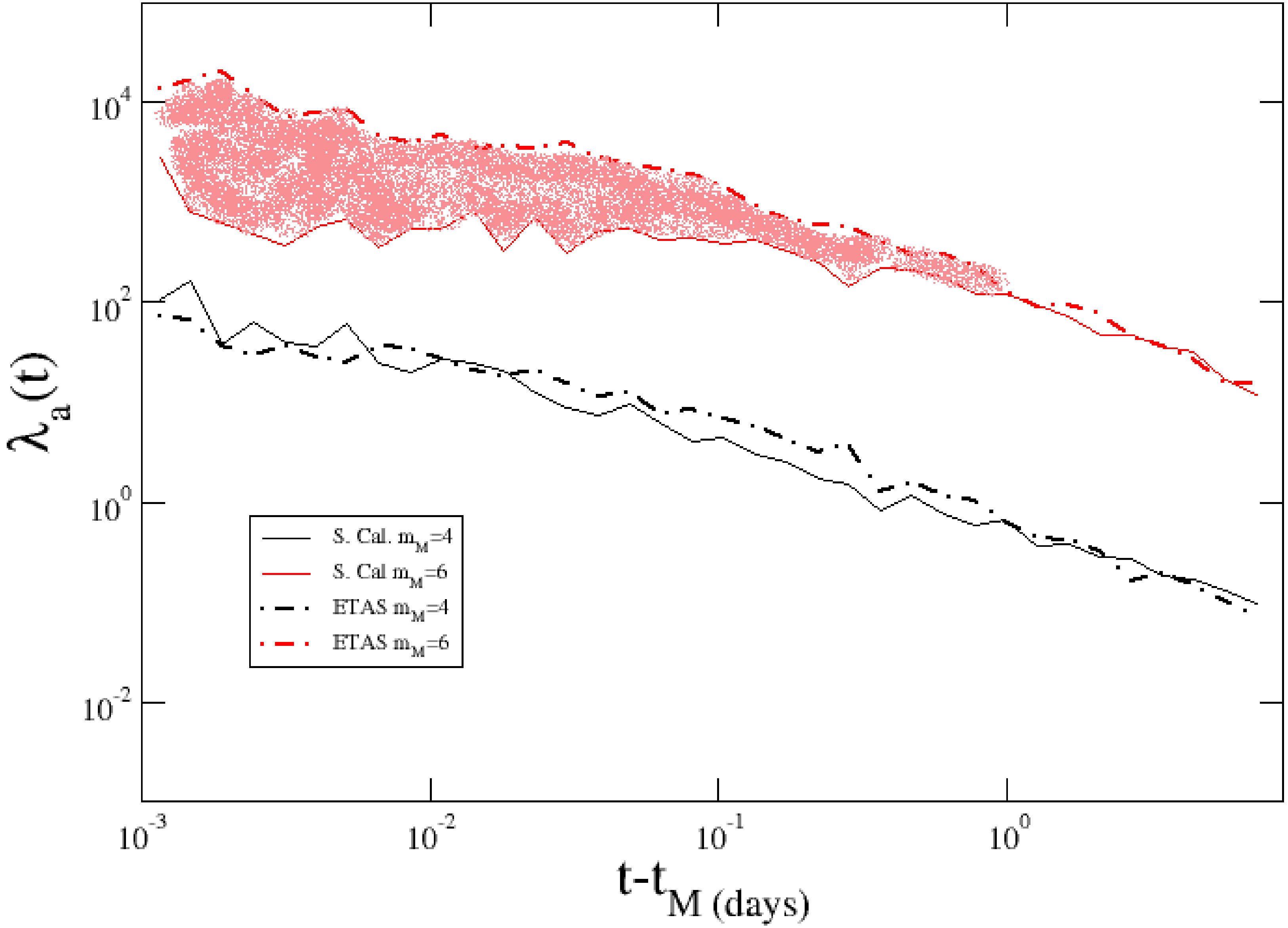
Parameter	Value
K_0	0.038
α	1.06
$b = \alpha$	1.06
p	1.27
c	0.024
d	0.006
γ	0.85
q	1.506

Seif et al., J. Geophysical Research: Solid Earth (2017),
Seif et al., Bull. Of the Seismologial Society of America (2018)

The Aftershocks occurrence rate



The Aftershocks occurrence rate - $ETAS_{fix}$



Incomplete catalog – The ETASI model

From the ETAS to ETASI

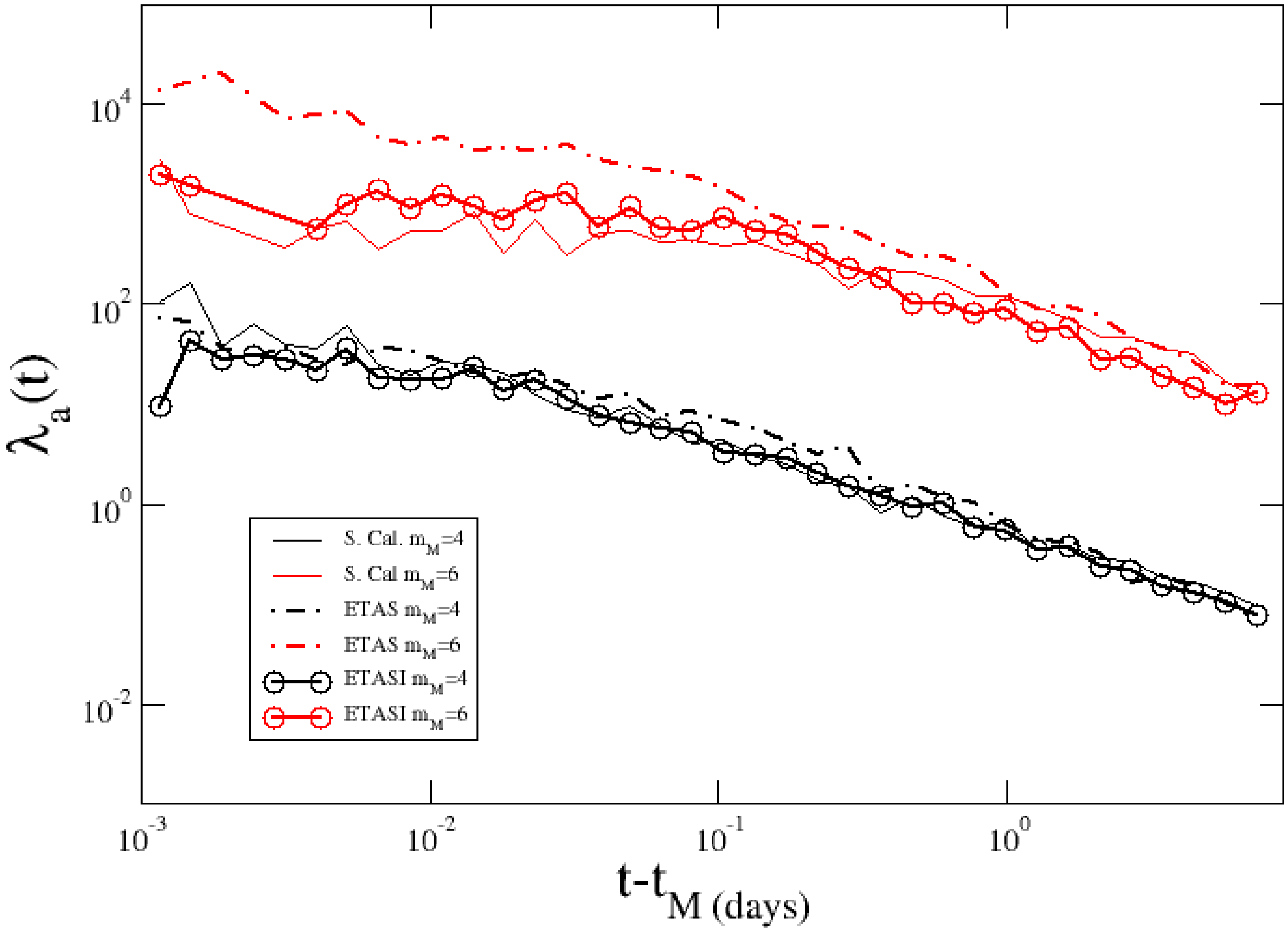
<u>Not all events with m < m_i^{th} are detected</u>

