

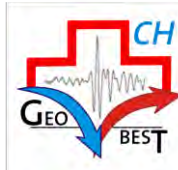
Statistical and Phenomenological Analysis of Induced Seismicity in Basel with a High-resolution Catalog

Marcus Herrmann, Toni Kraft, Stefan Wiemer

 *Swiss Seismological Service, ETH Zürich*

Schatzalp 2019 – 3rd Induced Seismicity Workshop

Davos | Friday, March 08, 2019



- **Basel EGS (Enhanced/Engineered Geothermal System)**
 - Hydraulic stimulation in Dec 2006



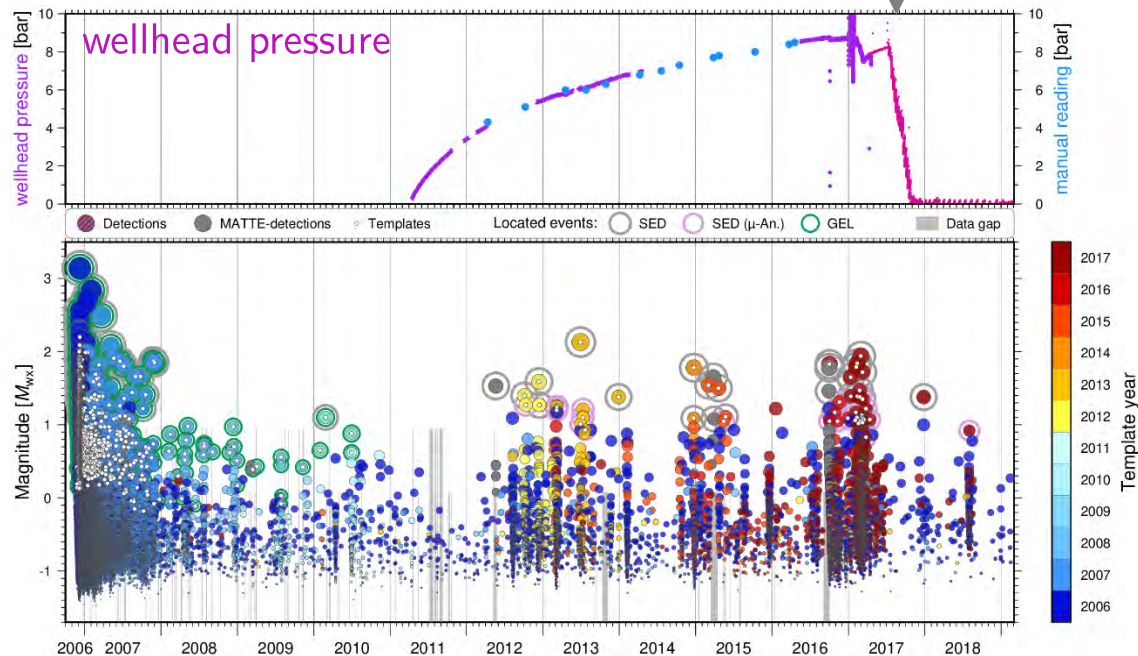
- **Basel EGS (Enhanced/Engineered Geothermal System)**

- Hydraulic stimulation in Dec 2006

- **>12 years of induced seismicity**

- ... and still seismically active (despite being suspended)

borehole re-opening
(weekly by ~1bar)

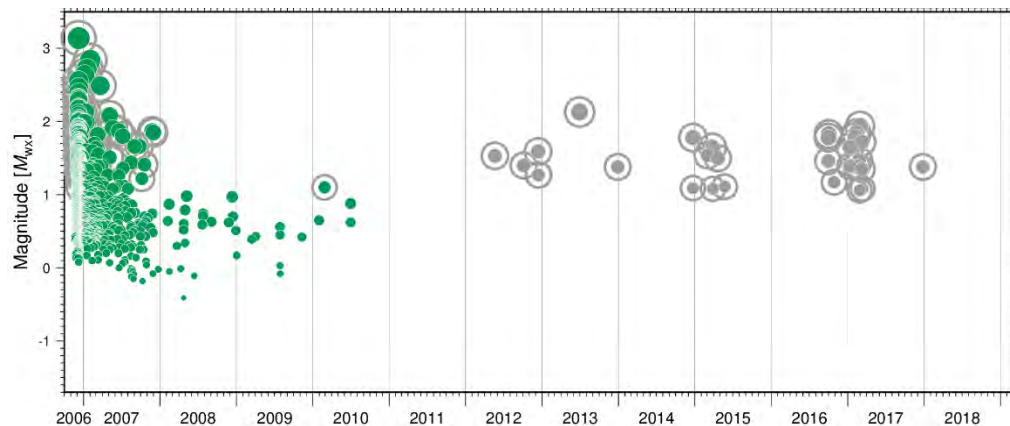


■ Basel EGS (Enhanced/Engineered Geothermal System)

- Hydraulic stimulation in Dec 2006
- **>12 years of induced seismicity**
 - ... and still seismically active (despite being suspended)
 - **Until now, no continuous & consistent catalog available:**

Existing catalogs:

1. **2006-2012: GEL catalog**; ~3'600 events
Borehole network operator (incl. deep borehole stations)
2. **2012+: SED catalog**; 23 events
Swiss Seismological Service (only surface stations)



■ Basel EGS (Enhanced/Engineered Geothermal System)

- Hydraulic stimulation in Dec 2006

■ >12 years of induced seismicity

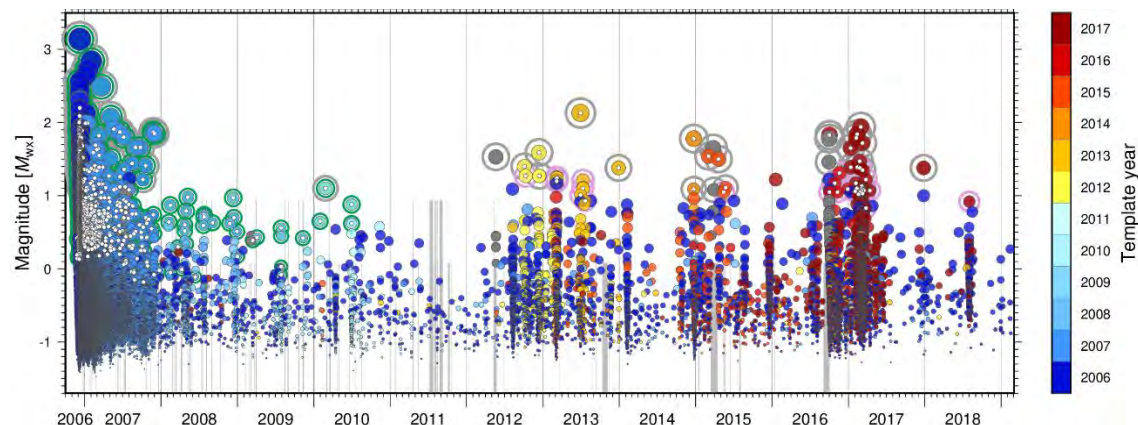
- ... and still seismically active (despite being suspended)
- Until now, no continuous & consistent catalog available

■ Now we created a high-resolution catalog

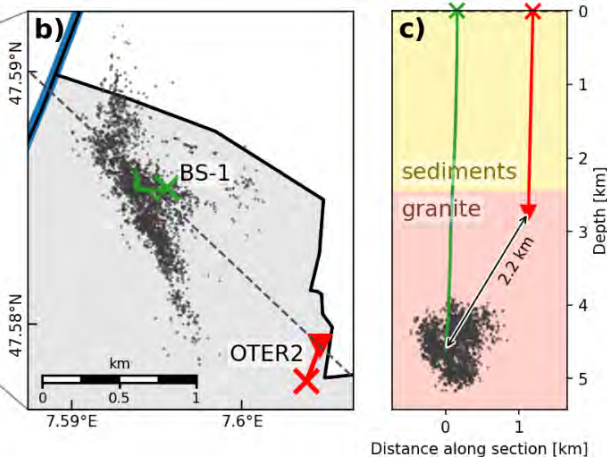
- of consistent quality!
- new possibilities for analysis
- new insights

Existing catalogs:

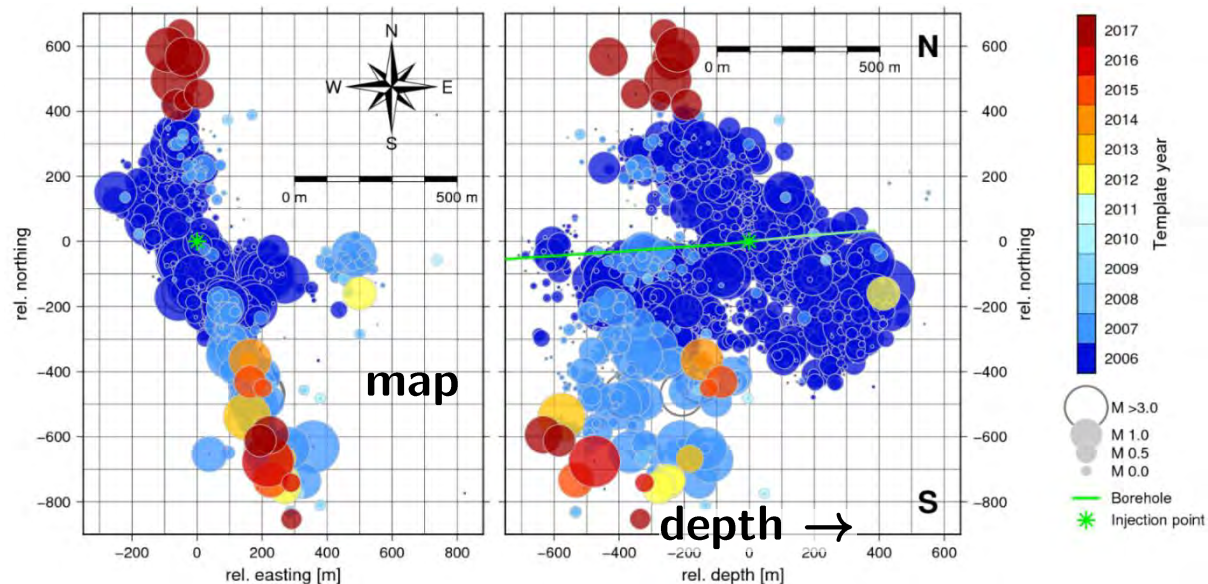
1. **2006-2012: GEL catalog**; ~3'600 events
Borehole network operator (incl. deep borehole stations)
2. **2012+ : SED catalog**; 23 events
Swiss Seismological Service (only surface stations)
3. **New catalog**
Template Matching (= Matched Filter Analysis)



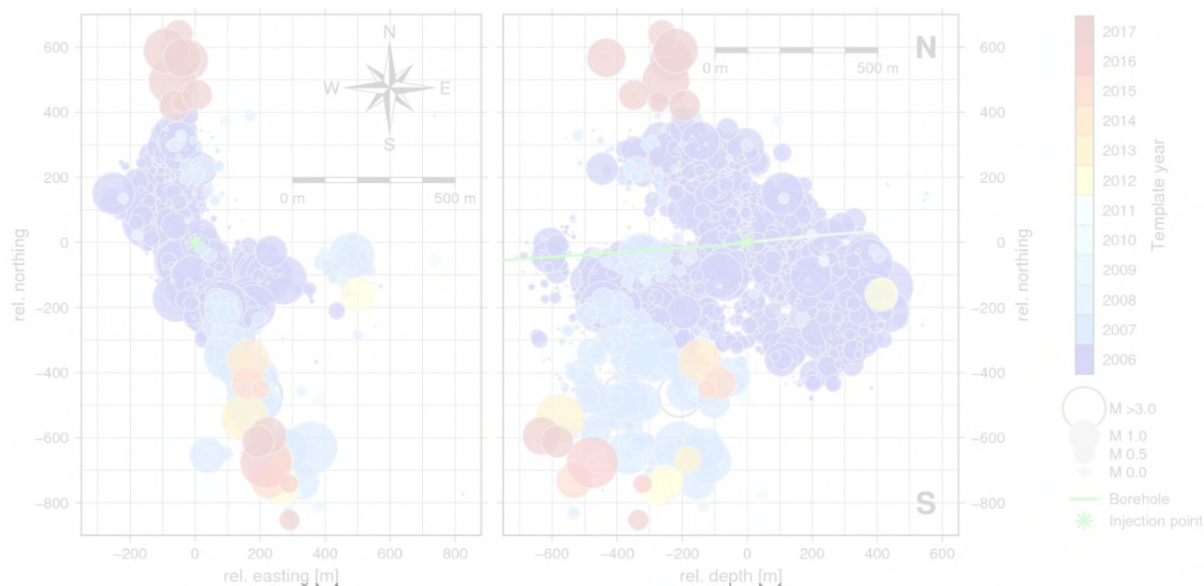
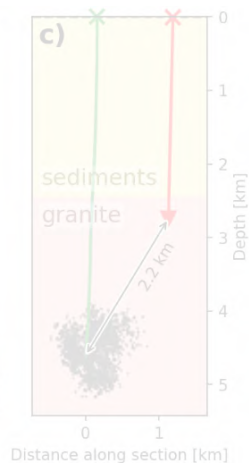
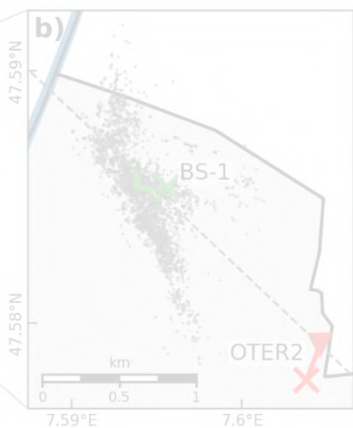
- 2'508 templates → representation of the “seismic cloud”



Locations:
[Dyer et al. 2010;
Deichmann et al. (2014)]

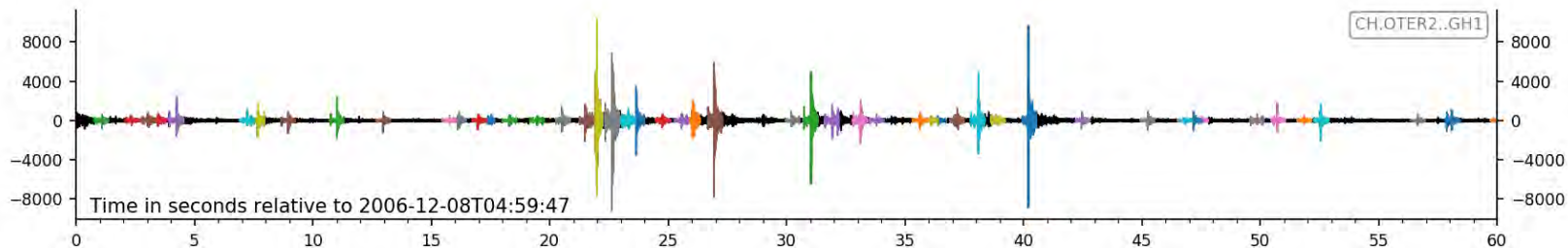


- 2'508 templates → representation of the “seismic cloud”



Locations:
[Dyer et al. 2010;
Deichmann et al. (2014)]

60 seconds:
50 detections
(highest rate
~3000 ev/h):



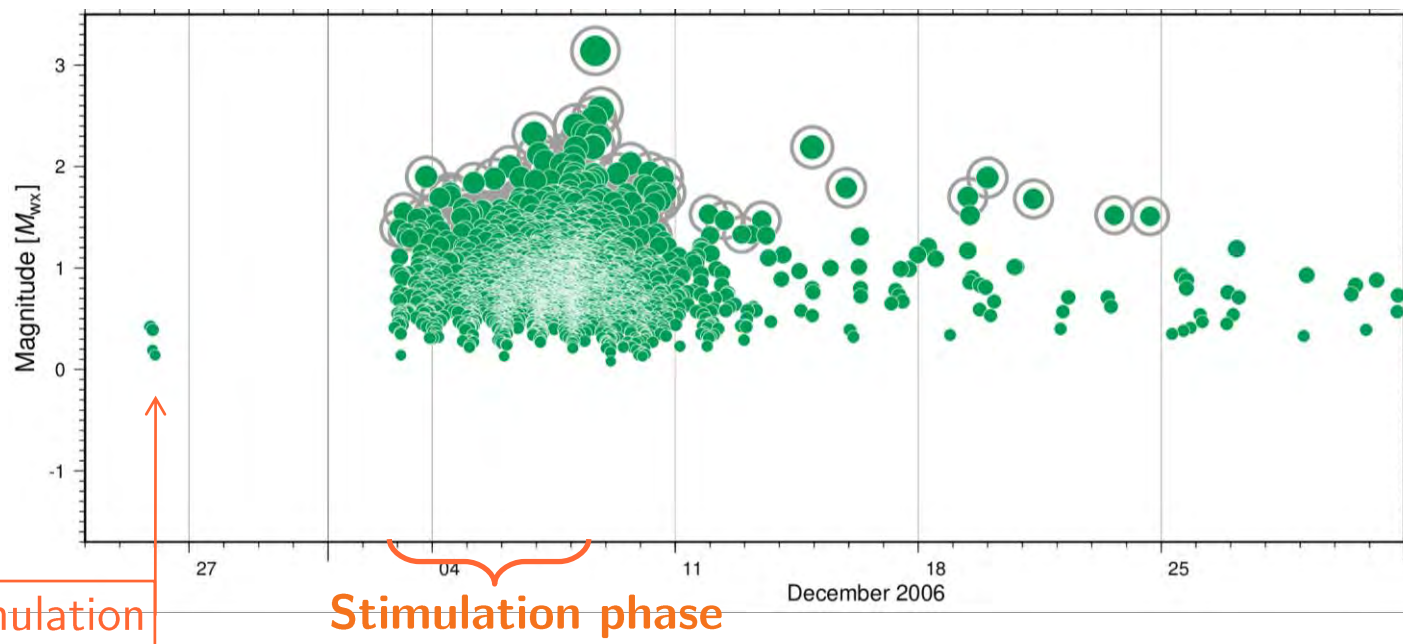
1. SED catalog

Swiss Seismological Service
(only surface stations)

