ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Induced seismicity risk mitigation:
An actuarial approach

A. Mignan (ETH Zurich)

in collaboration with M. Broccardo, S. Wiemer & D. Giardini

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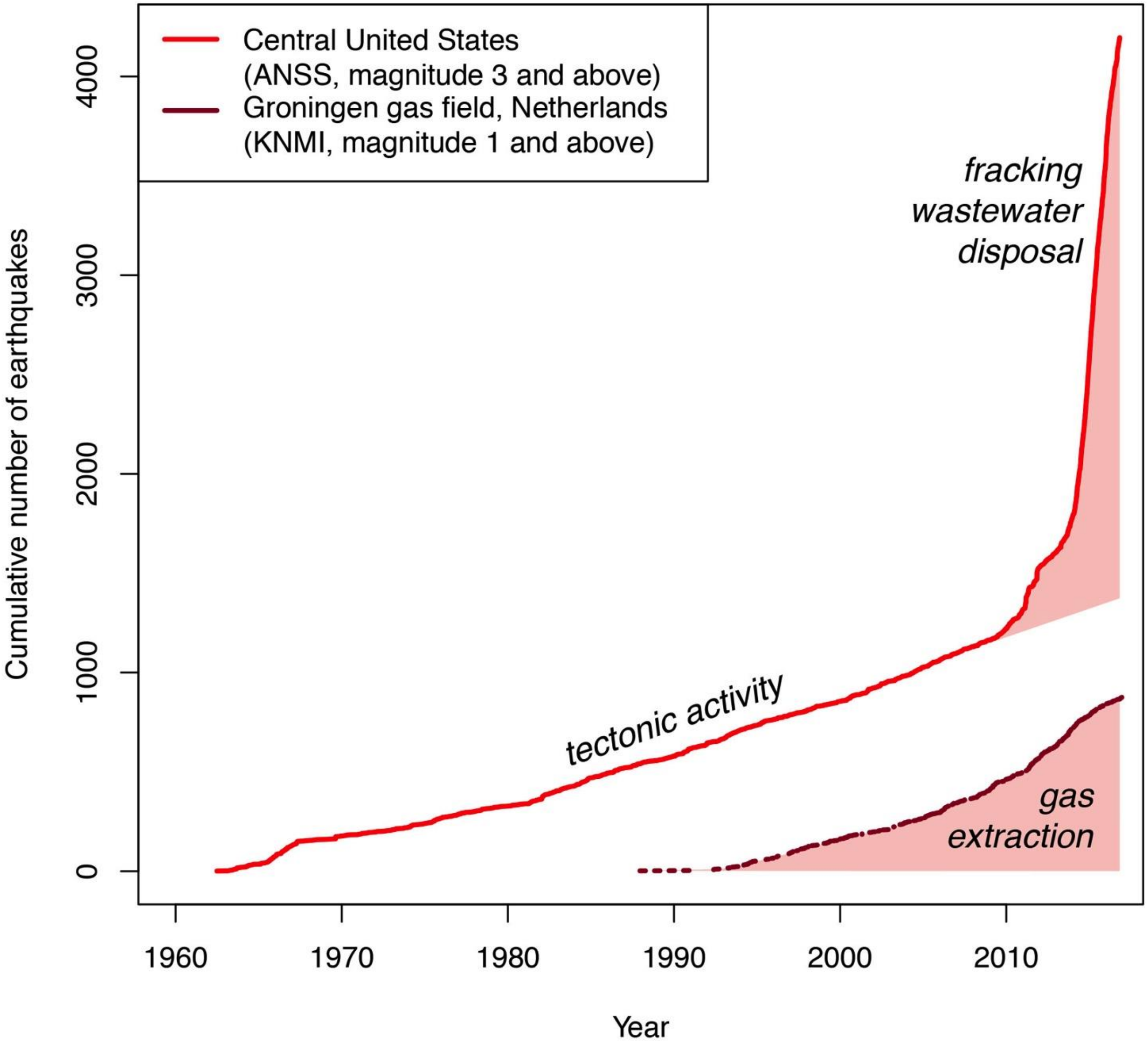
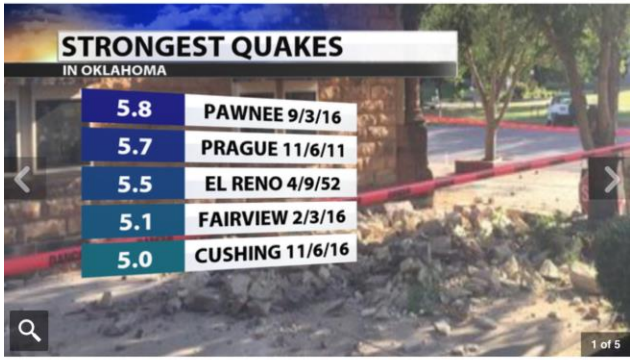
The challenge of mitigating induced seismicity