$$m_i^{th}(t - t_i) = m_i - w \log(t - t_i) - \delta_0$$

$$\Lambda_{ETASI}(m, x_i, t) = \Lambda_{ETAS}(m, x_i, t) \times \prod_j \Phi(m | m_j^{th}(t - t_j), \sigma)$$

Parameter	Value
w	0.7
δ_0	0.8

ETASI vs $ETAS_{fix}$



Comparison bewteen instumental and numerical catalogs

$$n_a(T, R, m_L, m_M) \qquad\qquad n_f(T, R, m_L, m_M)$$

The total number of aftershocks (n_a) and foreshocks (n_f) with magnitude $m \in [m_L, m_L + 0.5)$, with $dt_M < T$ and $dr_M < R$, linked to mainshocks with magnitude $m \in [m_M, m_M + 1)$.

Numerical catalog

$$\frac{n_{a,N}(T, R, m_L, m_M)}{n_{a,I}(T, R, m_L, m_M)} - 1 \qquad \frac{n_{f,N}(T, R, m_L, m_M)}{n_{f,I}(T, R, m_L, m_M)} - 1$$

Instrumental catalog

1000

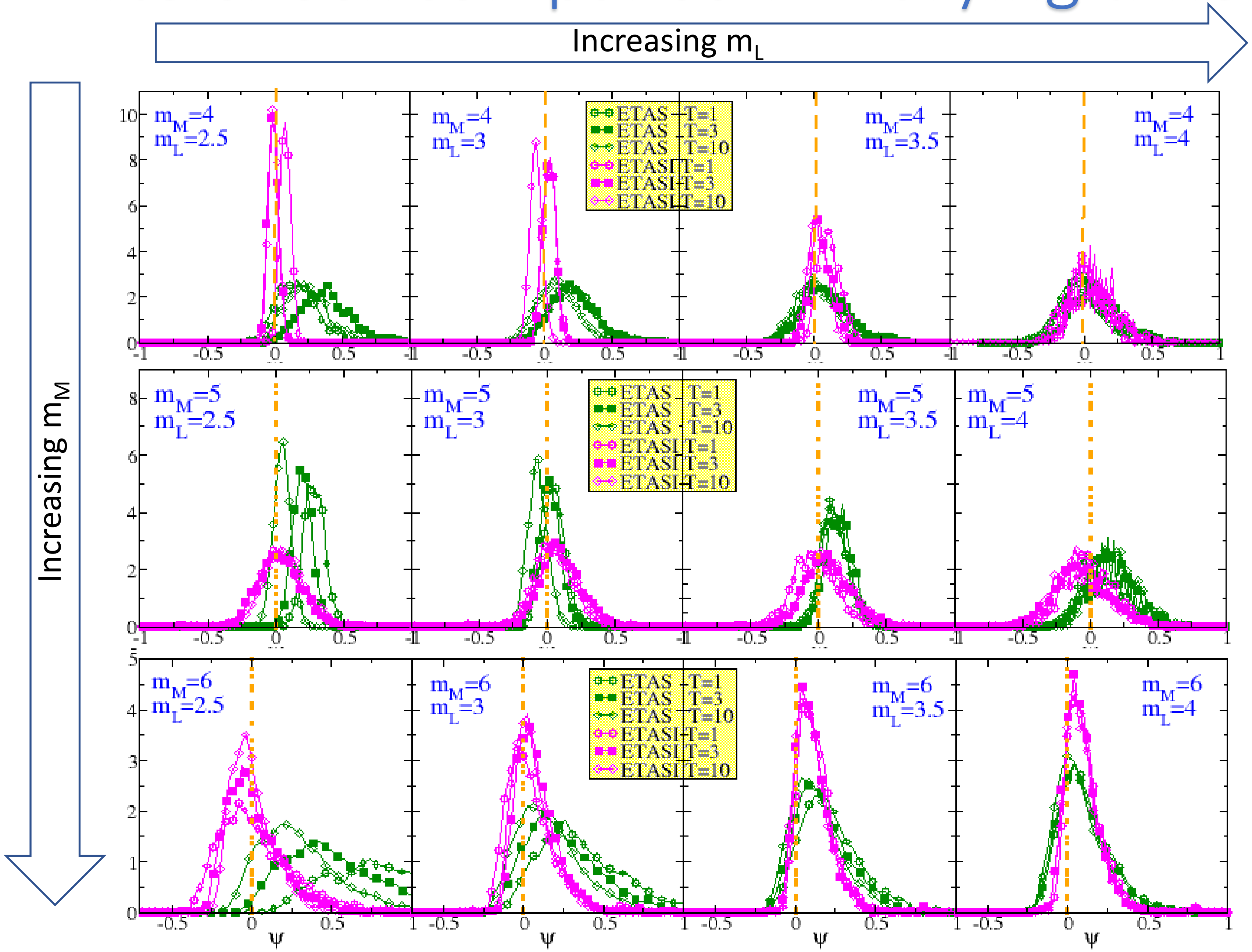
Simulated catalogs
$n^1_{a,N}(T, R, m_L, m_M)$
$n^2_{a,N}(T, R, m_L, m_M)$
$n^3_{a,N}(T, R, m_L, m_M)$
$n^4_{a,N}(T, R, m_L, m_M)$
$n^5_{a,N}(T, R, m_L, m_M)$
………..