2. GEL catalog

Borehole network operator
(incl. deep borehole stations)

■ What was known before:



Pre-Stimulation

Stimulation phase

1. SED catalog

Swiss Seismological Service
(only surface stations)

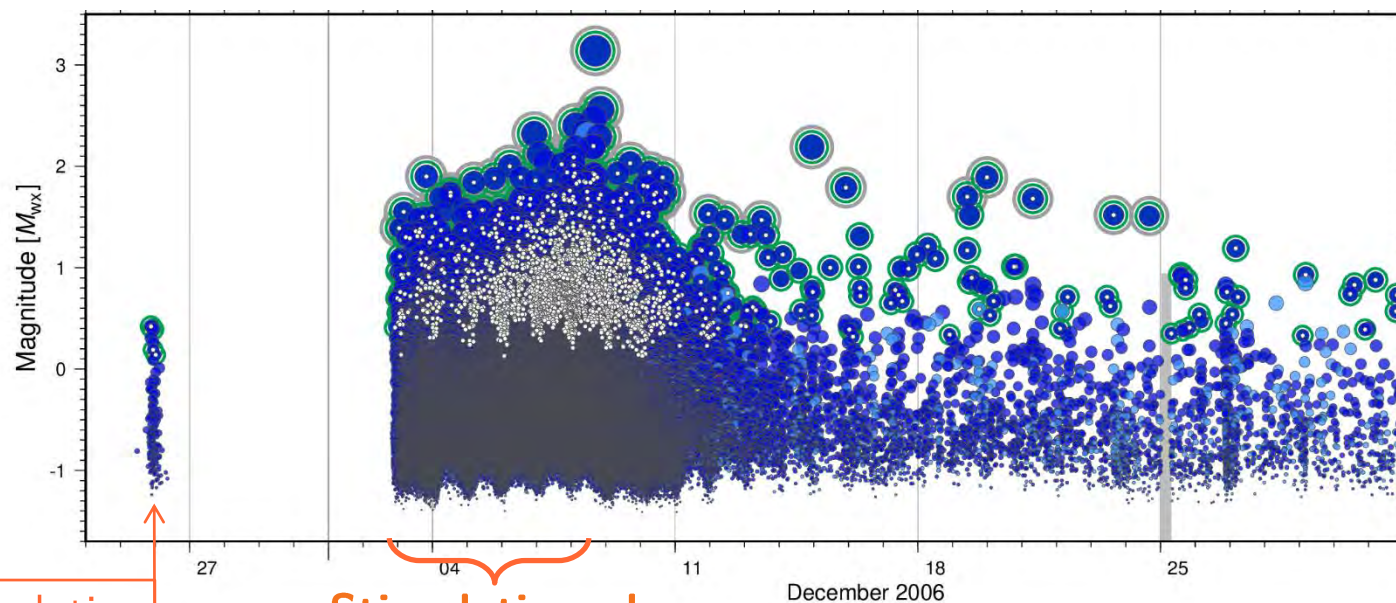
2. GEL catalog

Borehole network operator
(incl. deep borehole stations)

3. New catalog

Template Matching

- ~260'000 events (80x higher resolution)



Pre-Stimulation

Stimulation phase

1. SED catalog

Swiss Seismological Service
(only surface stations)

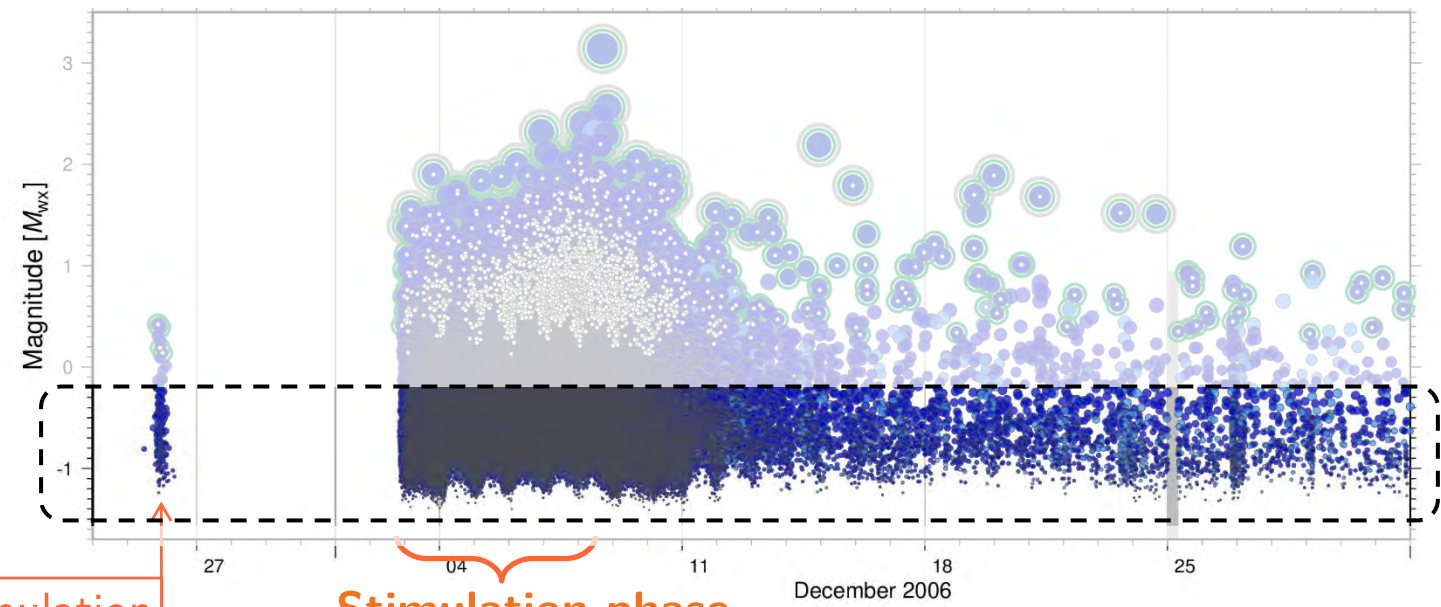
2. GEL catalog

Borehole network operator
(incl. deep borehole stations)

3. New catalog

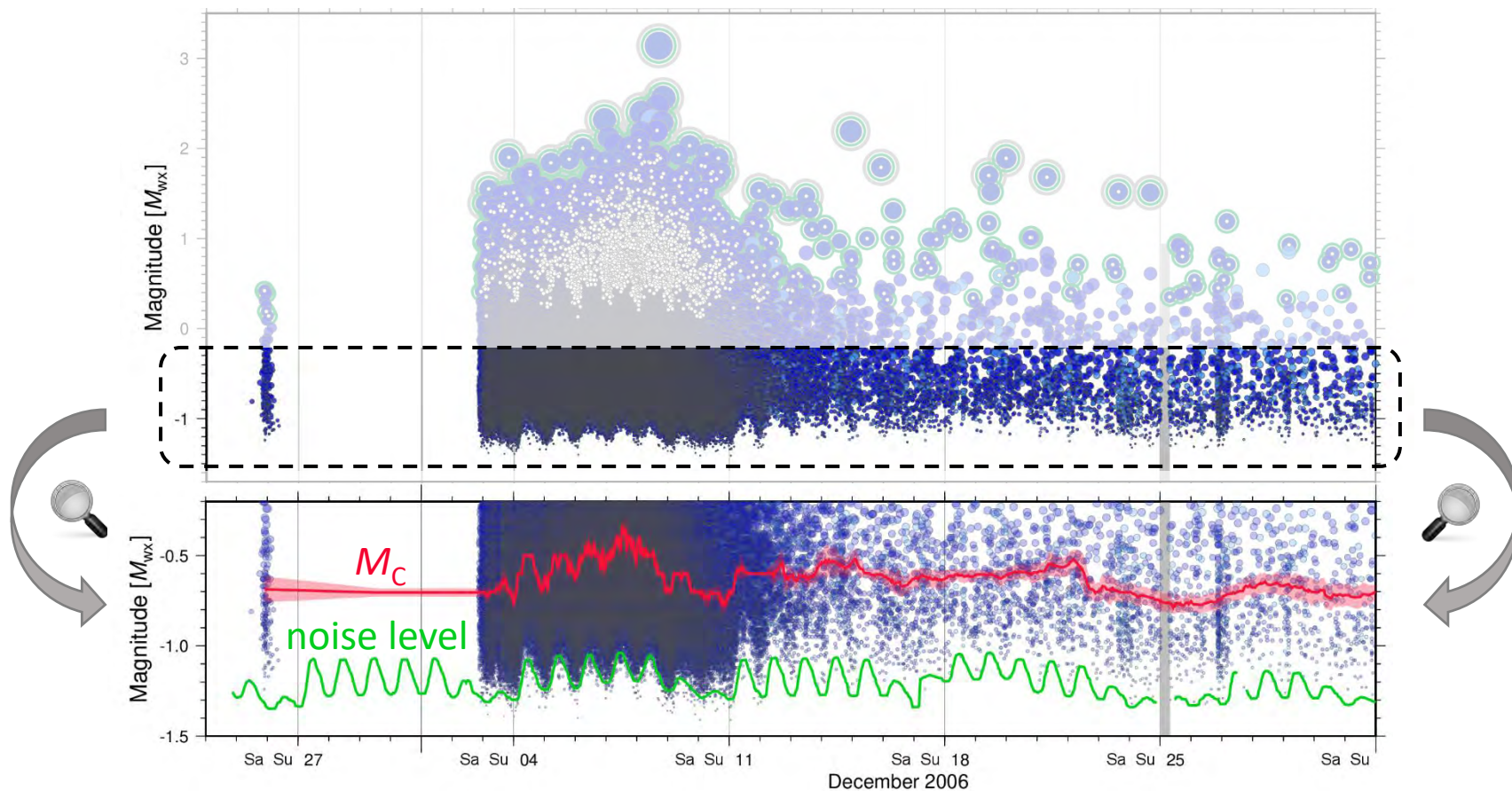
Template Matching

- ~260'000 events (80x higher resolution)



Pre-Stimulation

Stimulation phase



1. Removal of false detections

- Classification of waveforms with *supervised machine learning*

■ Details:

Herrmann, M., T. Kraft, T. Tormann, L. Scarabello, and S. Wiemer (2019).

«A Consistent High-resolution Catalog of Induced Seismicity in Basel Based on Matched Filter Detection and Tailored Post-processing.»

Submitted to *Journal of Geophysical Research: Solid Earth* (in review)

1. Removal of false detections

- Classification of waveforms with *supervised machine learning*

2. Moment magnitude (M_w) estimation

(*cluster-based* for each template)

$$M_w = \frac{2}{3} \log A + C$$

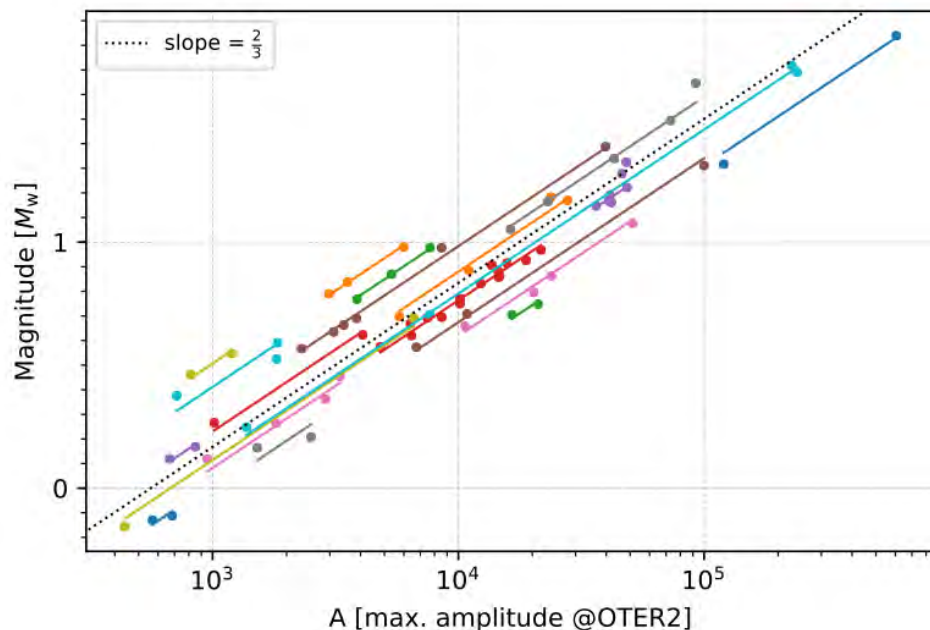
Theory: [Deichmann 2017]

■ Details:

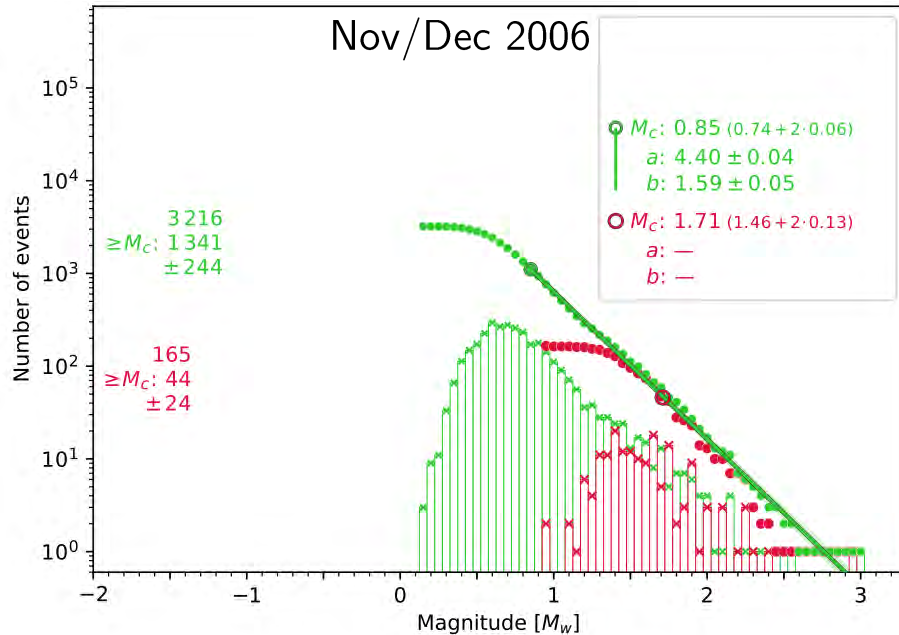
Herrmann, M., T. Kraft, T. Tormann, L. Scarabello, and S. Wiemer (2019).

«A Consistent High-resolution Catalog of Induced Seismicity in Basel Based on Matched Filter Detection and Tailored Post-processing.»