Disposal wells to shut down after Oklahoma earthquakes

Updated: Jul 27, 2017 - 11:49 AM



source: FOX 23 News

Shored-up homes are a common sight in earthquake-hit Groningen

Life & Culture June 2, 2016

A condemned and shored-up cafe. Photo: Graham Dockery

source: Dutch News

Traffic-Light Systems (TLS) as a solution

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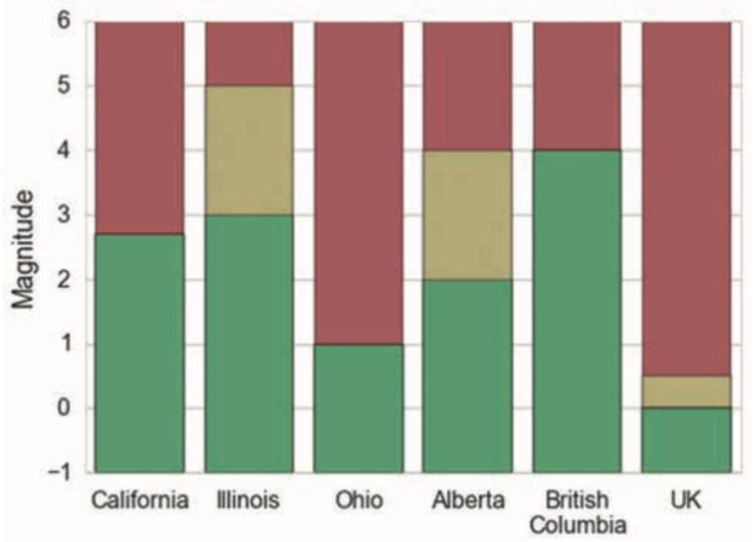
- ✓ Consists in minimizing induced seismicity based on:
  - ➢ **Decision variable** (e.g., earthquake magnitude, peak ground velocity)
  - ➢ **Threshold value** above which actions are taken (e.g., reduction or stopping of injection)

- ✓ Tools **still inherently heuristic & mostly based on expert elicitation**
  - ➢ Different regulations in different regions
  - ➢ How are those magnitude thresholds chosen?
  - ➢ How do they relate to risk? (risk-based safety norms in other hazardous industries, e.g., chemical plants)



source: Bosman et al. (2016)

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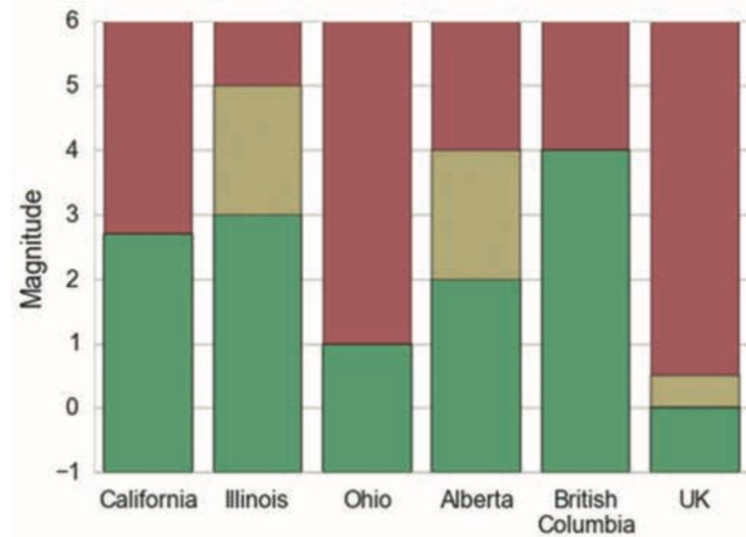