Reference instr. catalog
$n_{a,I}(T, R, m_L, m_M)$

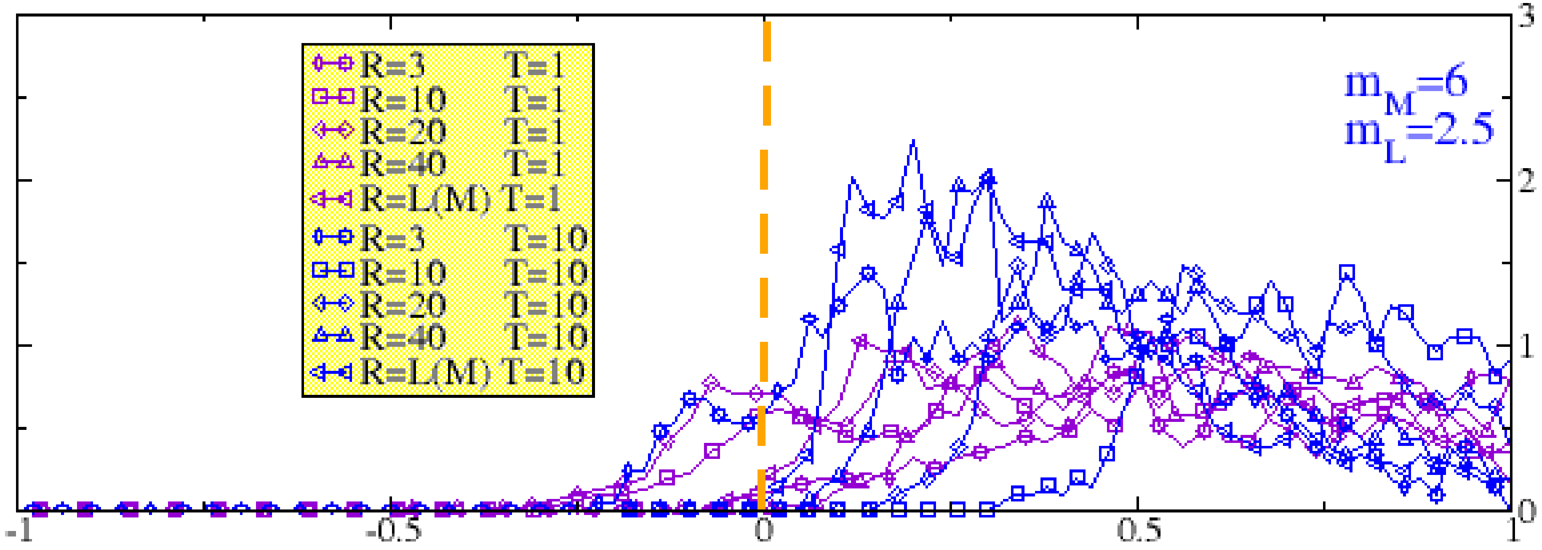
$$\frac{n_{a,N}(T, R, m_L, m_M)}{n_{a,I}(T, R, m_L, m_M)} - 1$$