Submitted to *Journal of Geophysical Research: Solid Earth* (in review)



■ Frequency–Magnitude Distribution (FMD)



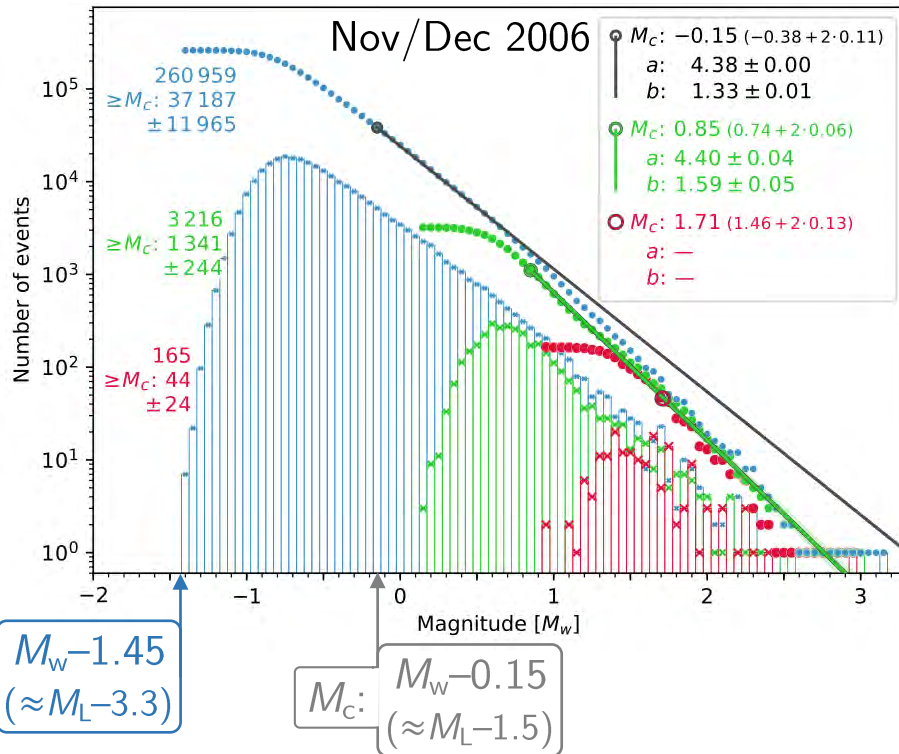
1. SED catalog

Swiss Seismological Service
(only surface stations)

2. GEL catalog

Borehole network operator
(incl. deep borehole stations)

■ Frequency–Magnitude Distribution (FMD)



1. SED catalog

Swiss Seismological Service
(only surface stations)

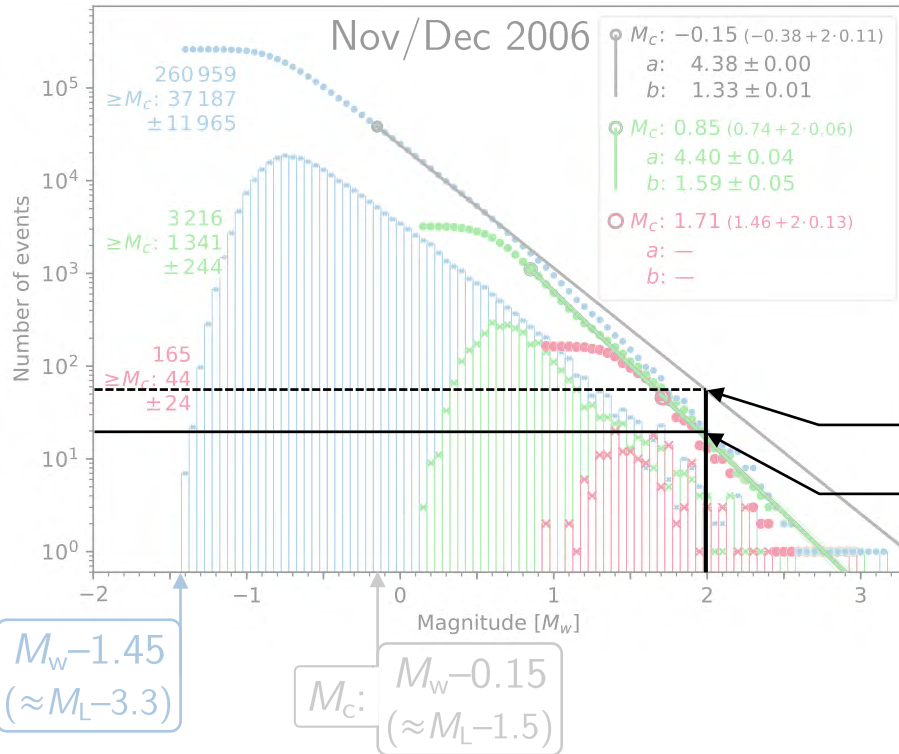
2. GEL catalog

Borehole network operator
(incl. deep borehole stations)

3. New catalog

(template matching)

■ Frequency–Magnitude Distribution (FMD)



1. SED catalog

Swiss Seismological Service
(only surface stations)

2. GEL catalog

Borehole network operator
(incl. deep borehole stations)

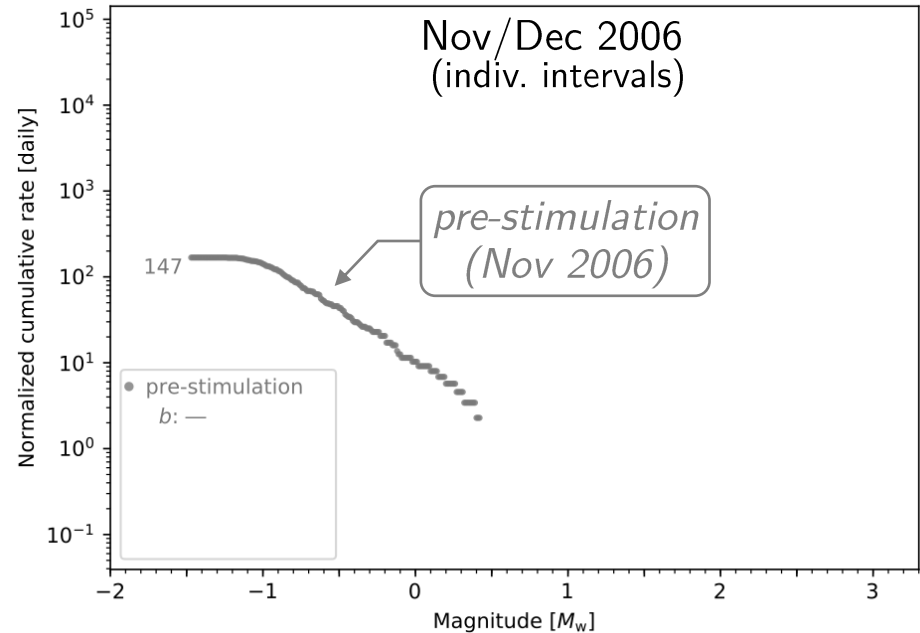
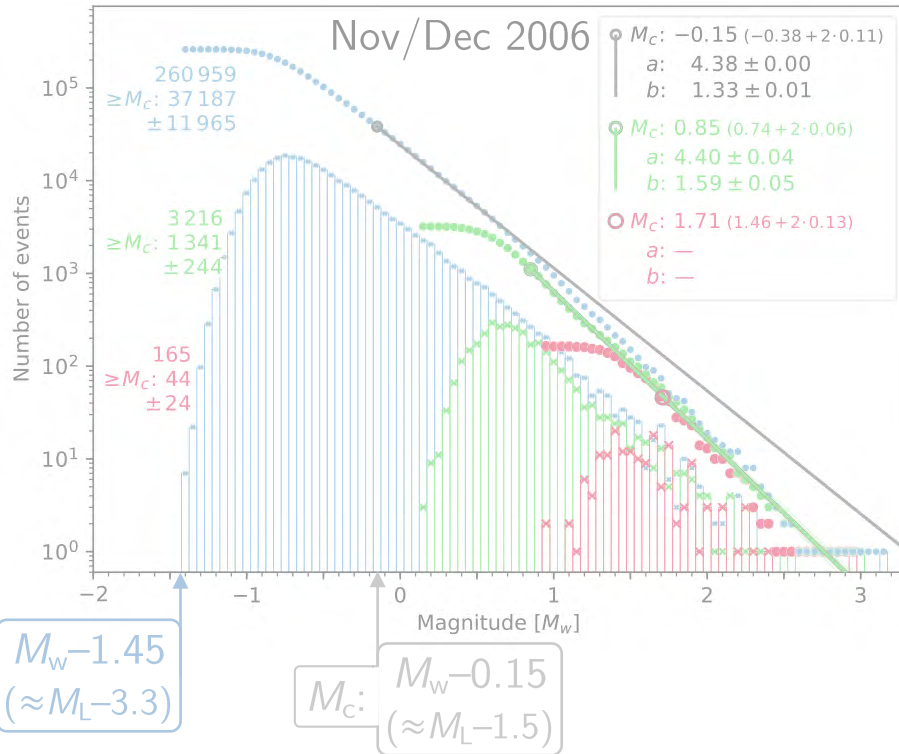
3. New catalog

(template matching)

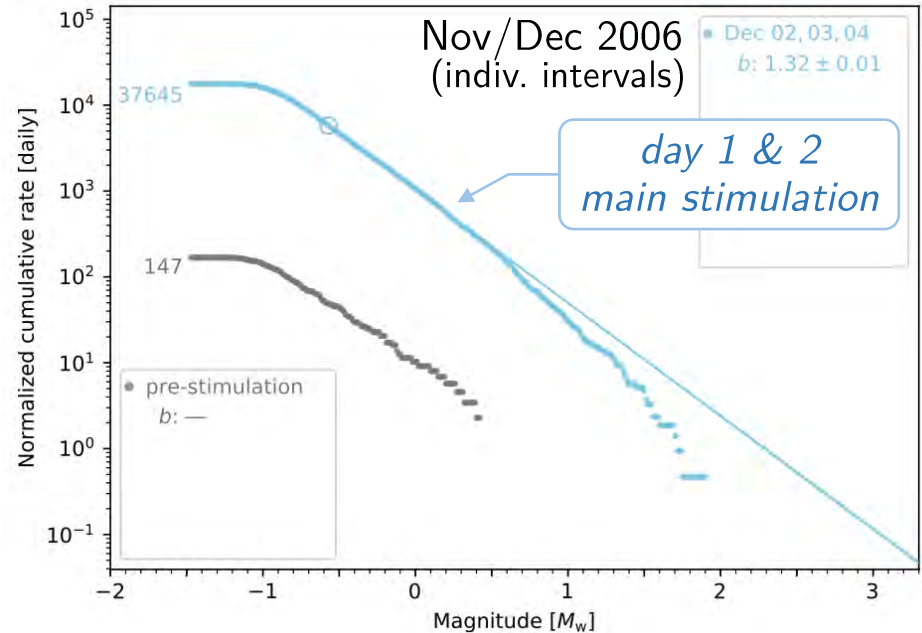
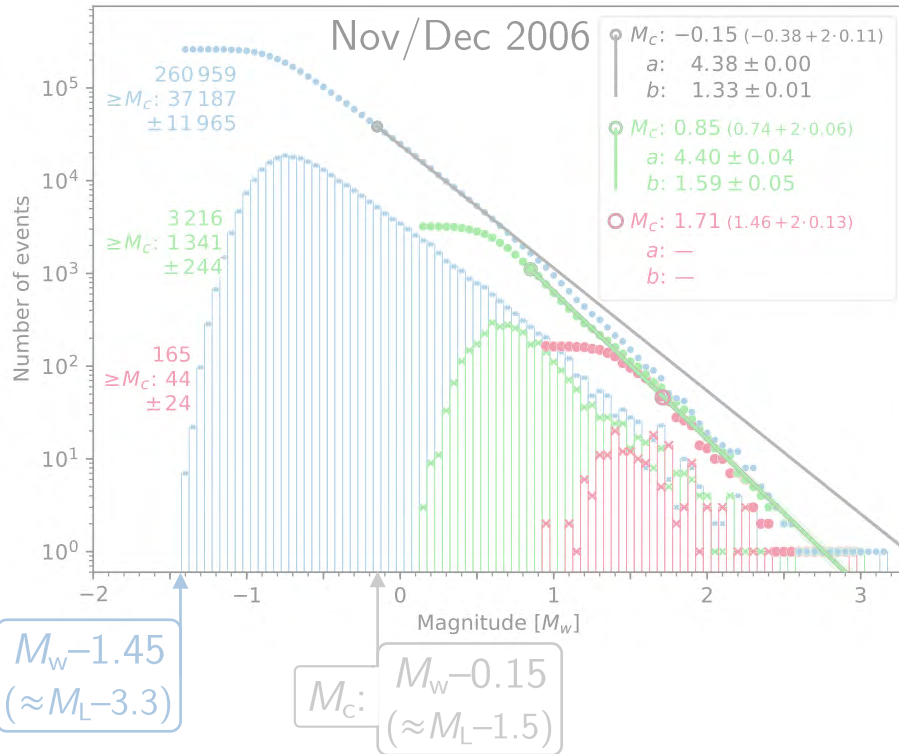
$N_{\text{est}} (M_w \geq 2.0) = 55$

$N_{\text{obs}} (M_w \geq 2.0) = 20$

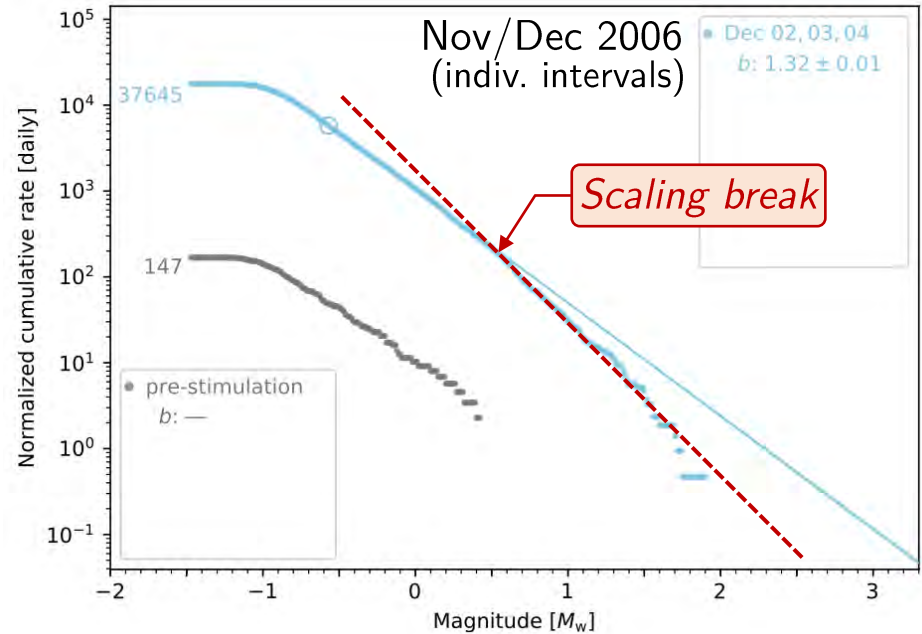
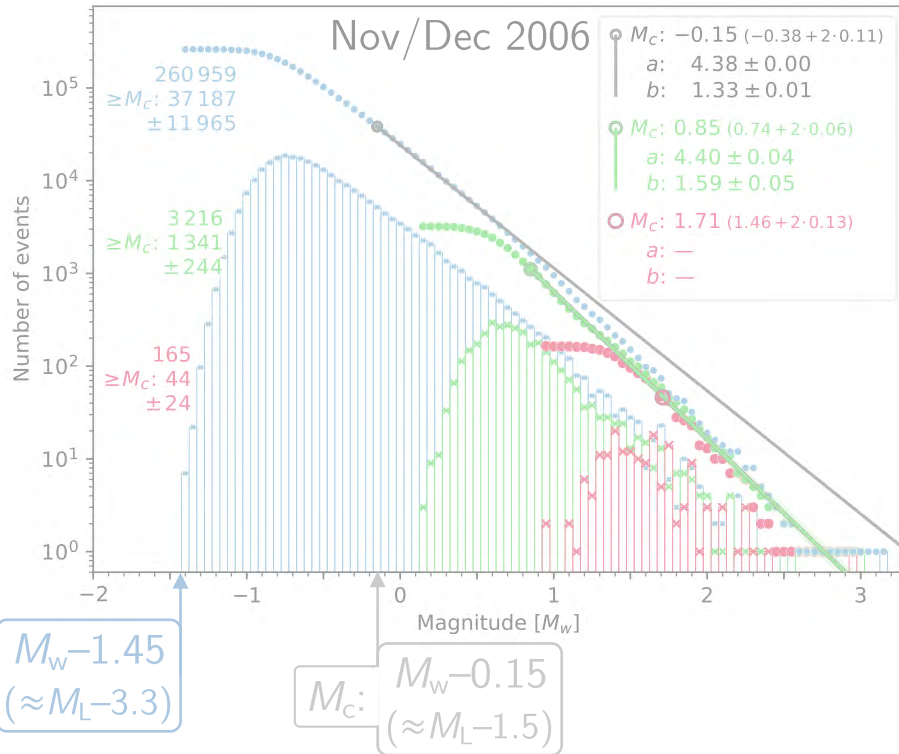
■ Frequency–Magnitude Distribution (FMD)