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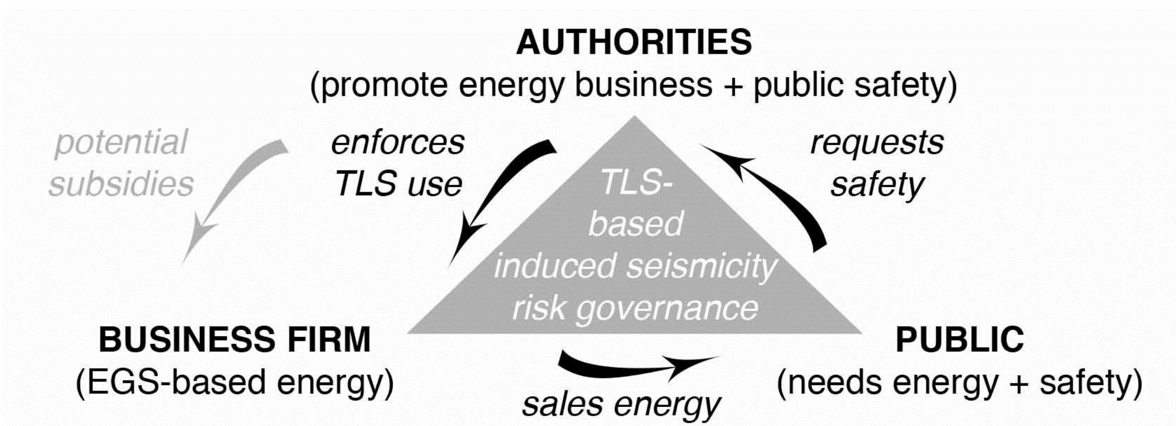
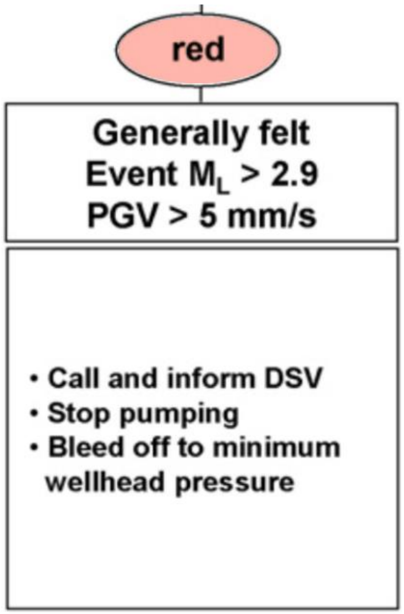
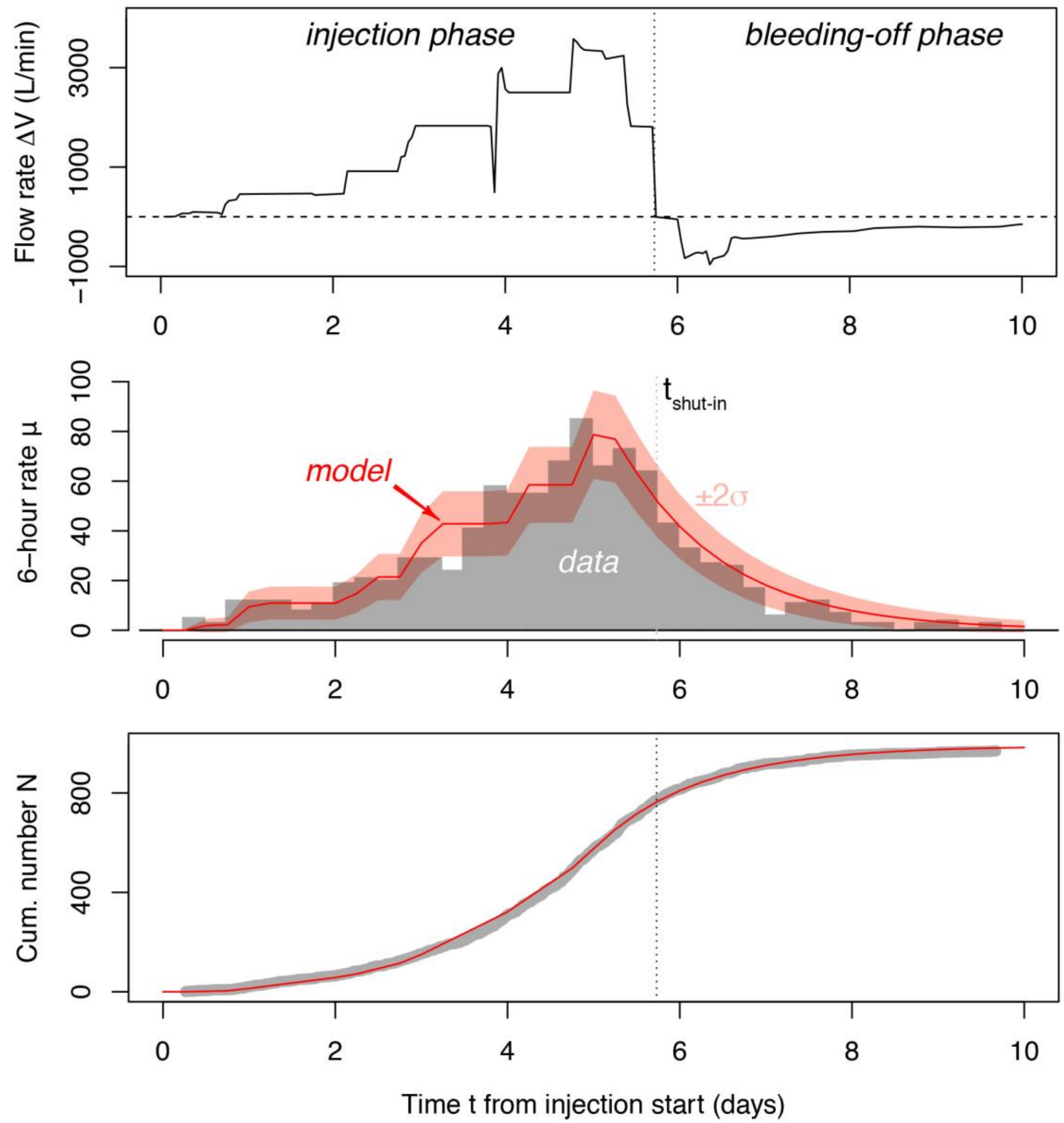
- ✓ One of the goals of T4.1 "*Risk, safety & public acceptance*" is to propose an **actuarial approach** to this problem in the scope of a **TLS-based induced seismicity risk governance** framework