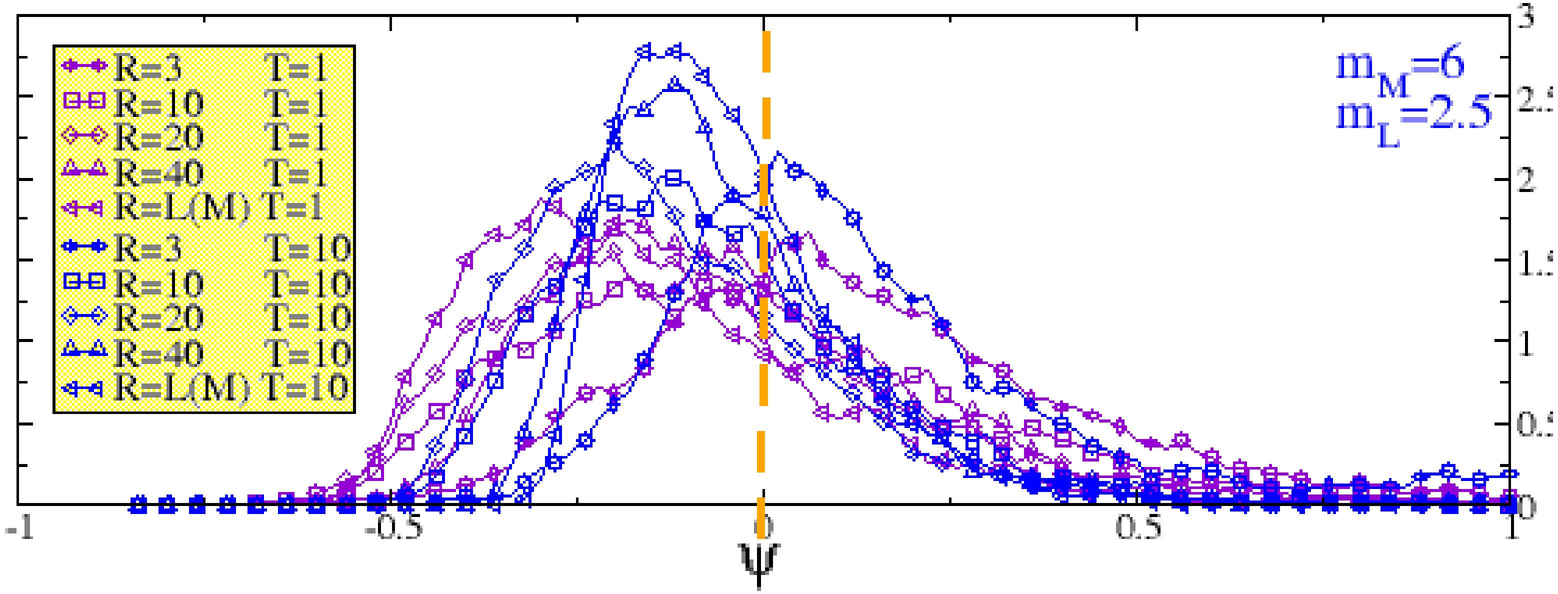
Realization index

Aftershock comparison – varying time



Aftershock comparison – varying space





Comparison bewteen instumental and numerical catalogs

$$n_a(T,R,m_L,m_M) \qquad\qquad n_f(T,R,m_L,m_M)$$

The total number of aftershocks (n_a) and foreshocks (n_f) with magnitude $m \in [m_L, m_L + 0.5)$, with $dt_M < T$ and $dr_M < R$, linked to mainshocks with magnitude $m \in [m_M, m_M + 1)$.

$$\frac{n_{a,N}(T,R,m_L,m_M)}{n_{a,I}(T,R,m_L,m_M)} - 1 \qquad \frac{n_{f,N}(T,R,m_L,m_M)}{n_{f,I}(T,R,m_L,m_M)} - 1$$

Numerical catalog

Instrumental catalog

1000

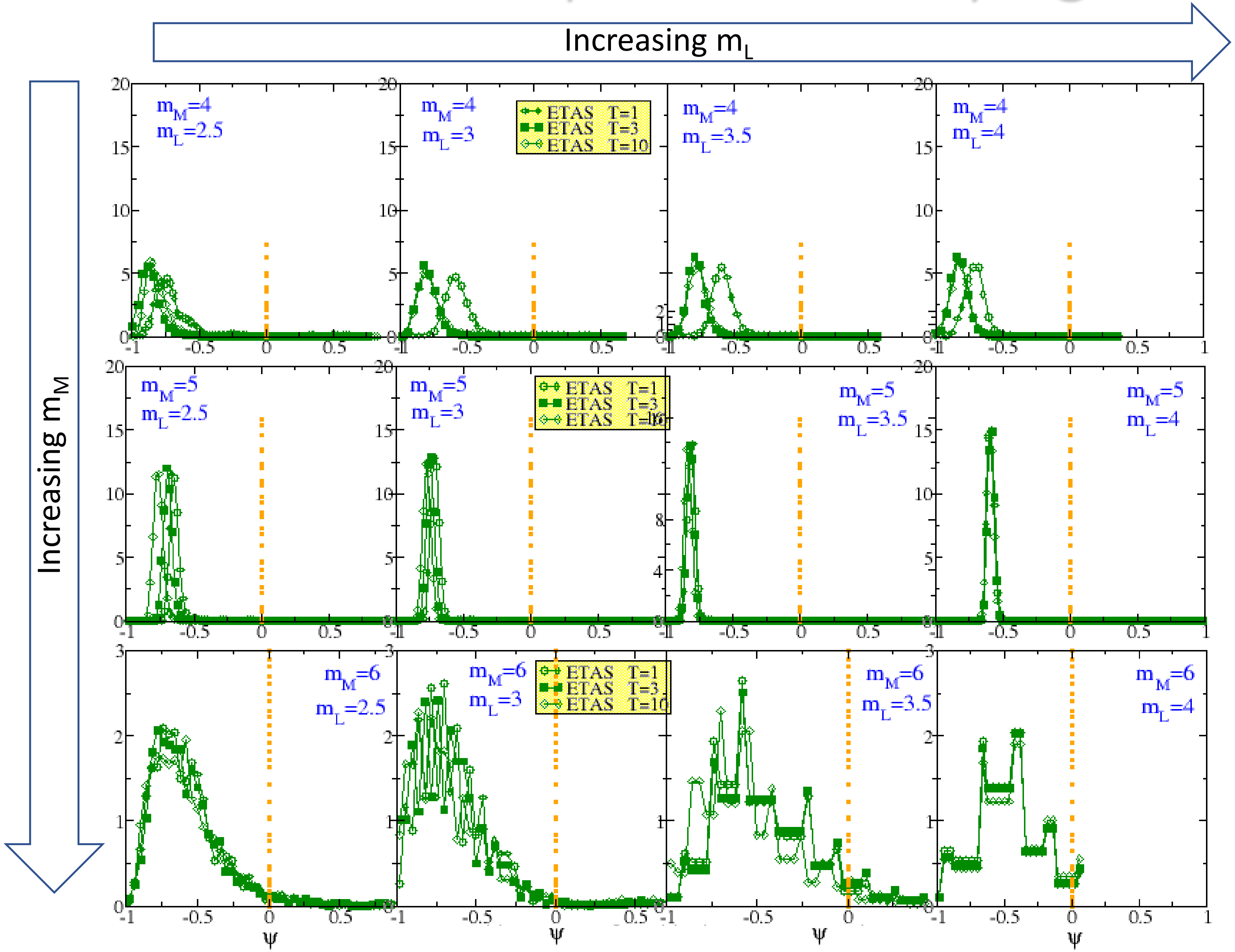
Simulated catalogs
$n^1_{f,N}(T,R,m_L,m_M)$
$n^2_{f,N}(T,R,m_L,m_M)$
$n^3_{f,N}(T,R,m_L,m_M)$
$n^4_{f,N}(T,R,m_L,m_M)$
$n^5_{f,N}(T,R,m_L,m_M)$
....