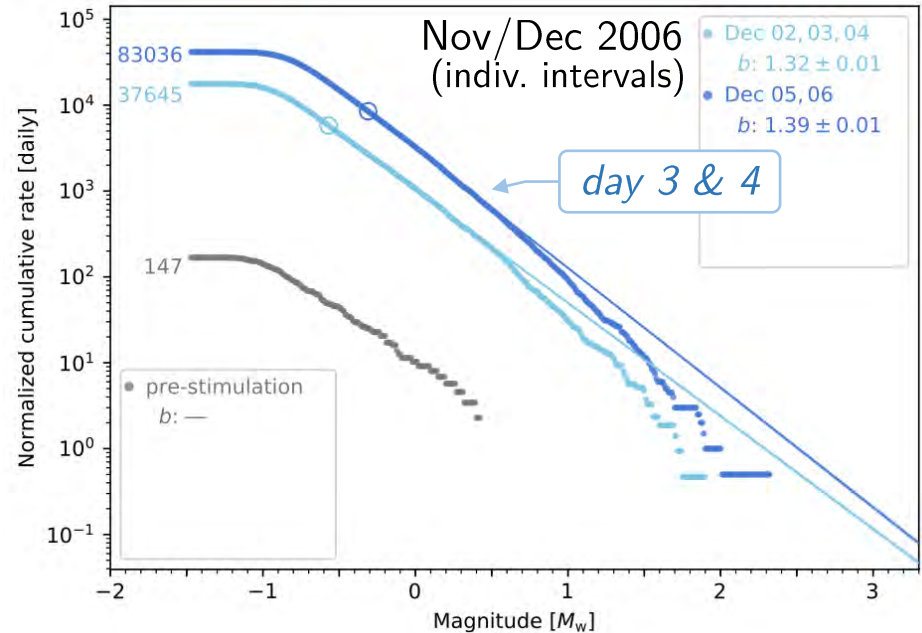
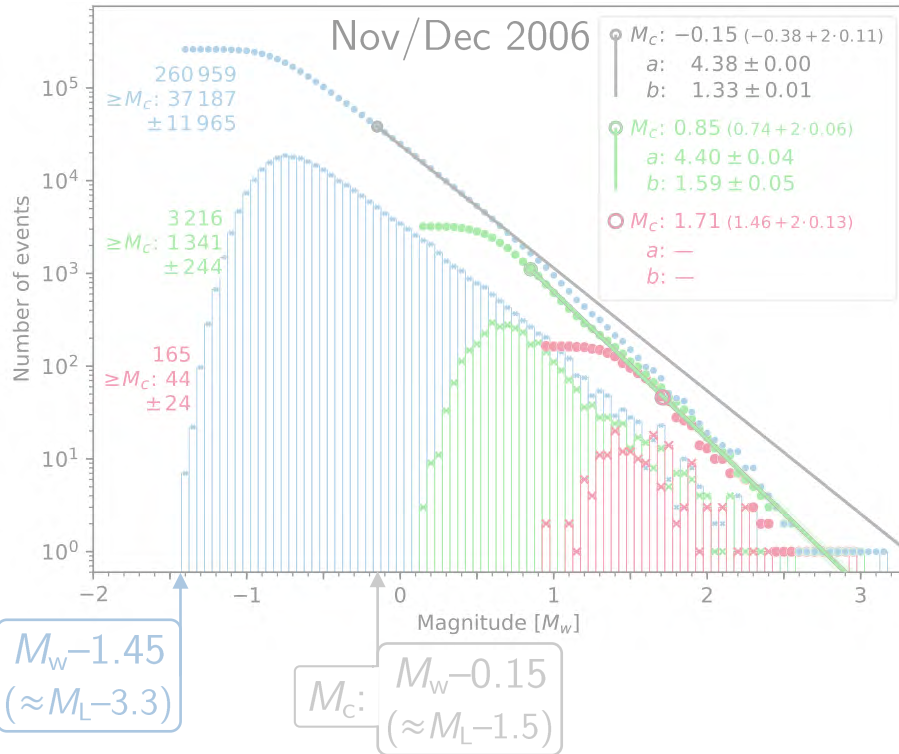
■ Frequency–Magnitude Distribution (FMD)



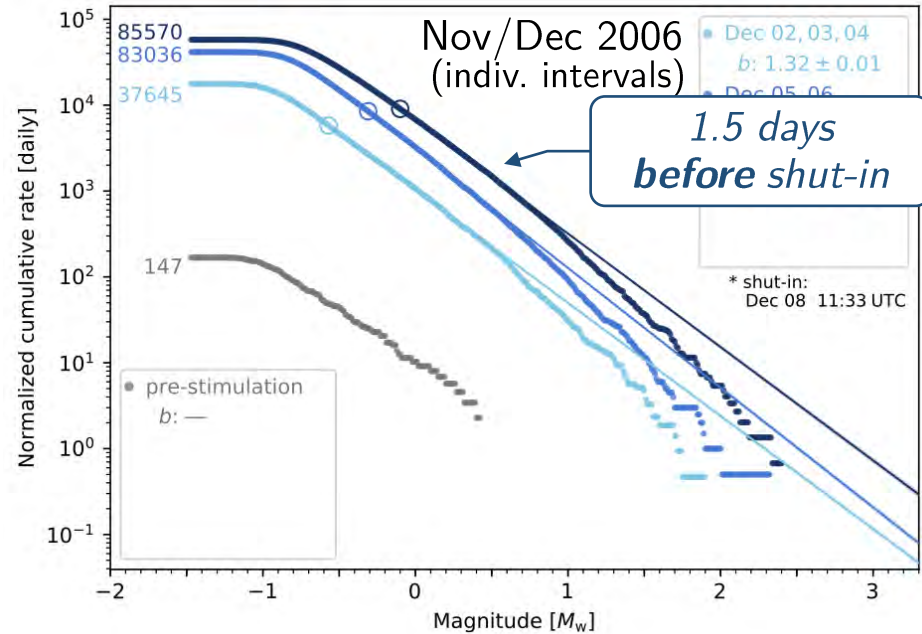
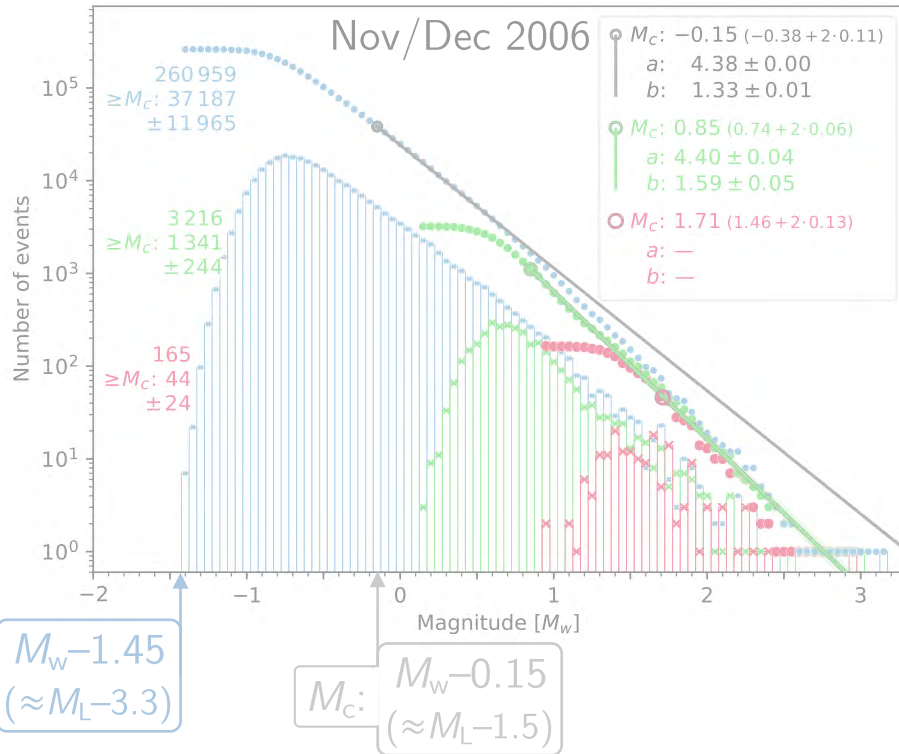
■ Frequency–Magnitude Distribution (FMD)



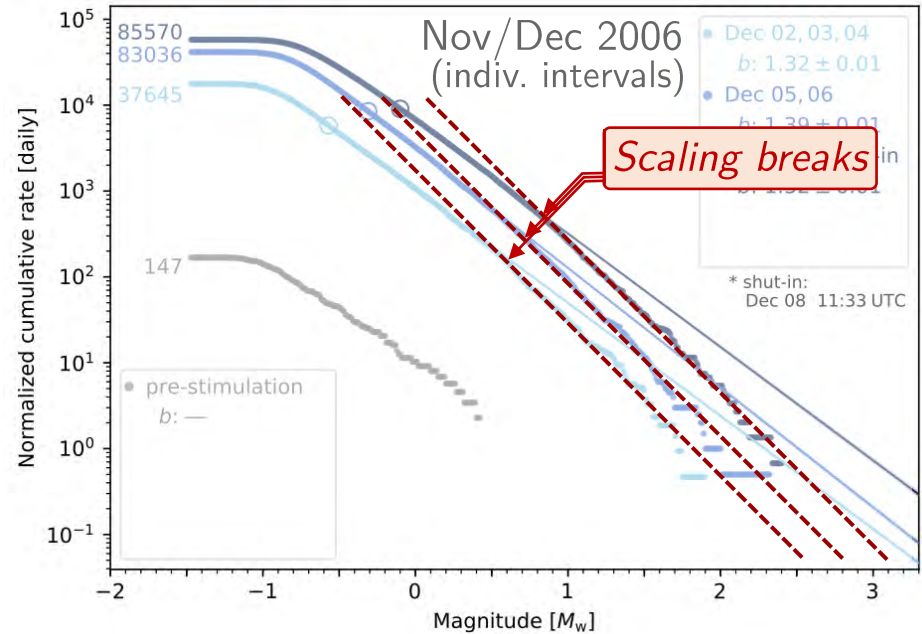
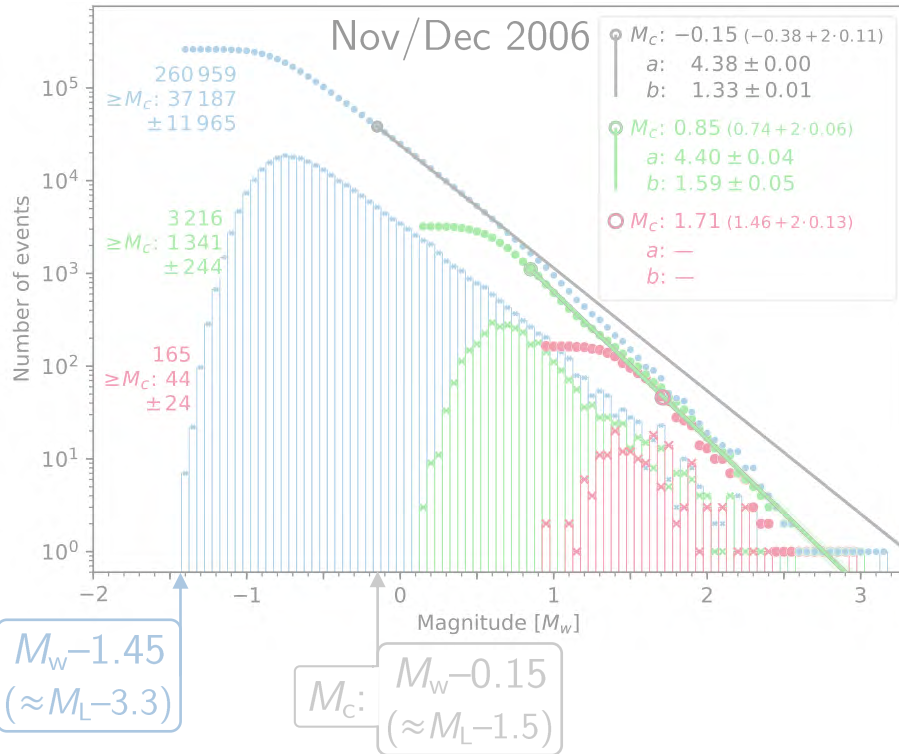
■ Frequency–Magnitude Distribution (FMD)



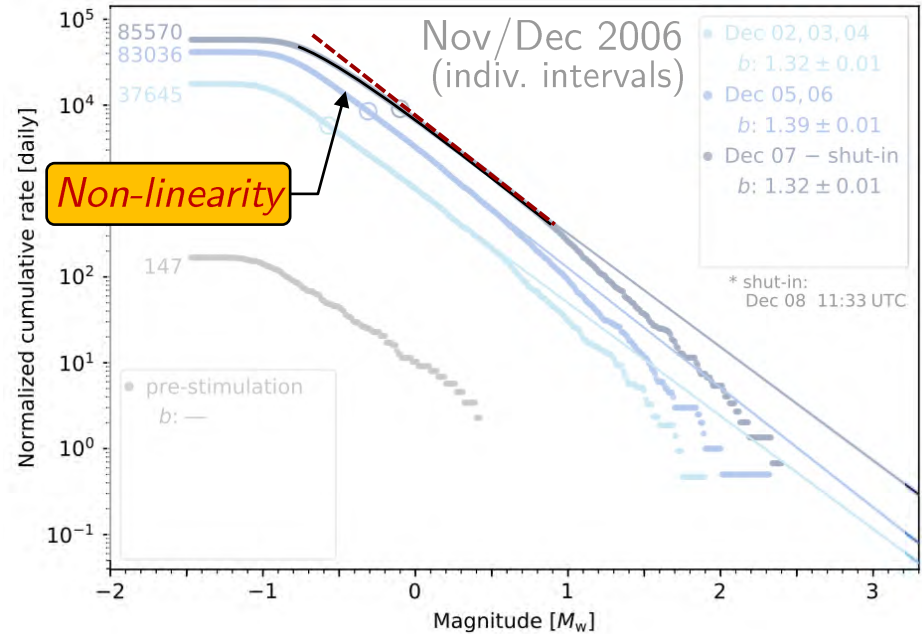
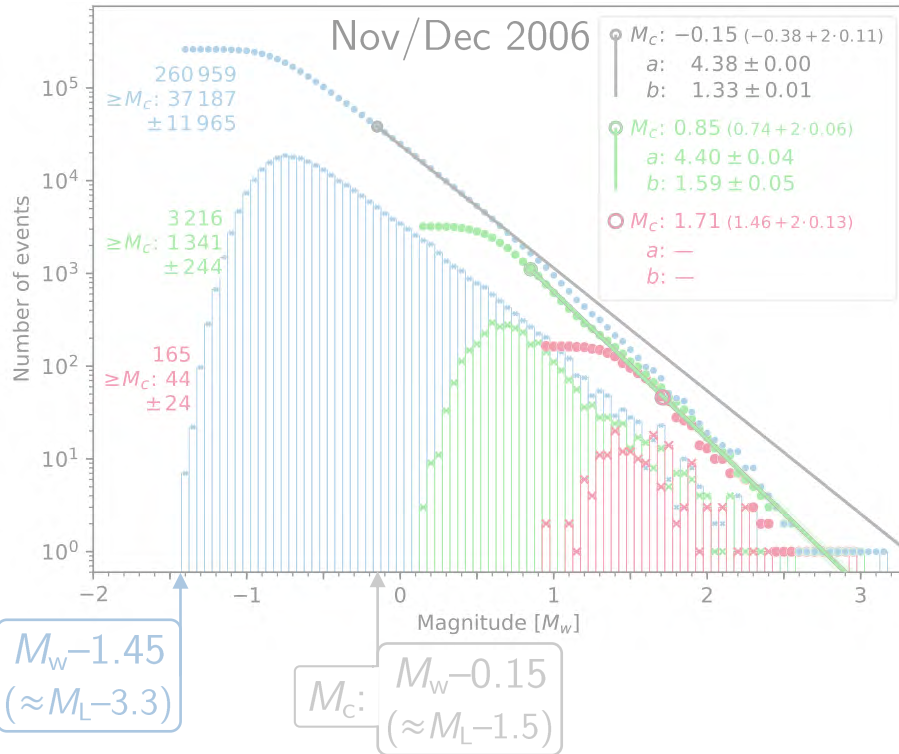
■ Frequency–Magnitude Distribution (FMD)