A closer look at what happened in Basel, 2006



TLS source:
Häring et al. (2008)

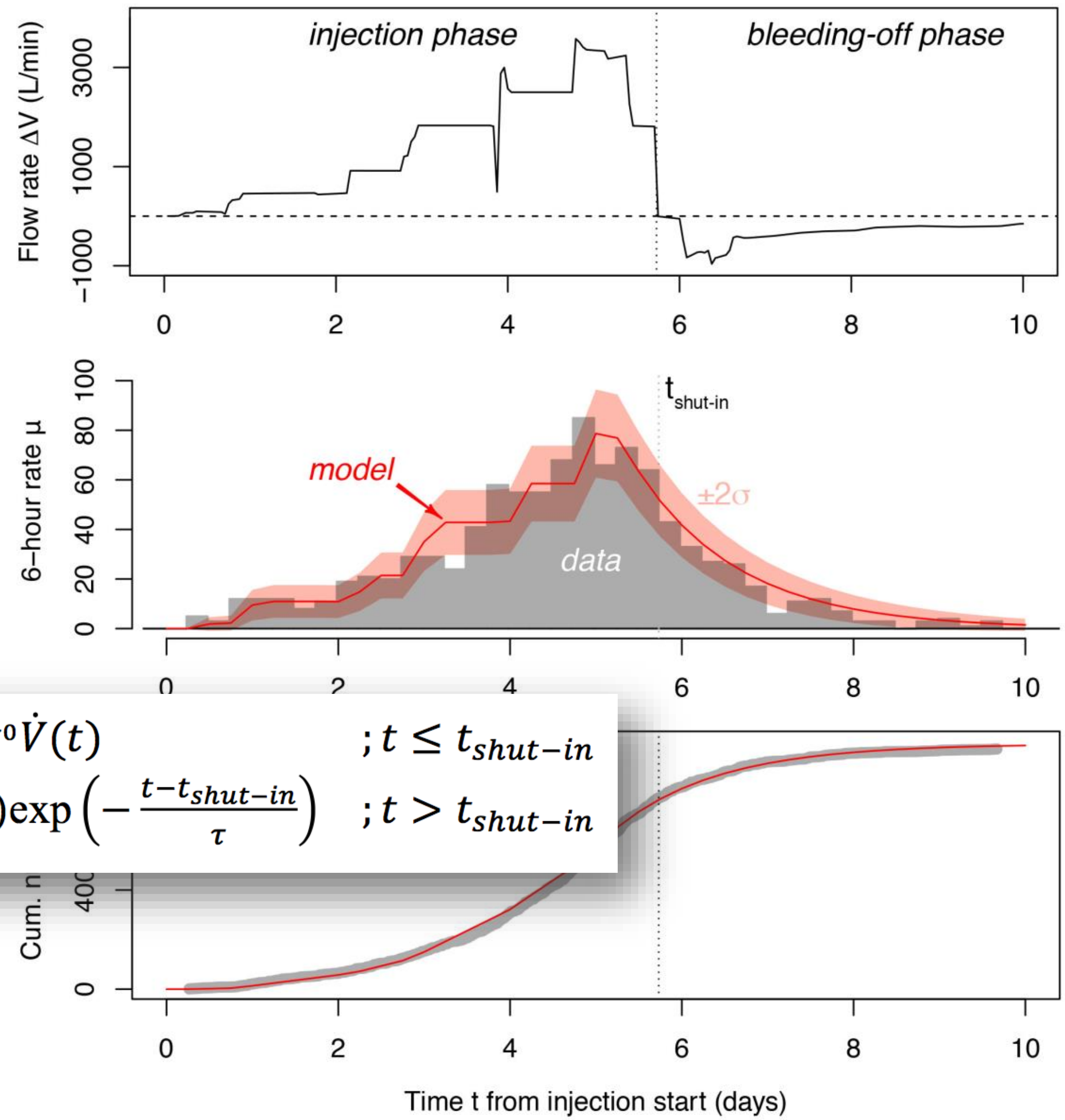


2006 Basel EGS data sources:
Häring et al. (2008);
Kraft & Deichmann (2014)

source: modified from Mignan (2016)

Induced seismicity rate model

- ✓ **Linear relationship between flow rate ΔV(*t*) and induced seismicity rate λ(*t*)**
- ✓ Overall activity or "**underground feedback**" represented by a_{fb}
- ✓ Normal diffusion in post-injection phase with mean relaxation time τ



$$\lambda(t, m \geq m_0; \theta) = \begin{cases} 10^{a_{fb} - bm_0}\dot{V}(t) & ; t \leq t_{shut-in} \\ 10^{a_{fb} - bm_0}\dot{V}(t_{shut-in})\exp\left(-\frac{t - t_{shut-in}}{\tau}\right) & ; t > t_{shut-in} \end{cases}$$

2006 Basel EGS data sources: Häring et al. (2008); Kraft & Deichmann (2014)

source: modified from Mignan (2016)