Reference instr. catalog
$n_{f,I}(T,R,m_L,m_M)$

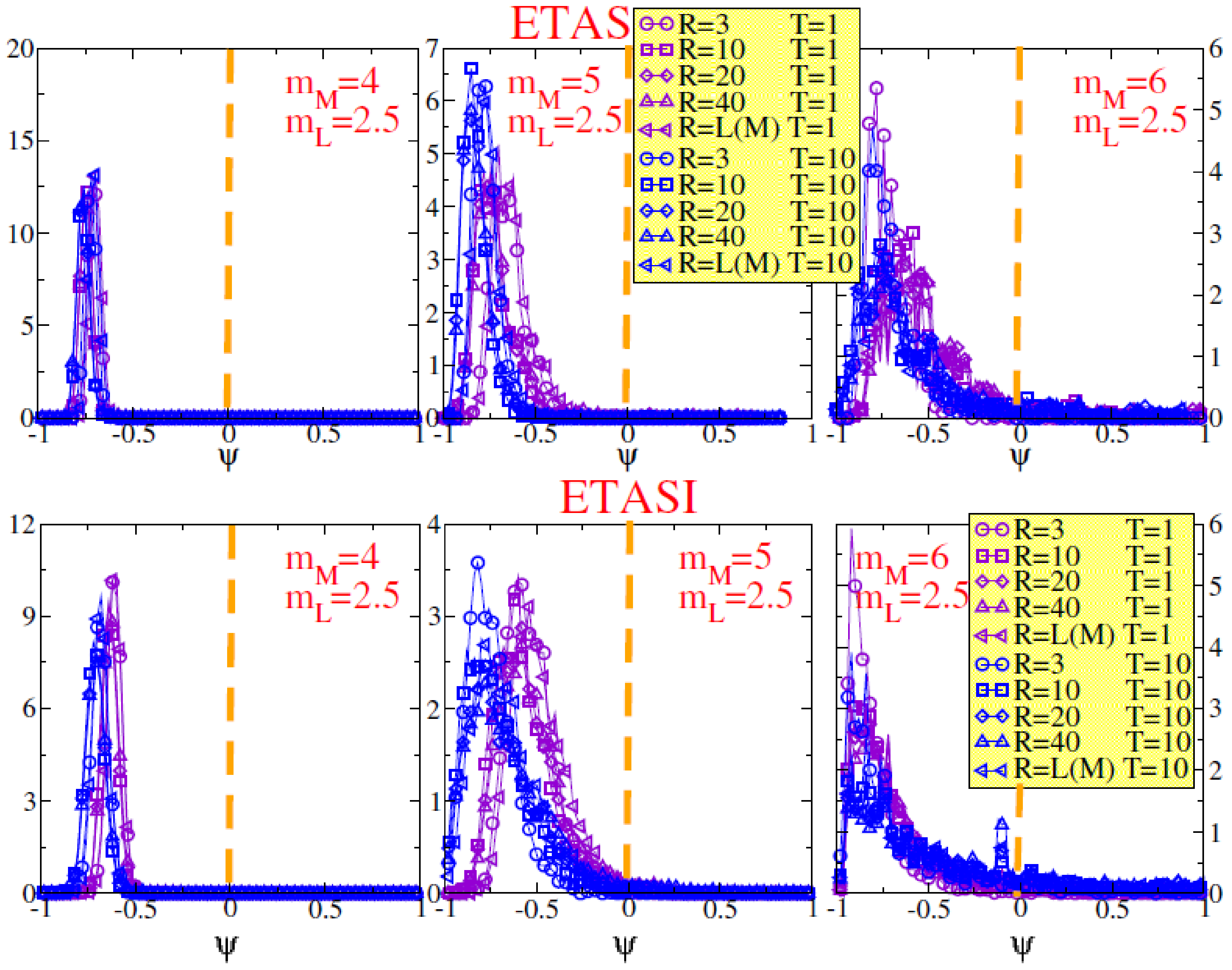
$$\frac{n_{f,N}(T,R,m_L,m_M)}{n_{f,I}(T,R,m_L,m_M)} - 1$$

Realization index

Foreshock comparison – varying time



Foreshock comparison – varying space



The ETAFS model

$$\Lambda(m, x_i, t) = \Lambda_{ETAS}(m, x_i, t) + \sum_k 10^{-bm} Q_f(d_{ik}, t_k - t, m_k)$$

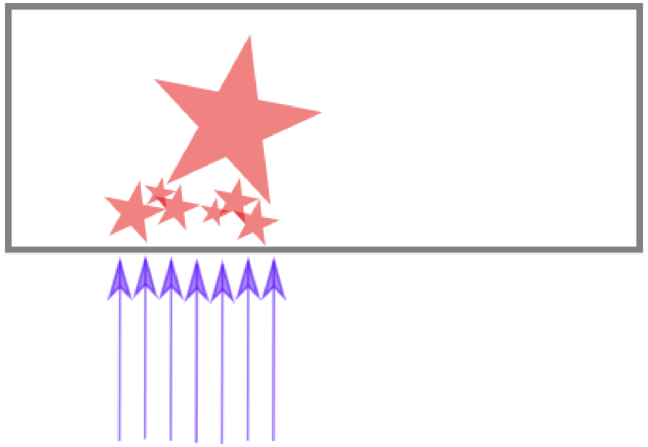
$$Q_f(d_{ik}, t_k - t, m_k) = \frac{K_f(p_f - 1)}{c} \frac{q_f - 1}{\pi d_f 10^{\gamma_f(m_j - m_0)}} 10^{\alpha_f(m_k - m_0)} \left(1 + \frac{t_k - t}{c_f}\right)^{-p_f} \left(\frac{d_{ik}}{d_f 10^{\gamma_f m_k}} + 1\right)^{-q_f}$$