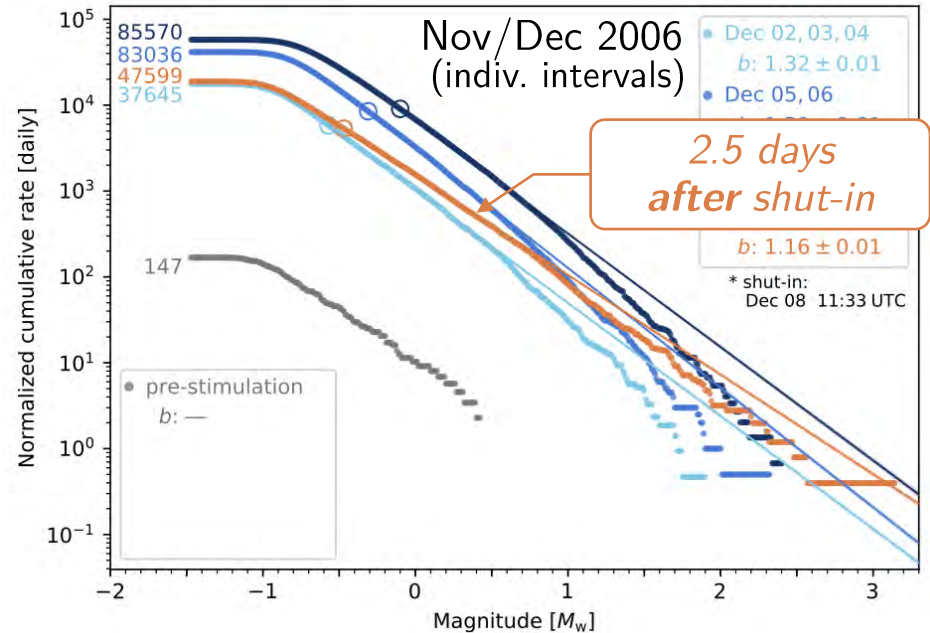
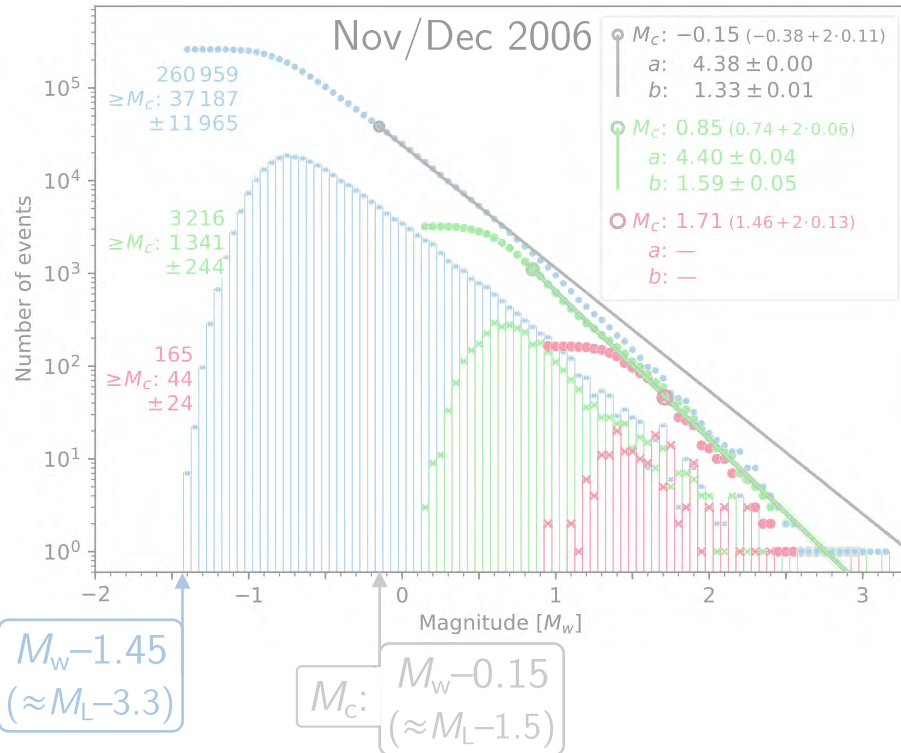
■ Frequency–Magnitude Distribution (FMD)



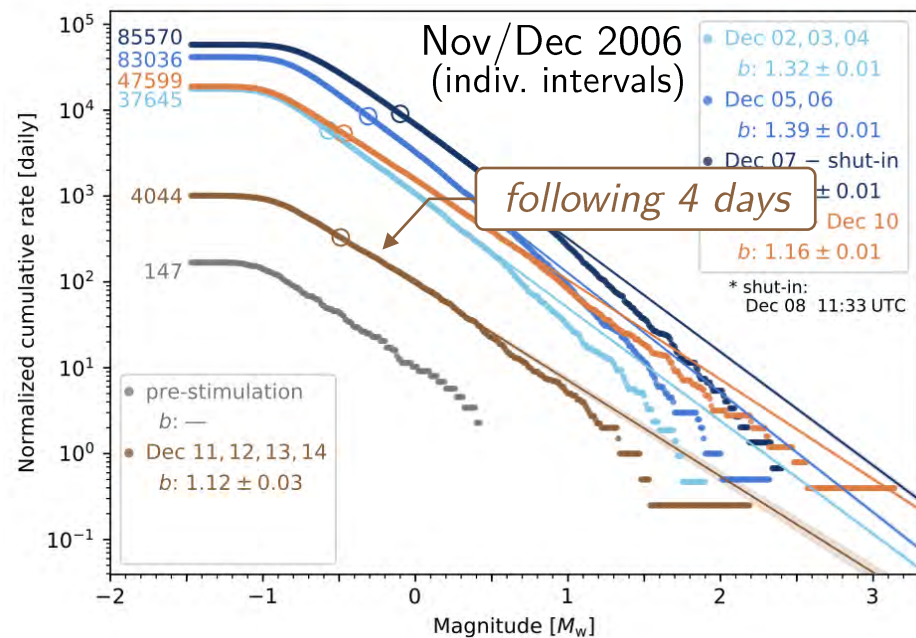
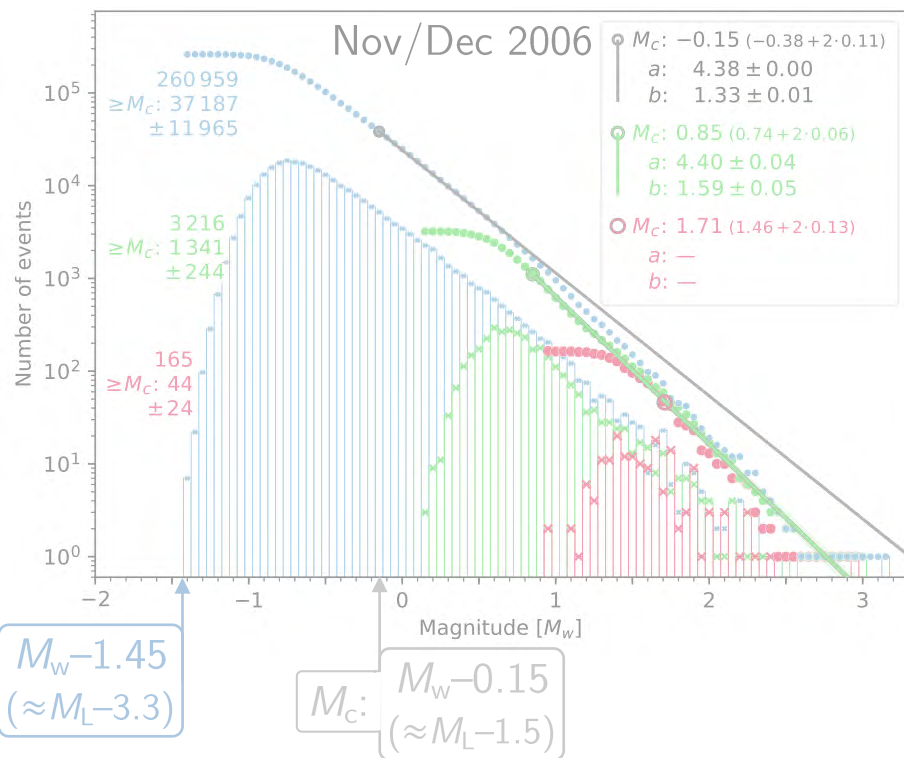
■ Frequency–Magnitude Distribution (FMD)



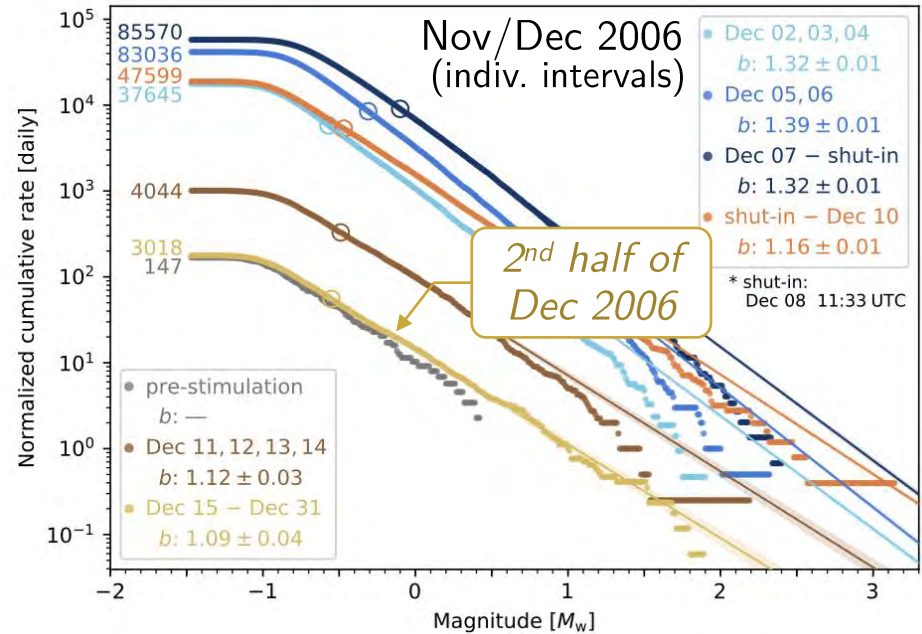
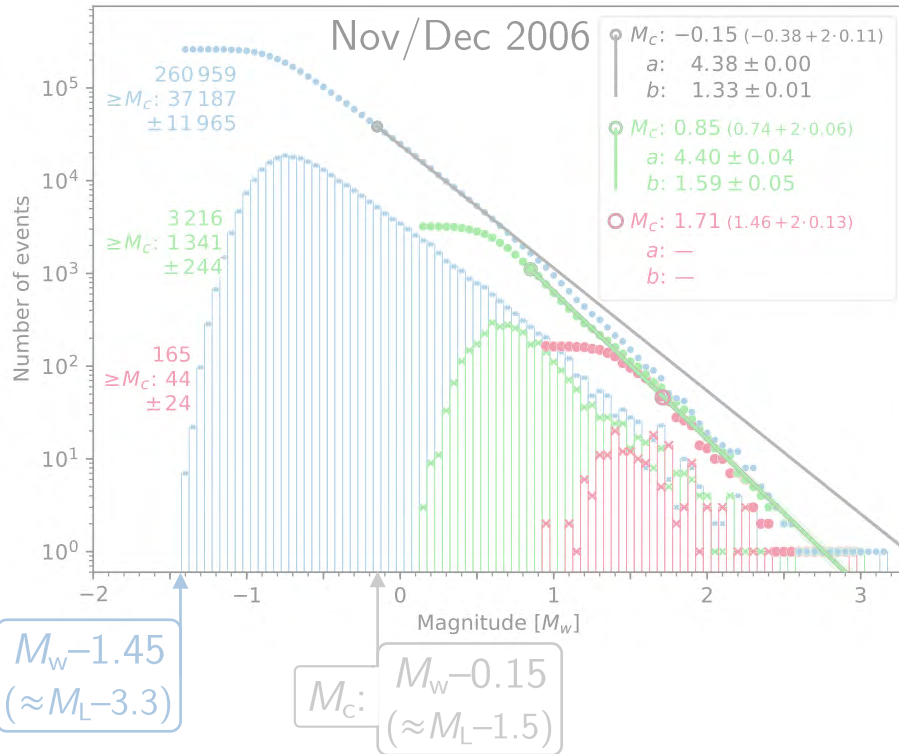
■ Frequency–Magnitude Distribution (FMD)

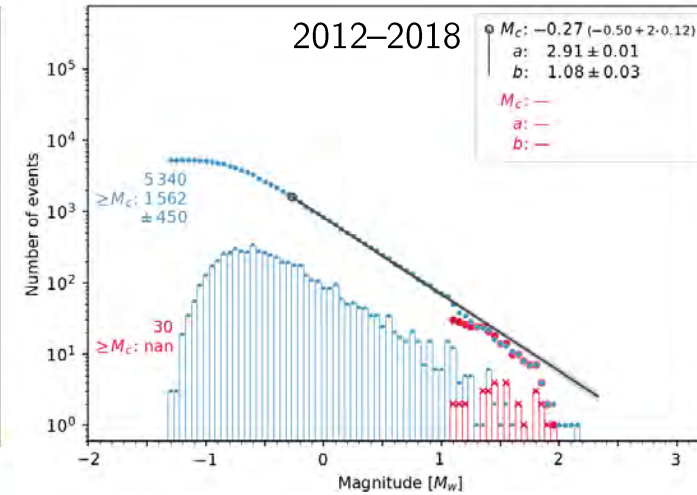
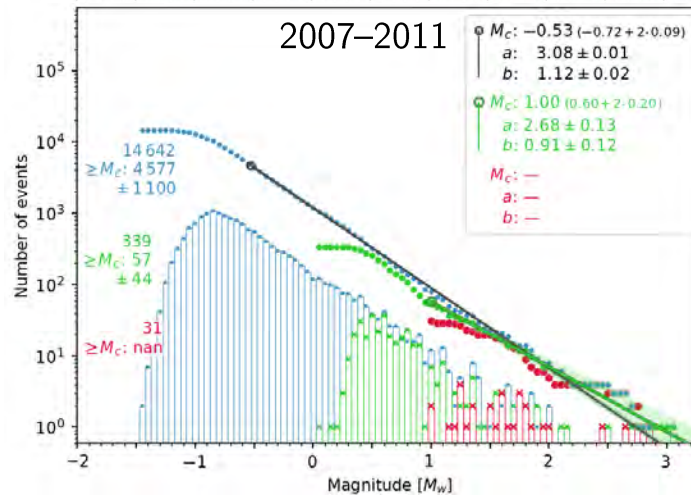
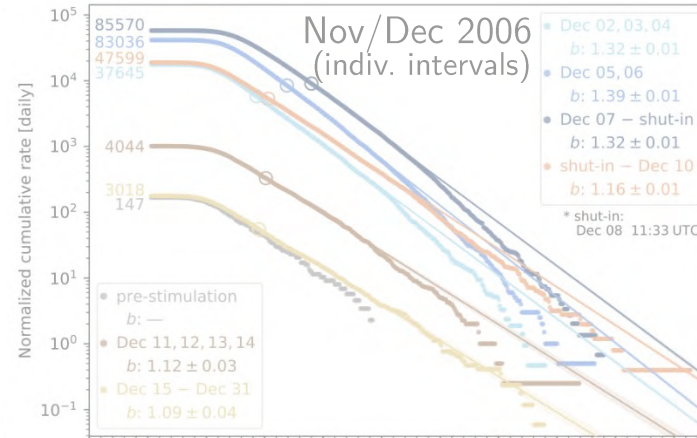
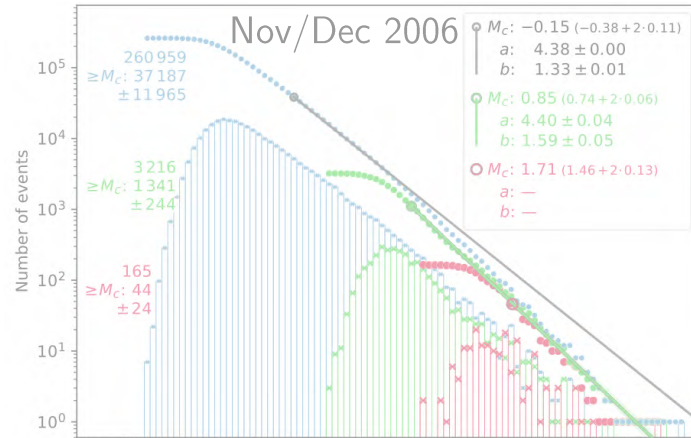


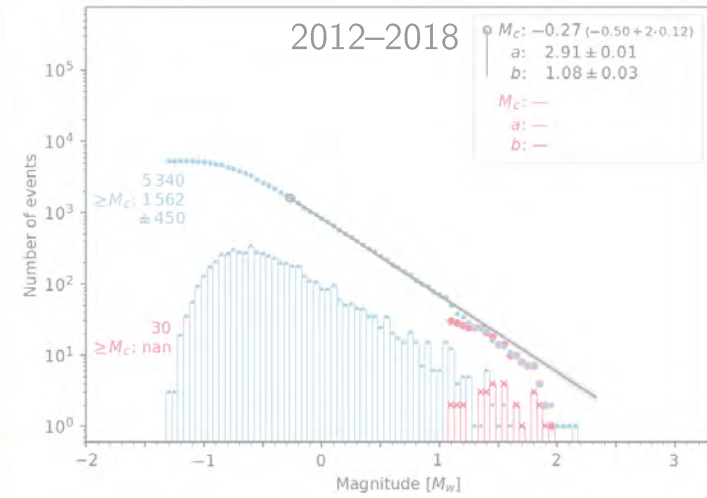
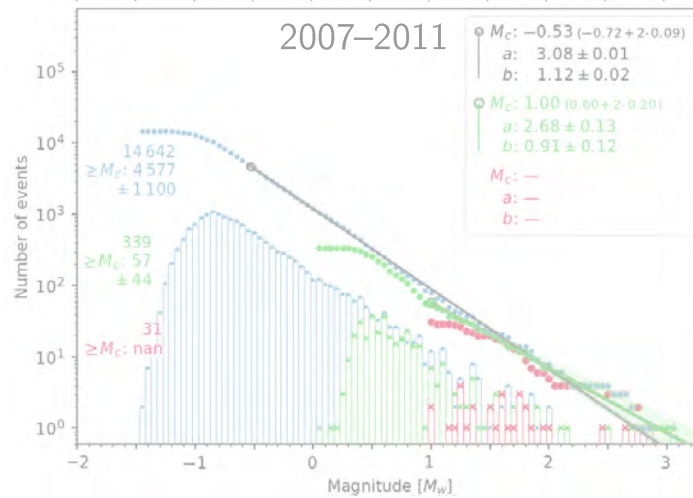
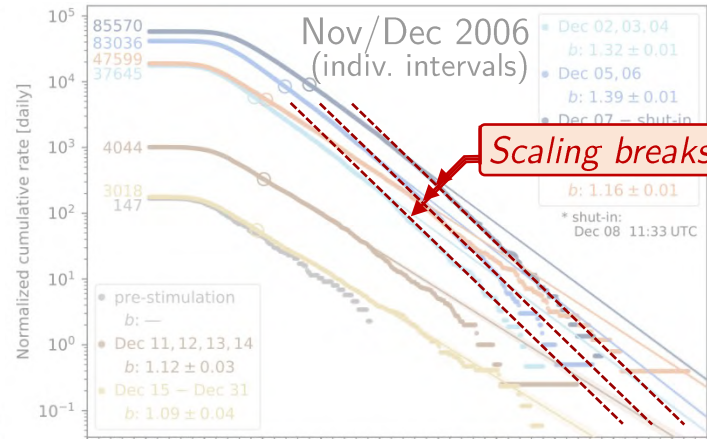
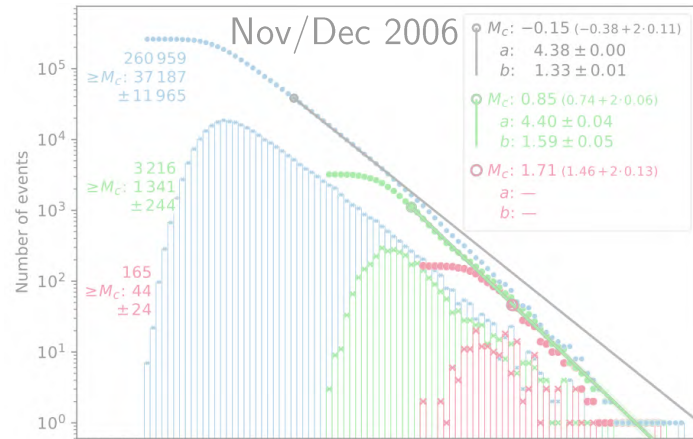
■ Frequency–Magnitude Distribution (FMD)