New Parameter	Value
K_f	0.05
α_f	0.54

$p_f = p \quad c_f = c \quad d_f = d \quad q_f = q$

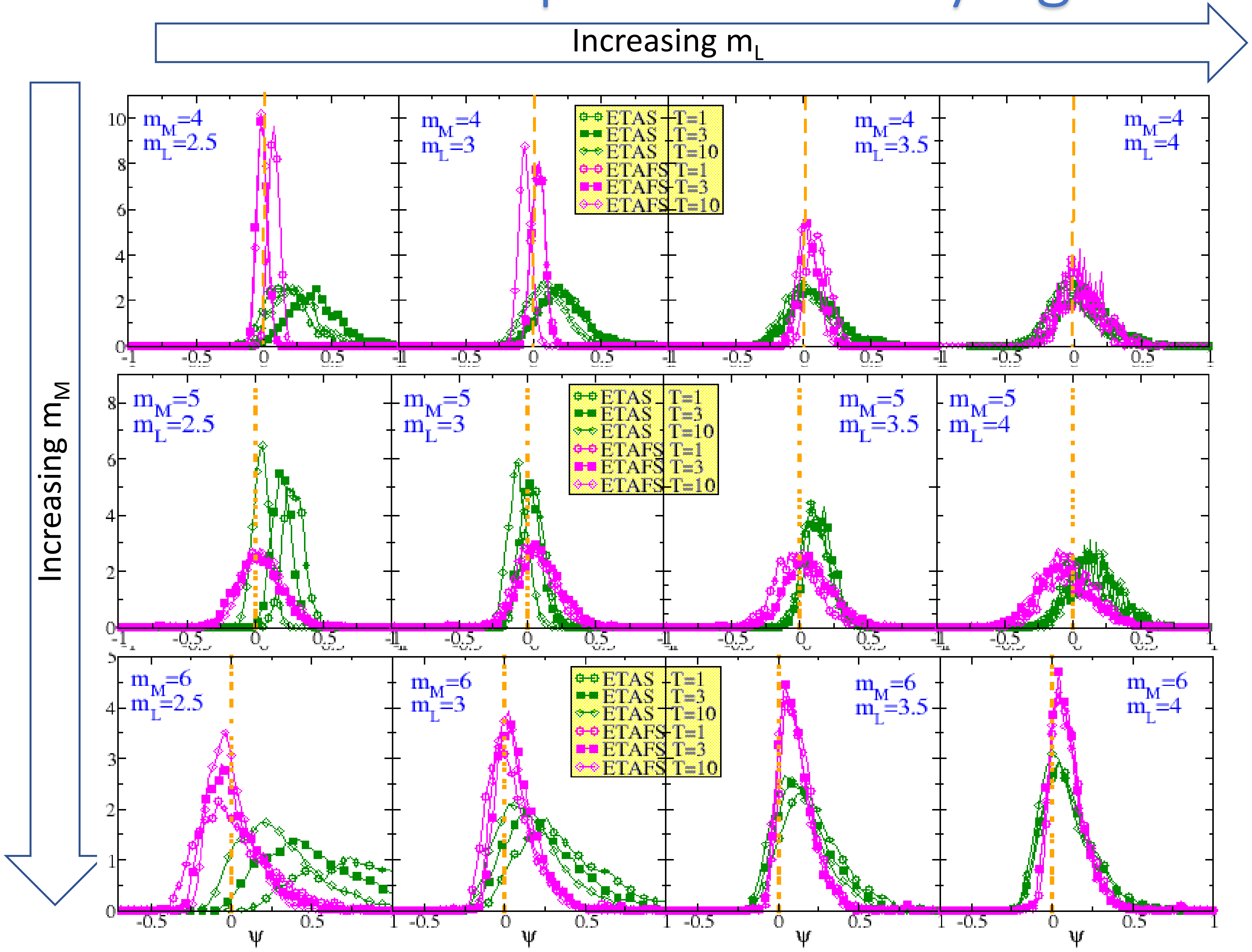
ETAFS model - Foreshock hypotesis

Top-down loading

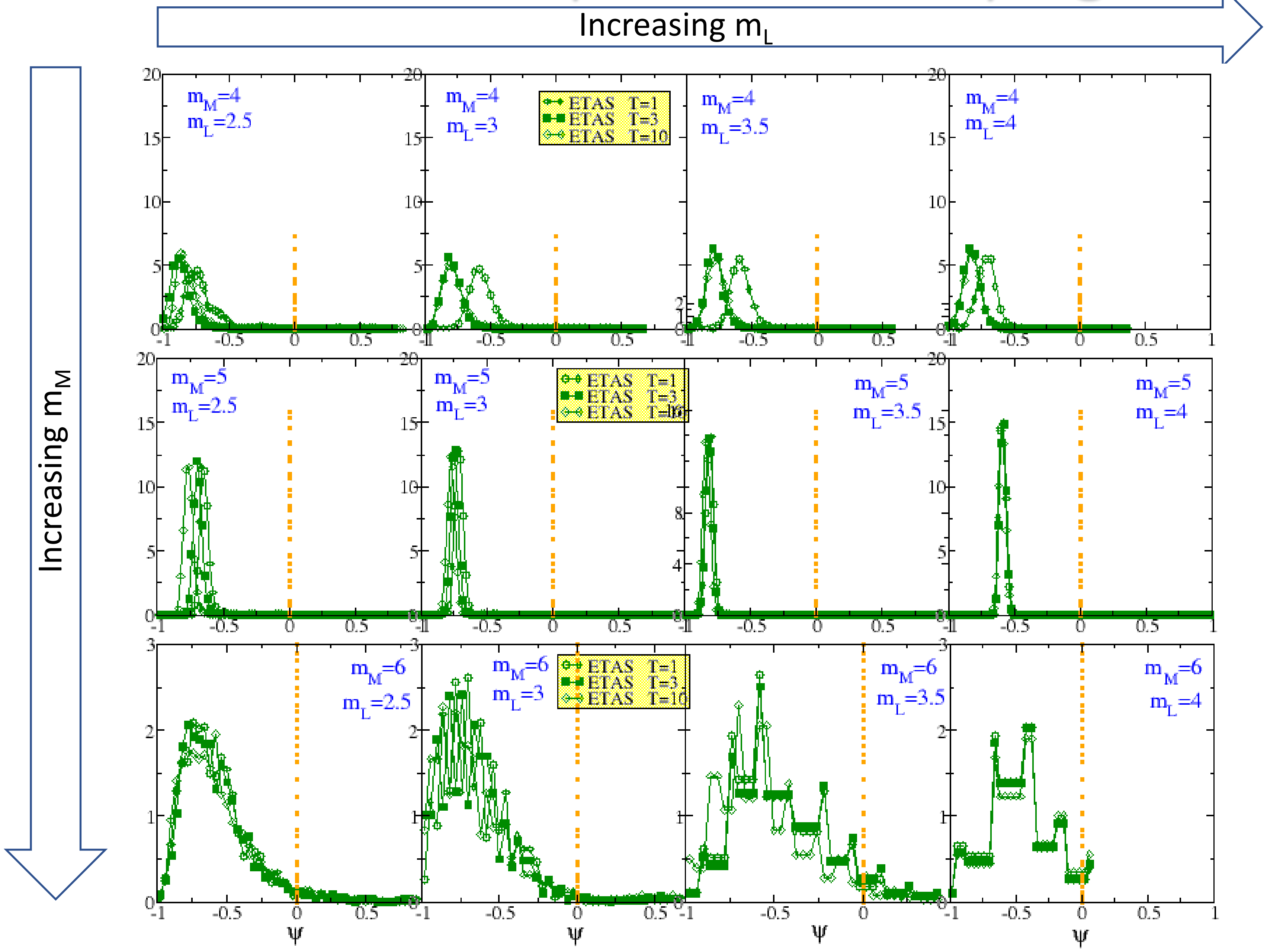


The mainshock is due to constant tectonic loading on the hosting fault. Foreshocks correspond to the part of background seismicity that is influenced by the same loading process. ETAFS predicts a concentration of foreshocks at the location of the future mainshock hypocentre.

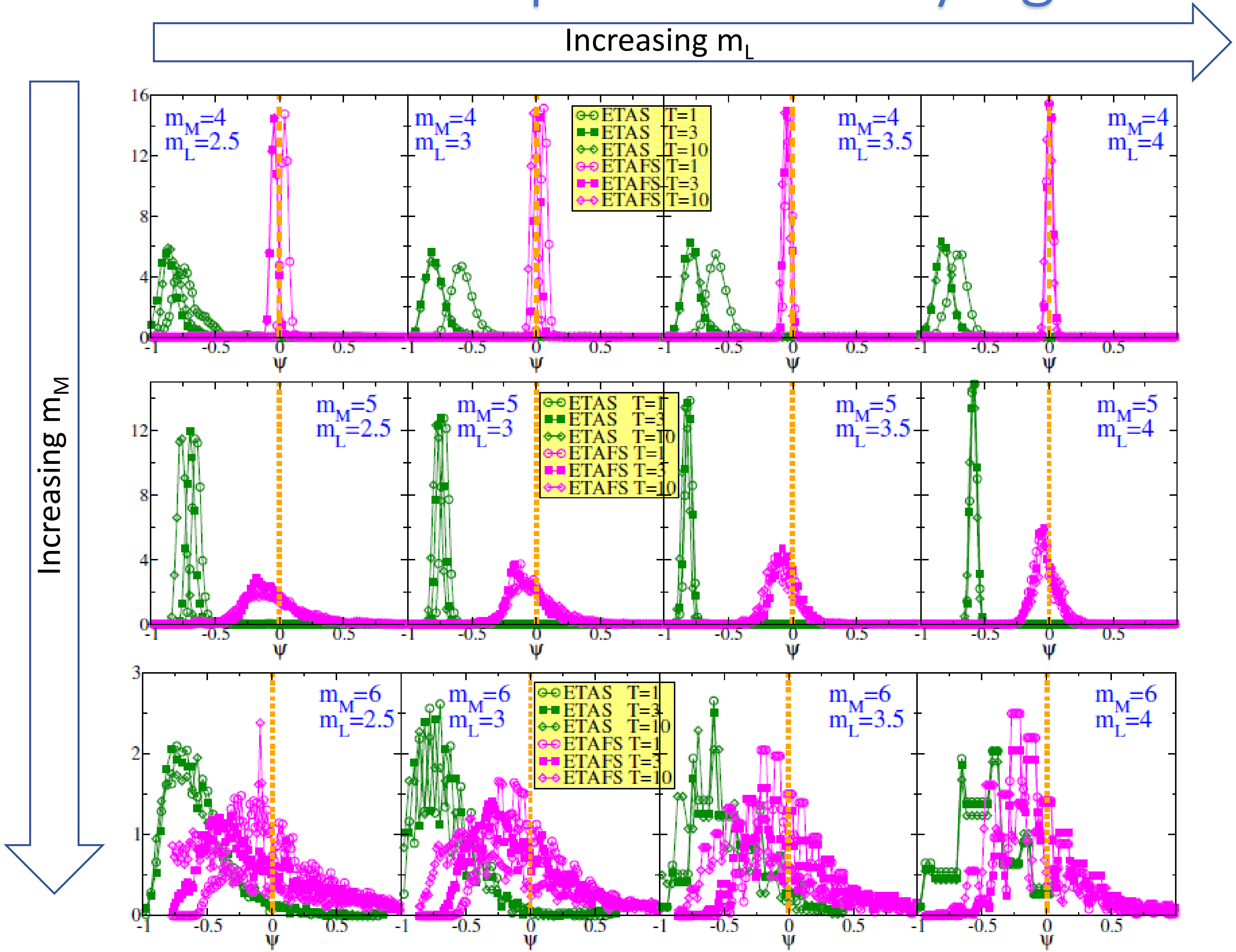
Aftershock comparison – varying time



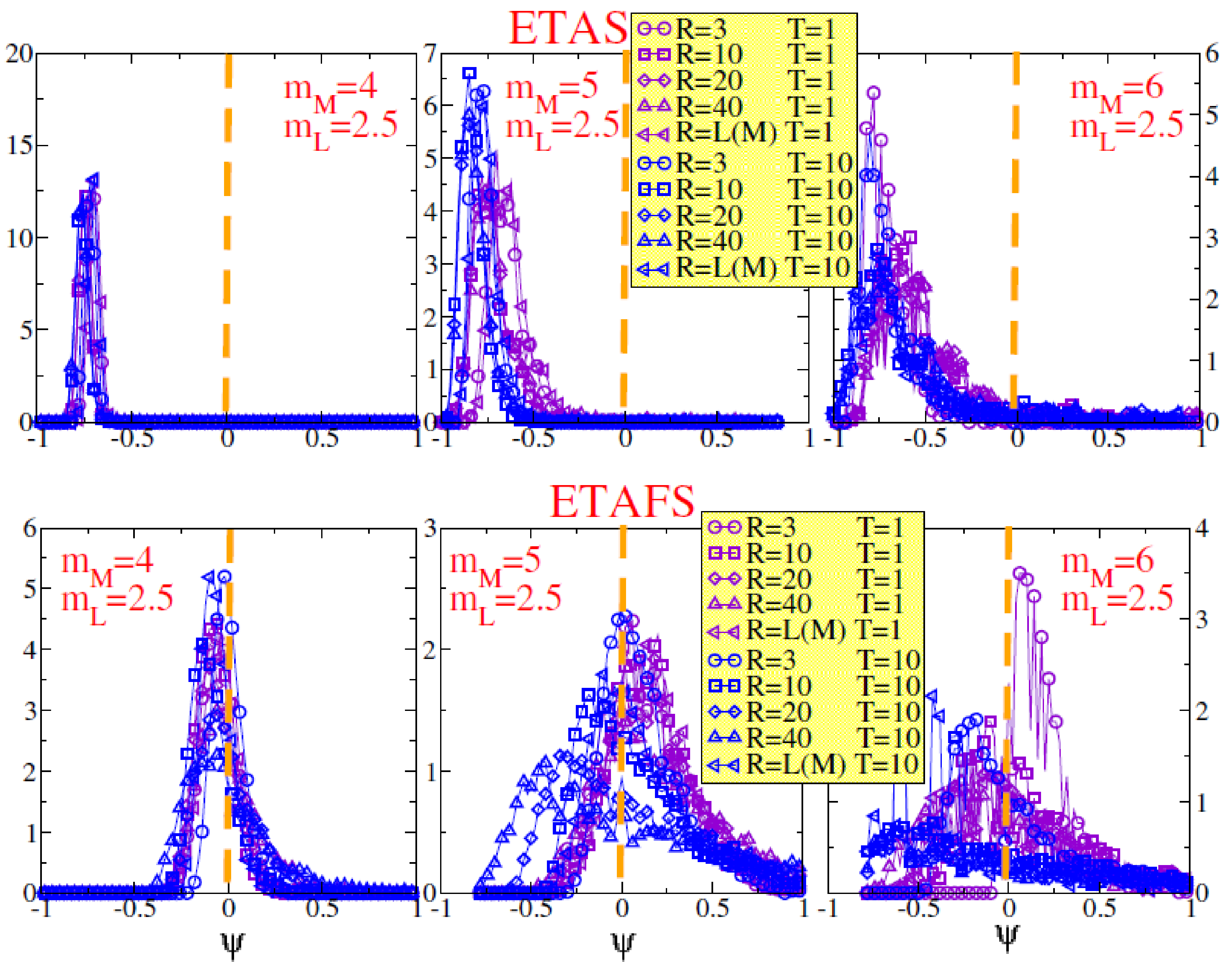
Foreshock comparison – varying time



Foreshock comparison – varying time



Foreshock comparison – varying space



Statistical validation of the model – comparison of likelihood instrumental catalog and 1000 realizations of numerical catalogs

$$JLL = \sum_{k=1}^{n_M(m_M)} \log\left(ccdf^{(X)}\left(n_f(T, R, m_L, m_k)\right)\right)$$

Numerical catalogs JJL(X)

Instrumental catalog

$$JJL\ (X) \leq JLL$$

We reject the null-hypothesis if the p-value is smaller than 0.05

Results of the test

ETAS & ETASI

ETAFS

The hypothesis that ETAS and ETASI model can capture foreshocks statistics must be discarded with a very high confidence level

The hypotesis that ETAFS catalogs present a different number of foreshocks than the instrumental catalog must be discarded with high confidence level

Models

Three variants of ETAS model

- ETAS $b = \alpha$ → Model verified as the model providing the most accurate description of the southern California seismicity in Seif et al. (2018)
  - Predicts too many aftershocks and too few foreshocks