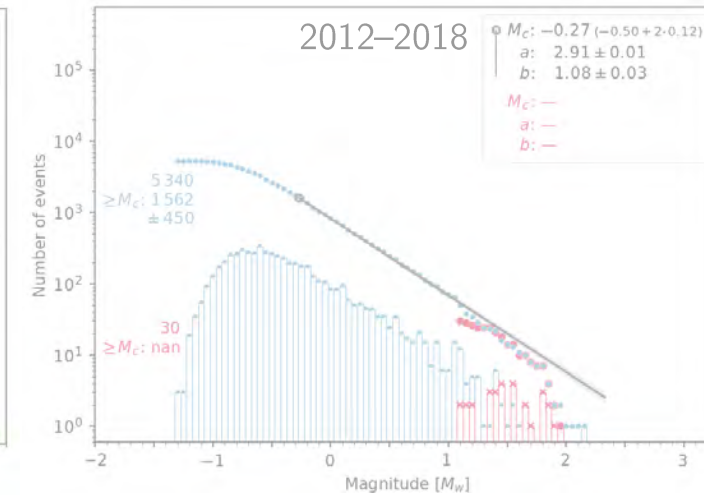
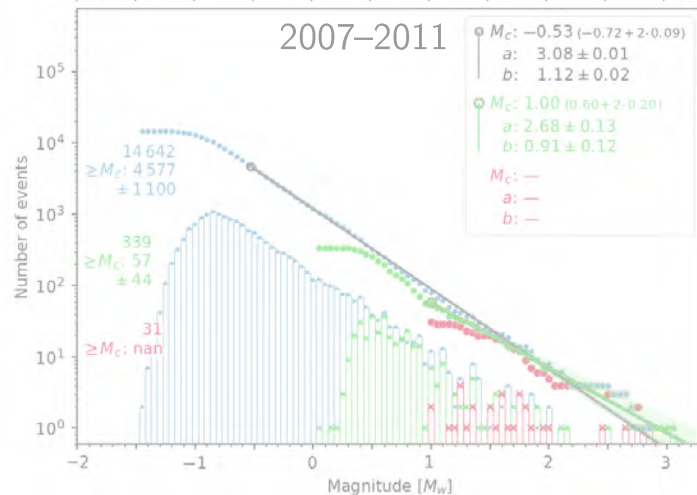
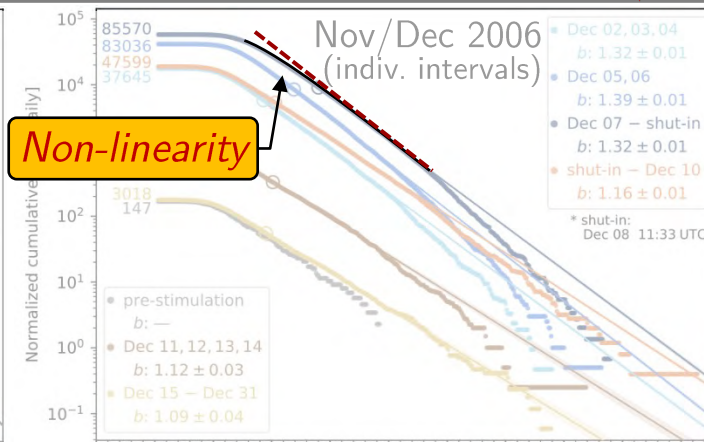
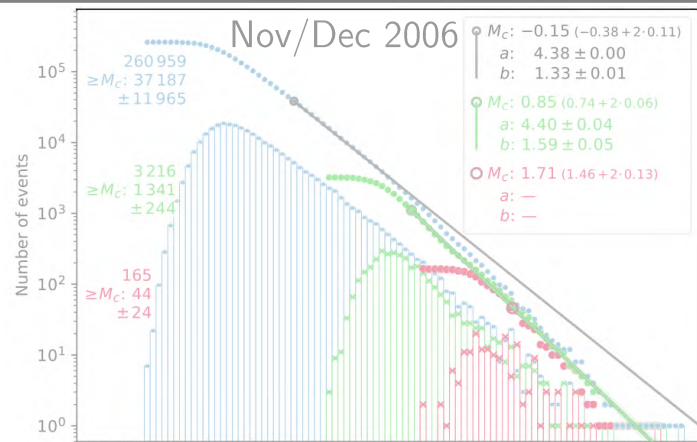


■ Frequency–Magnitude Distribution (FMD)

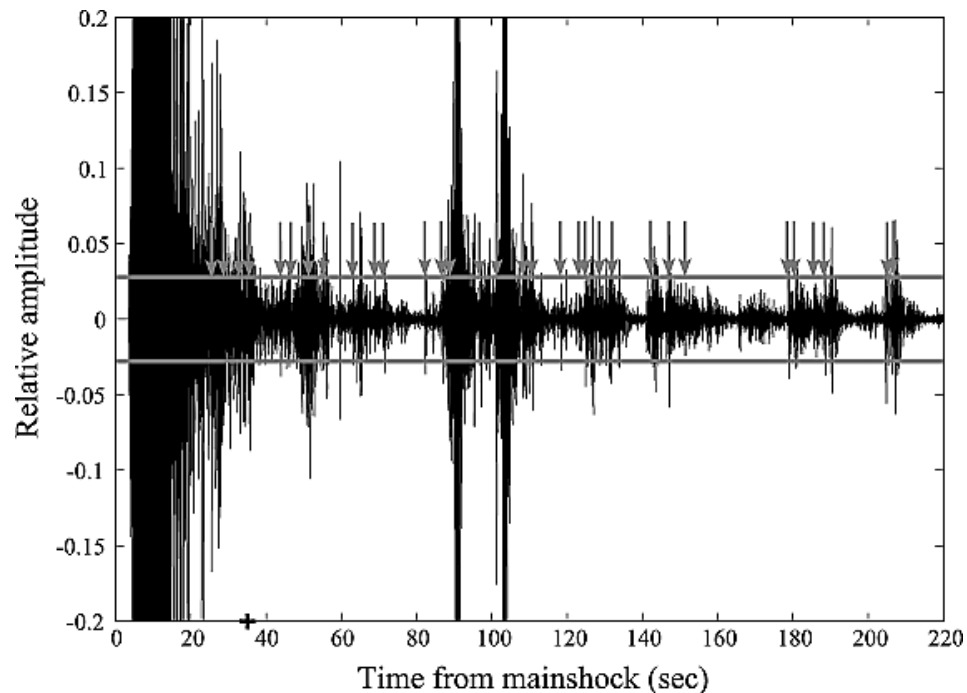




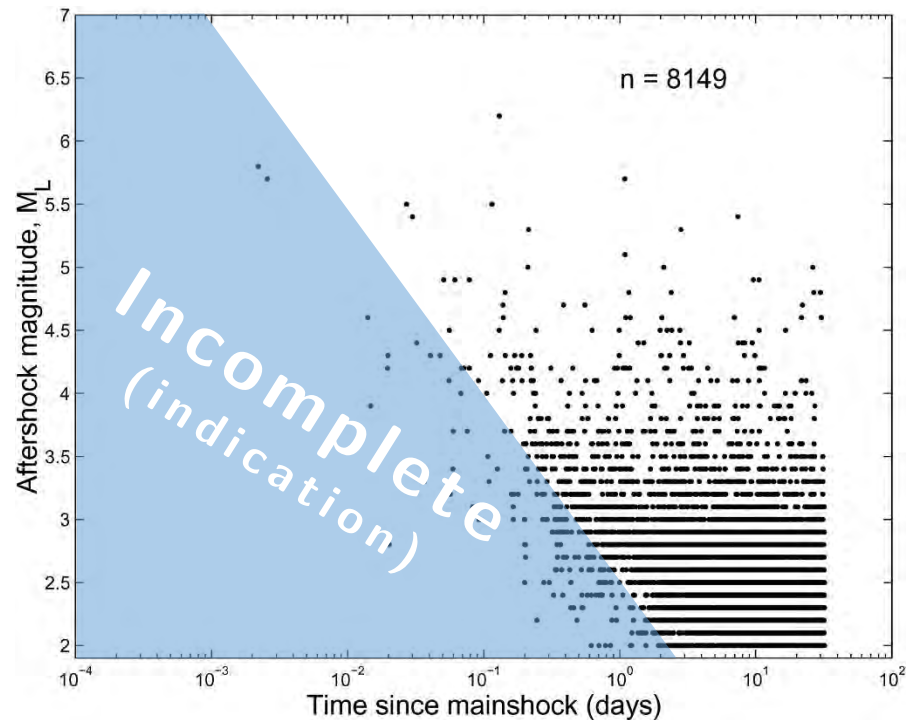




- Typically observed regionally/globally in aftershock sequences:



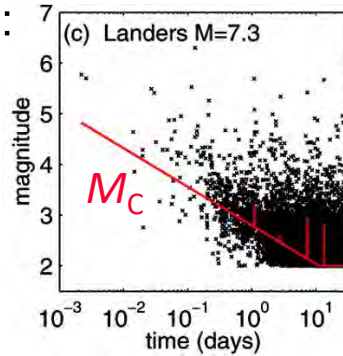
[Enescu et al. 2007]



[Kagan 2004] (modified)

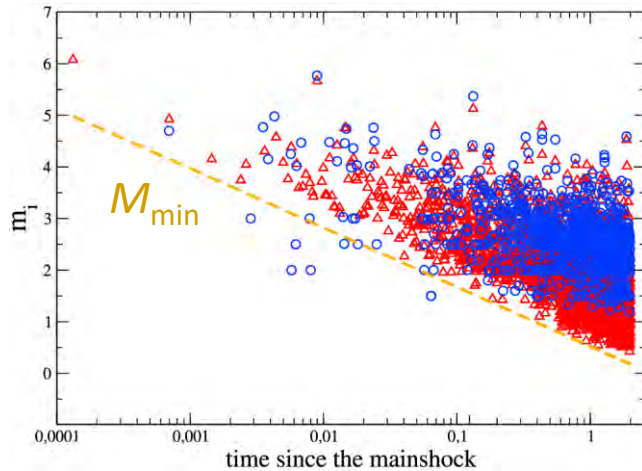
- Other's work:

- Quantify M_c :



[Helmstetter et al. 2006]

- Improve M_{\min} :



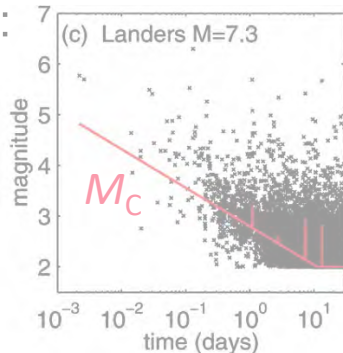
[de Arcangelis et al. 2018]

using template matching following Peng et al. 2007

- Other's work:

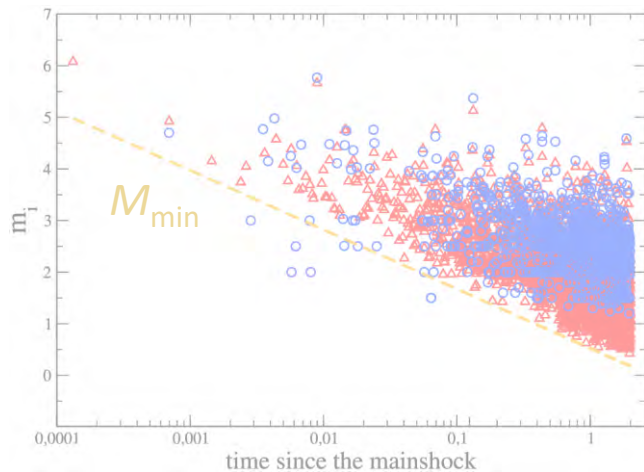
- Quantify M_C :

[Helmstetter et al. 2006]

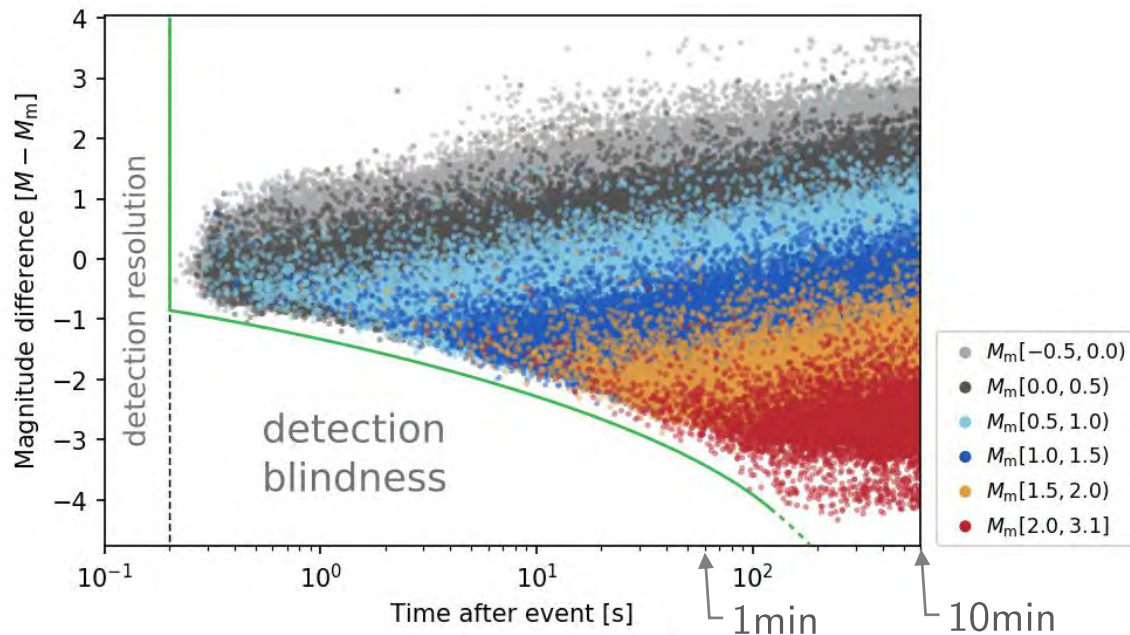


- Improve M_{\min} :