- ETASI → Model which takes explicity into account that many aftershocks are hidden by coda-waves of a previous larger events
  - Predicts the number of aftershocks well but badly that of foreshocks
- ETAFS → Model which incorporates both the bottom-up triggering (ETAS model) and the top-down loading leading to foreshocks.
  - Predicts the number of aftershocks and the number of foreshocks well

Conclusions

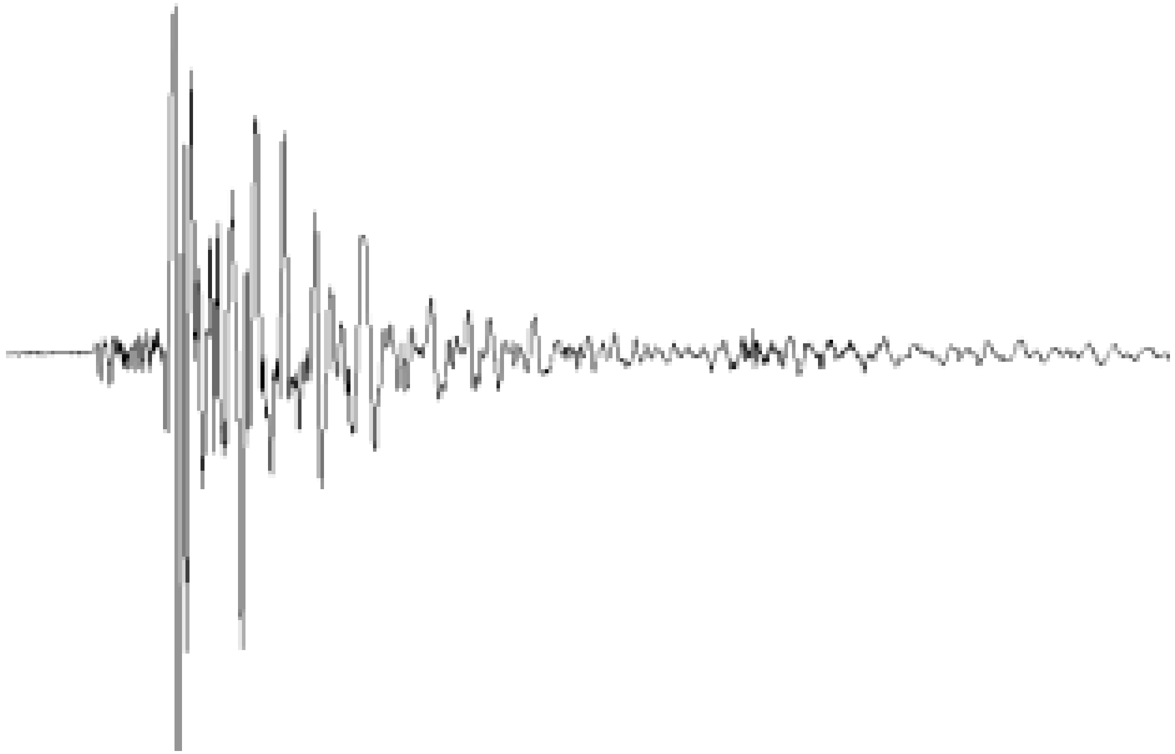
The ETAFS model is an hybrid model which incorporates within the standard bottom-up ETAS model the top-down loading mechanism leading to Foreshocks.

!!!!!

Our results do not exclude the existence of a bottom-up triggering model able to reproduce instrumental catalogs from both the side of aftershocks and foreshocks. However, no model has achieved this task so far and therefore our conclusion is that the top-down loading scenario represents the most plausible explanation for the occurrence of foreshocks.

!!!!!

Thank you



G Petrillo, E Lippiello, Testing of the foreshock hypothesis within an epidemic like description of seismicity, *Geophysical Journal International*, Volume 225, Issue 2, May 2021, Pages 1236–1257, https://doi.org/10.1093/gji/ggaa611