[de Arcangelis et al. 2018] using matching-filtering

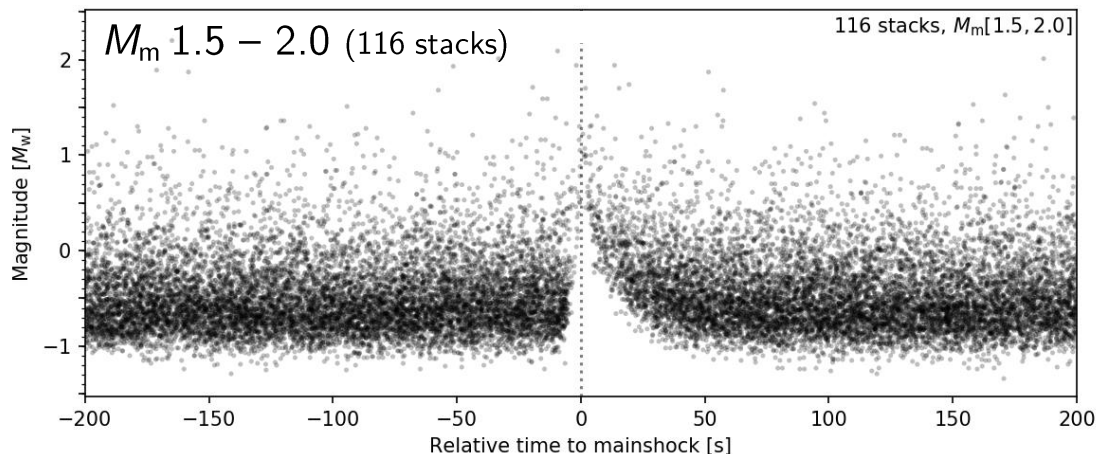
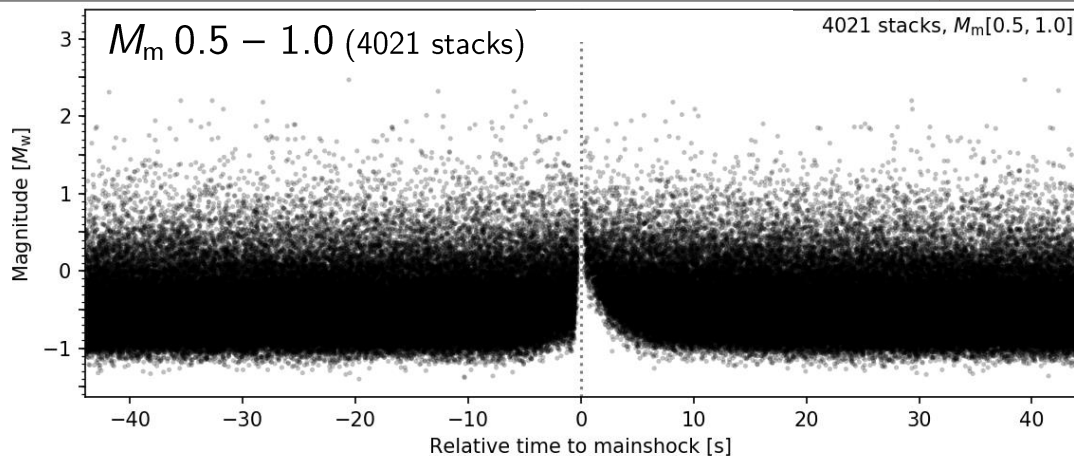


- We observe it, too!** Here: during the injection period



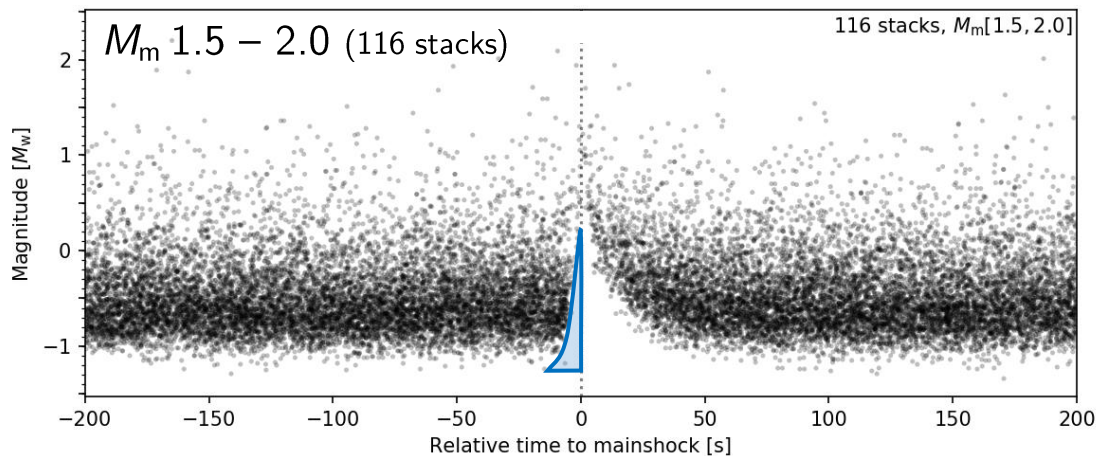
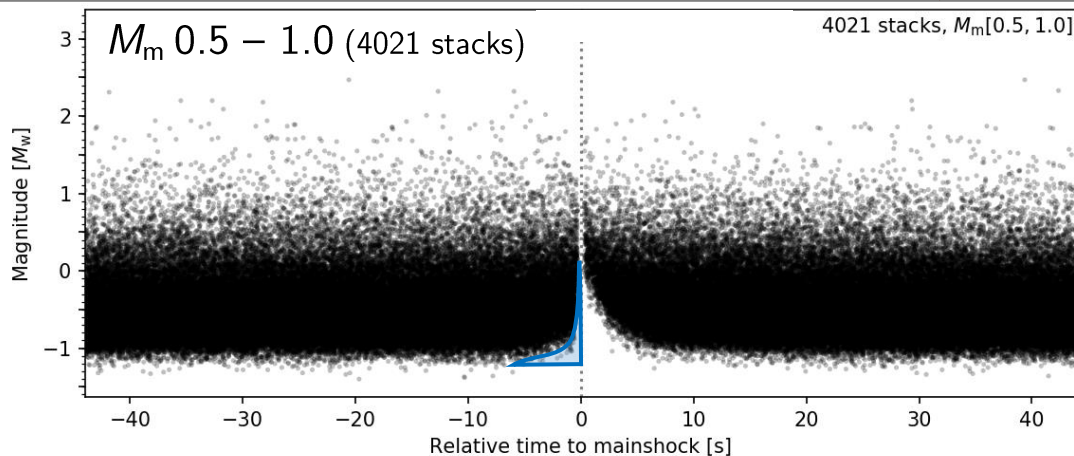
Catalog stacking:
(for different M_m)

- **Constant rate**
before and after the events
(during injection period)



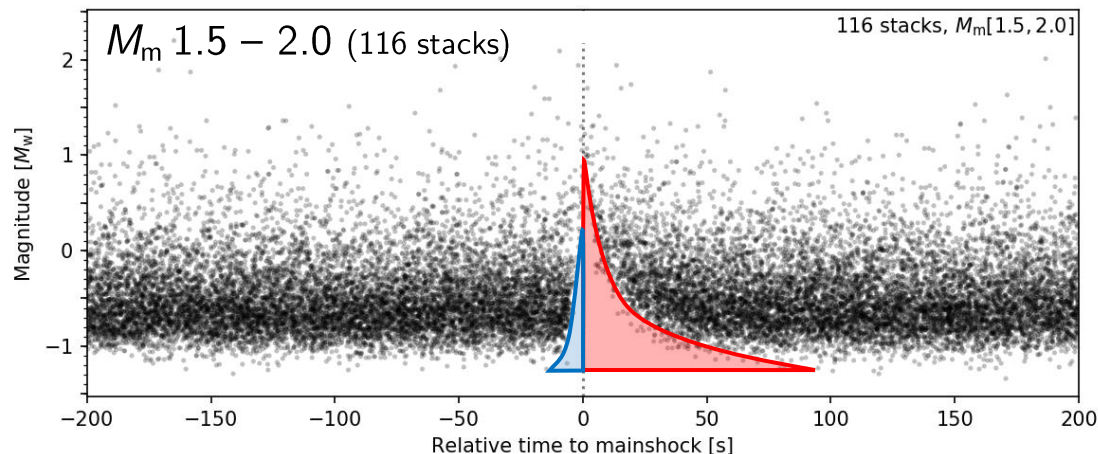
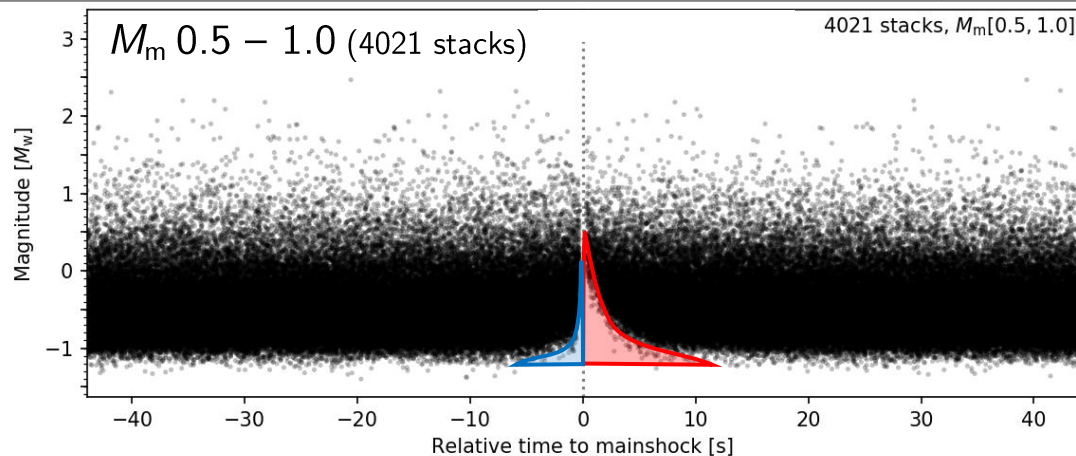
Catalog stacking: (for different M_m)

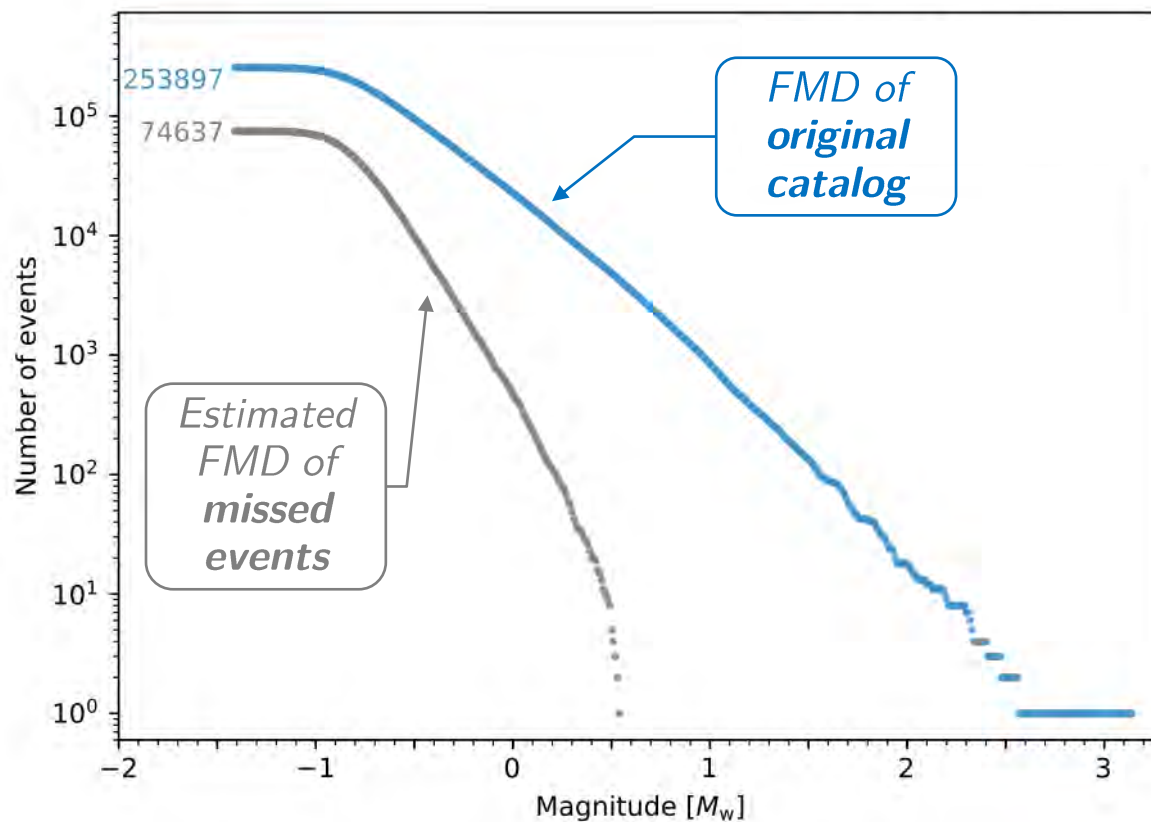
- **Constant rate**
before and after the events
(during injection period)
- ... except for the incompleteness:
 - **Prior to “mainshocks”:**
non-causal filter effect

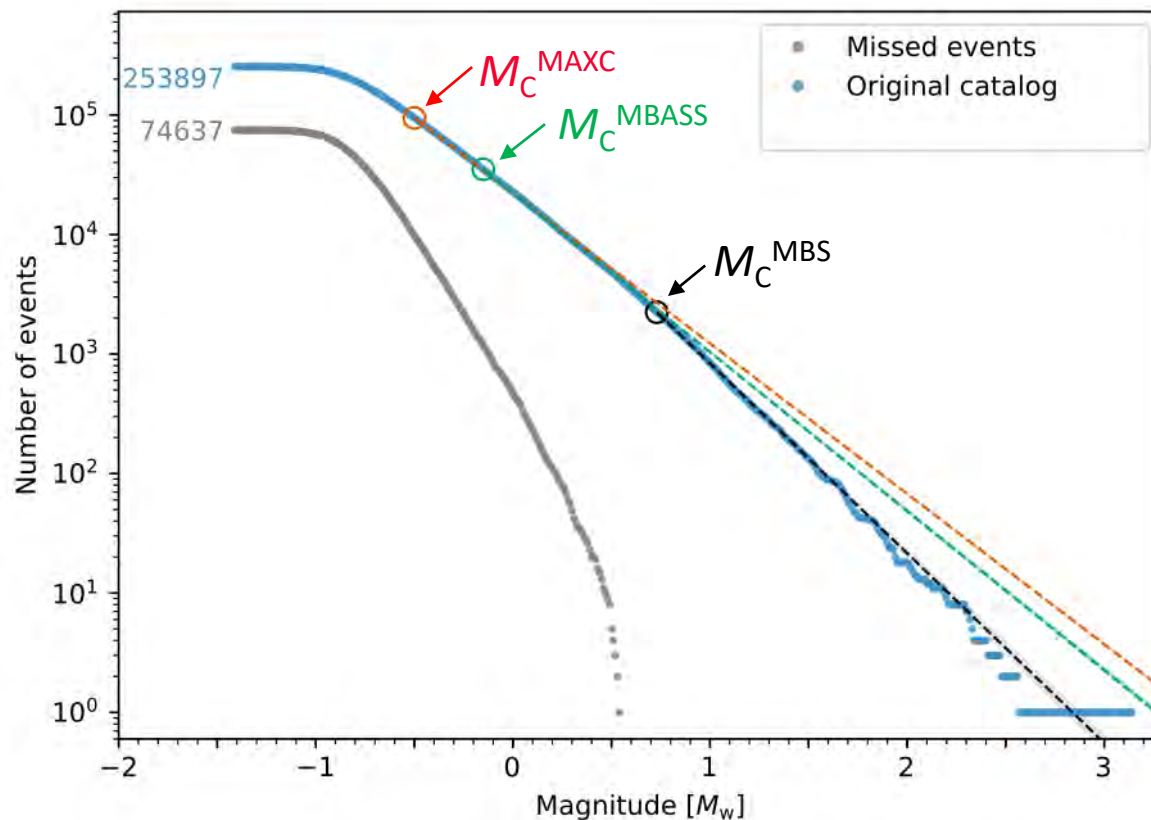


Catalog stacking: (for different M_m)

- **Constant rate**
before and after the events
(during injection period)
- ... except for the incompleteness:
 - Prior to “mainshocks”:
non-causal filter effect
 - **Afterwards:**
aftershock blindness

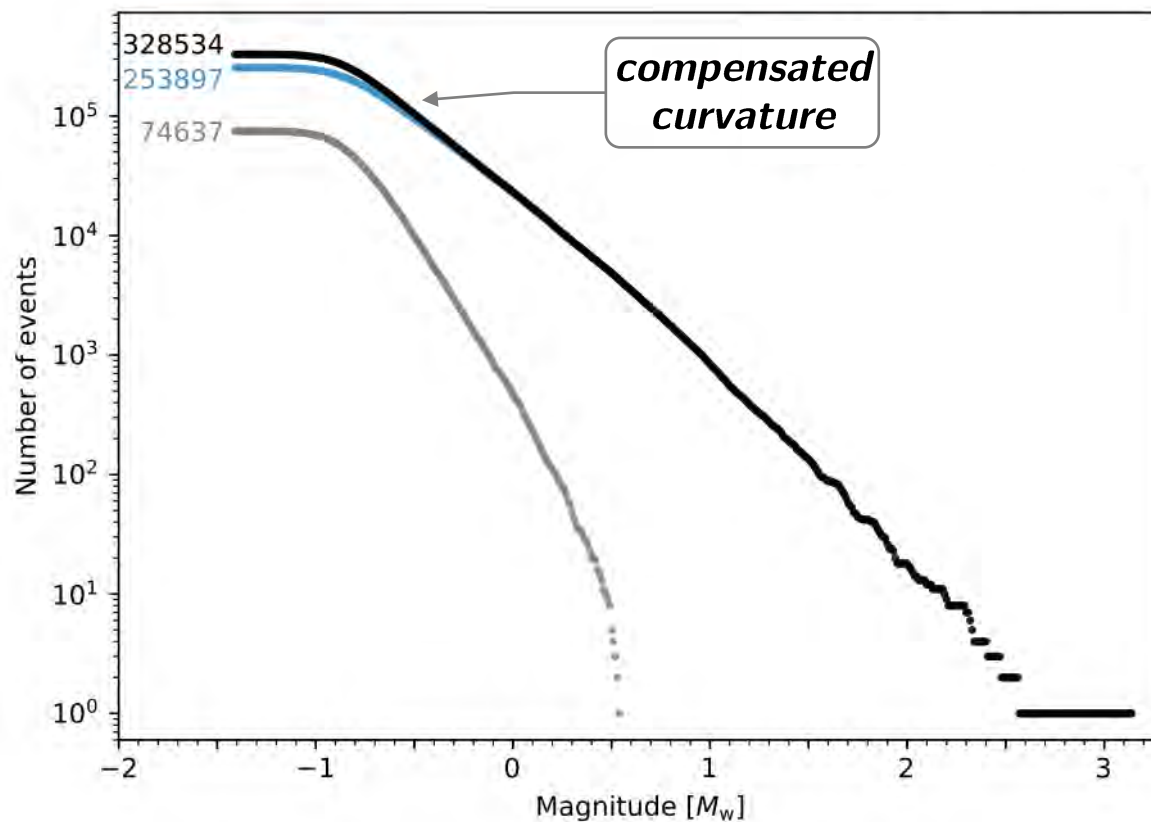


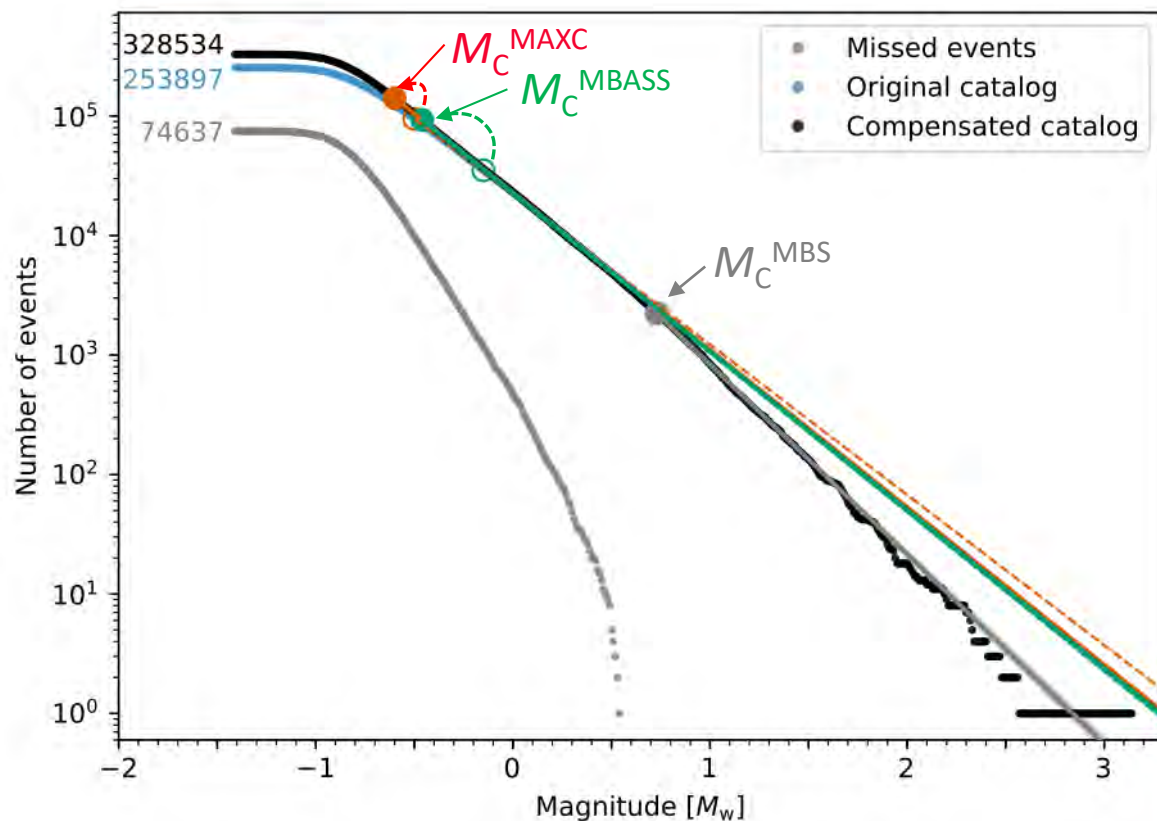




M_c estimations:

- **MAXC** +0.2
(*maximum curvature*)
[Wössner & Wiemer 2007]
- **MBASS** +2 σ
(*median-based analysis of the segment slope*)
[Amorèse 2007]
- **MBS**
(*b-value stability*)
[Cao & Gao 2002]

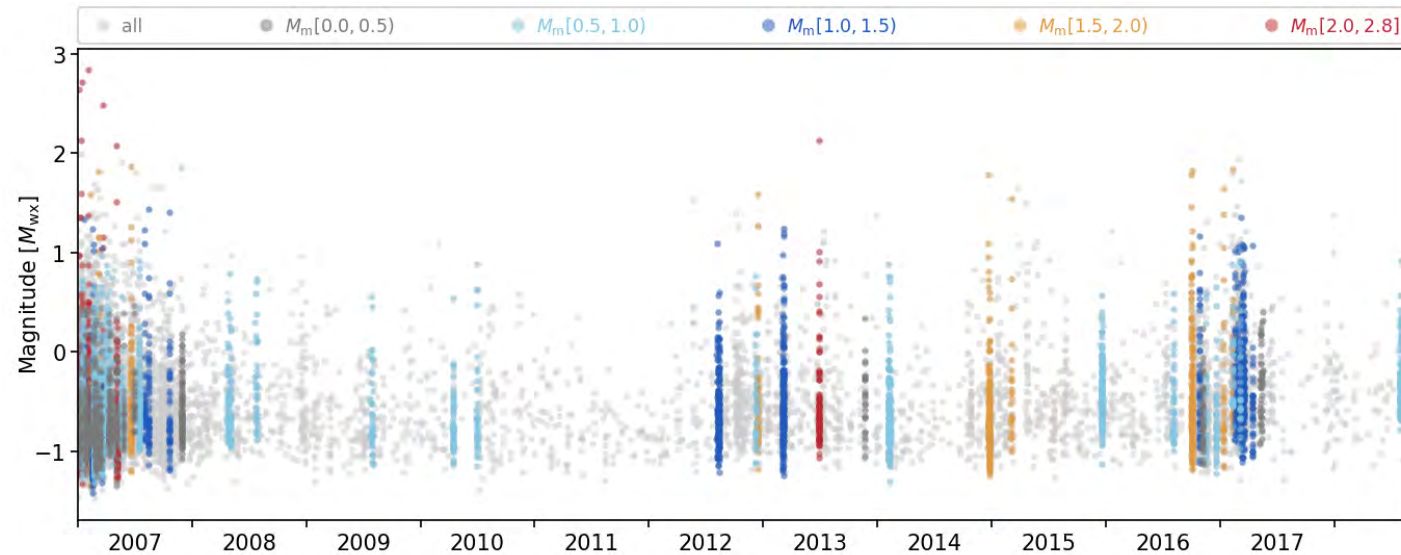


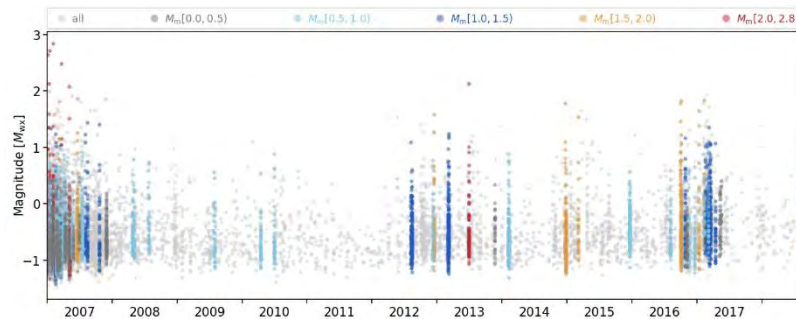


M_C estimations:

- **MAXC** +0.2
(maximum curvature)
[Wössner & Wiemer 2007]
- **MBASS** +2 σ
(median-based analysis of the segment slope)
[Amorèse 2007]
- **MBS**
(b-value stability)
[Cao & Gao 2002]

- Identified clusters (and grouped by 'main event' size, M_m)

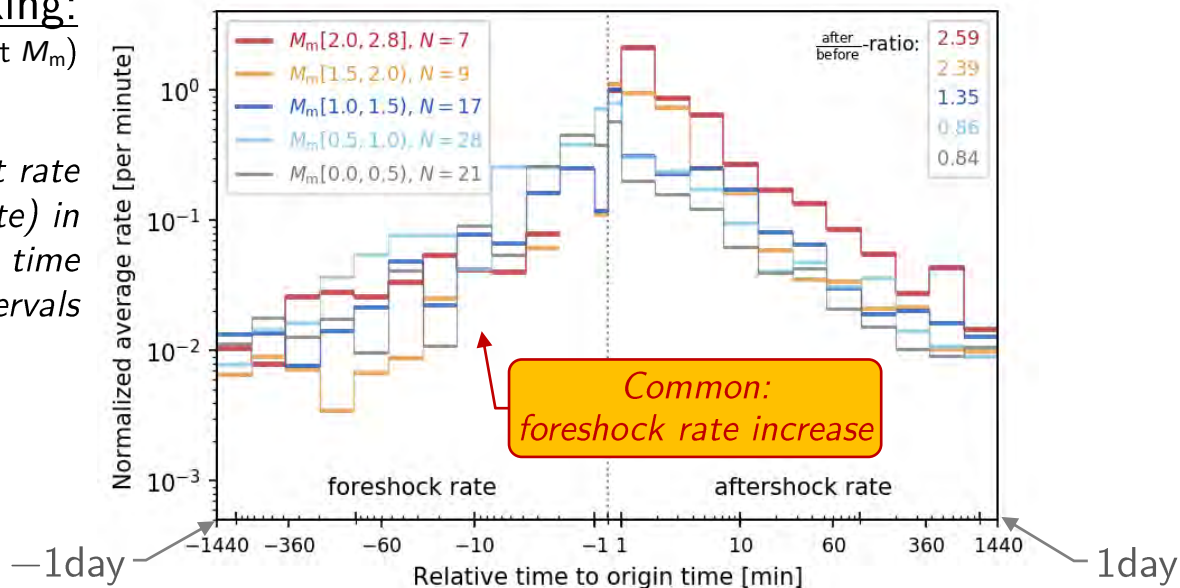


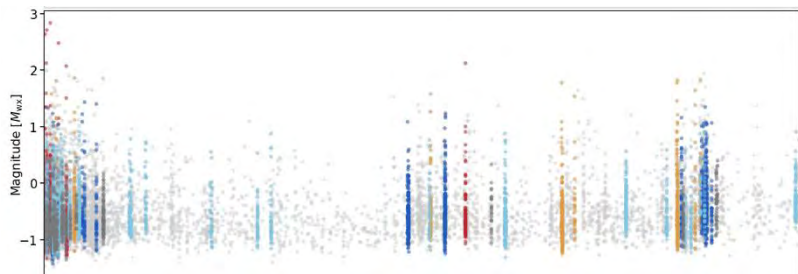


Stacking:

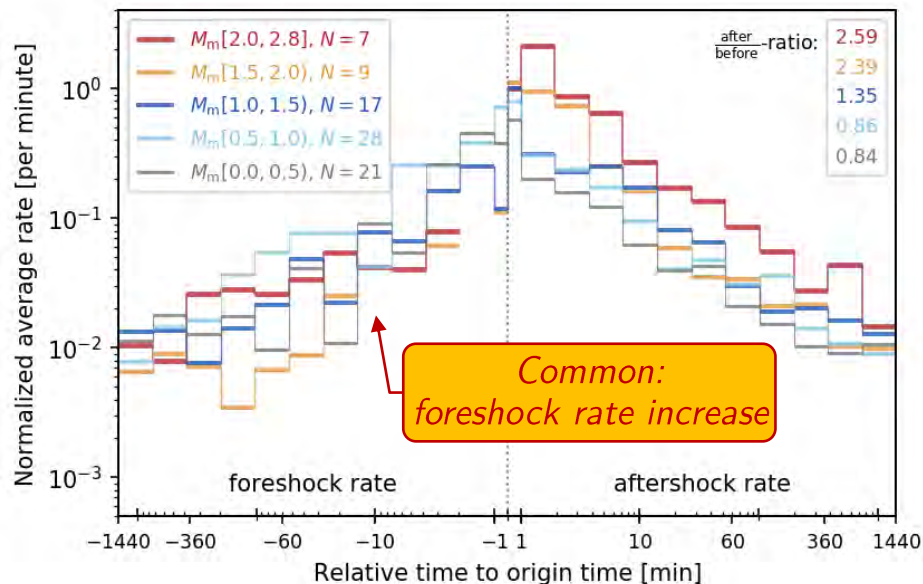
(for different M_m)

Average event rate
(per minute) in
log-spaced time
intervals



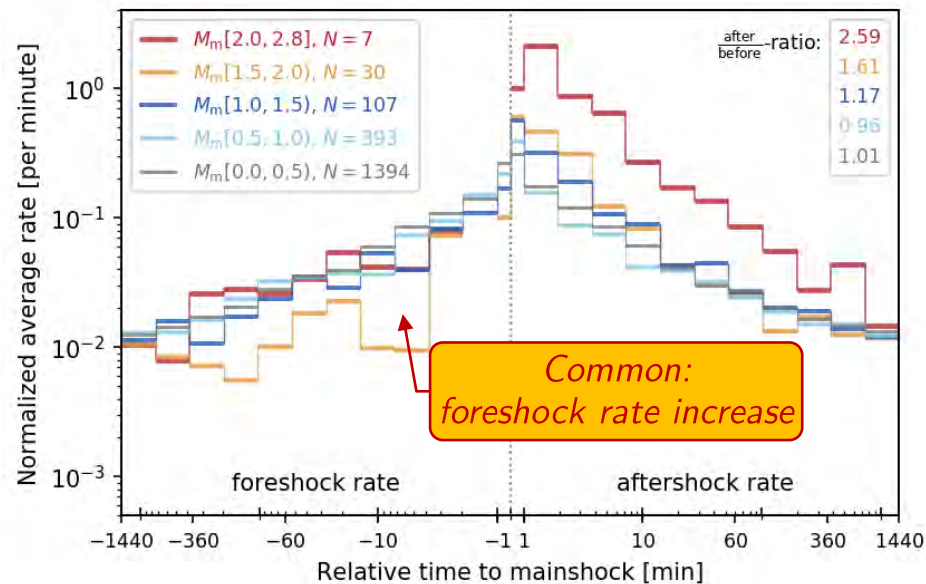


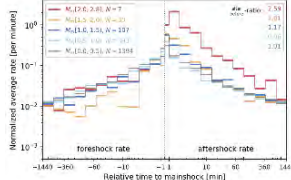
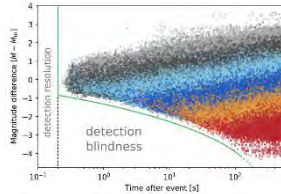
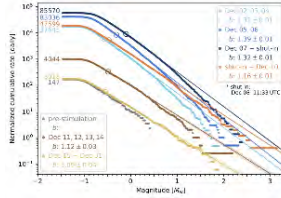
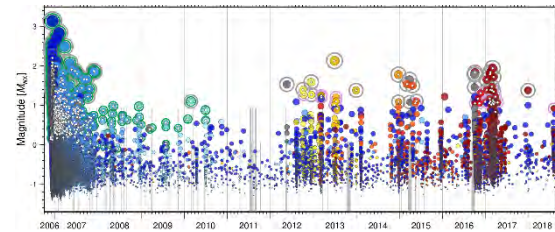
Stacking 'main events' that form clusters



(e.g., including aftershocks of larger events)

Comparison: Stacking all events





- **Consistent high-res. catalog** covering the whole life span of Basel EGS
 - New possibilities for analyses and understanding of
 - Basel sequence
 - Induced seismicity in general (?)

- **Scaling break in FMD** (during injection)
 - need to work on models that explain that
 - implications for future mitigation strategies

- **Detection limitation**
 - method-independent!
 - ➔ needs robust M_c estimation method (e.g., MBASS)

- **Indications of precursory signals**
 - caused by ...?

Thank you!

- Scaling break in FMD (during injection)
 - need to work on models that explain that
 - implications for future mitigation strategies
- Detection limitation
 - method-independent!
 - ➔ needs robust M_c estimation method (e.g., MBASS)
- Indications of precursory signals
 - caused by ...?