Deep fluid injections around the world

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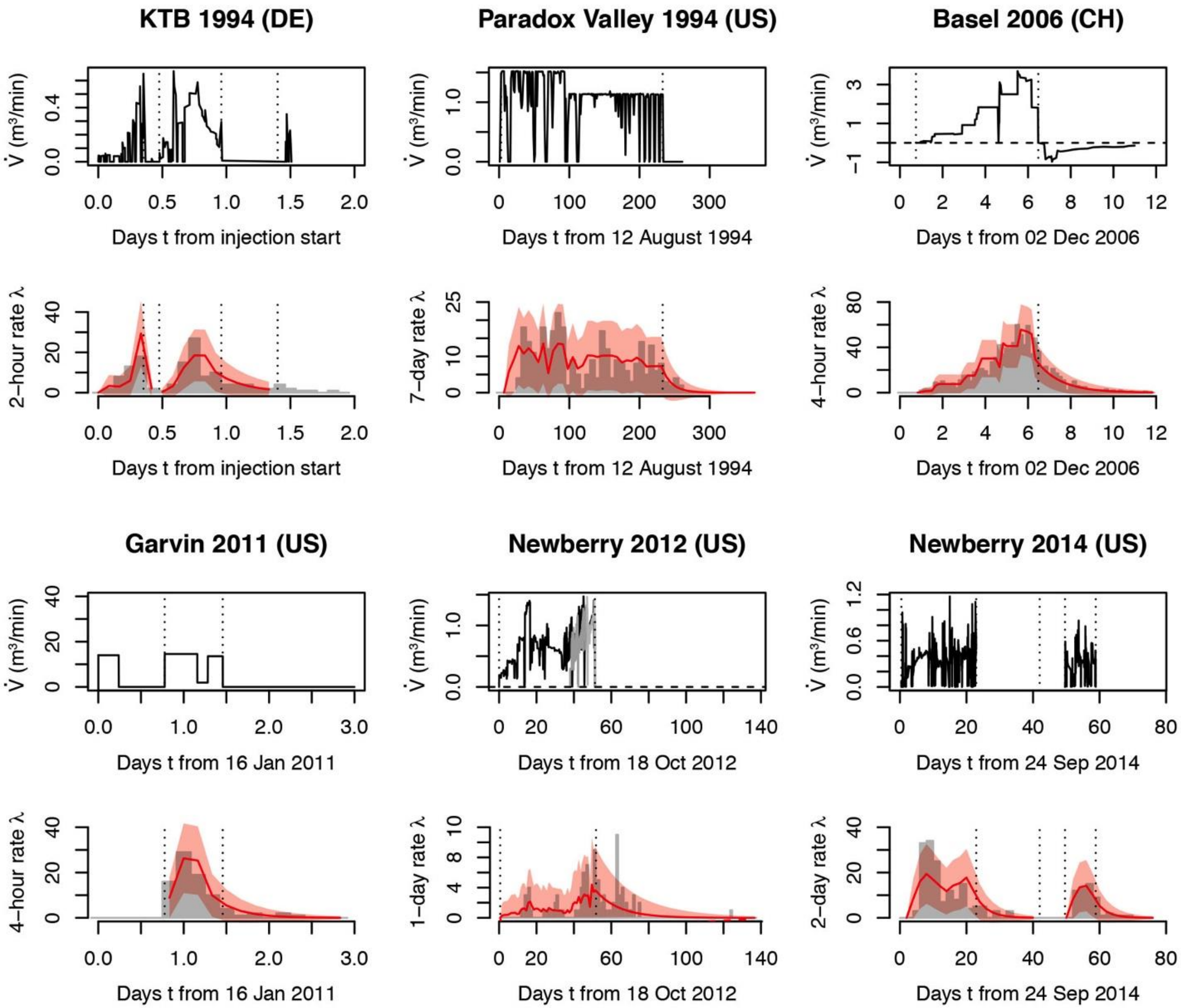

- ✓ **Simple model fits reasonably well** most of the sequences (based on MLE & KS test)
- ✓ **High variability of underground feedback**
  - ➢ $-2.8 \leq a_{fb} \leq 0.1$ m^{-3}
  - ➢ $0.8 \leq b \leq 1.6$
  - ➢ $0.2 \leq \tau \leq 20$ days
- ✓ Second-order deviations from model still to be understood
  - ➢ Missing on-site data?
  - ➢ Second-order physics?

source: Mignan et al. (in rev., Sci. Rep.)

Developing a TLS based on the rate-model (1/2)

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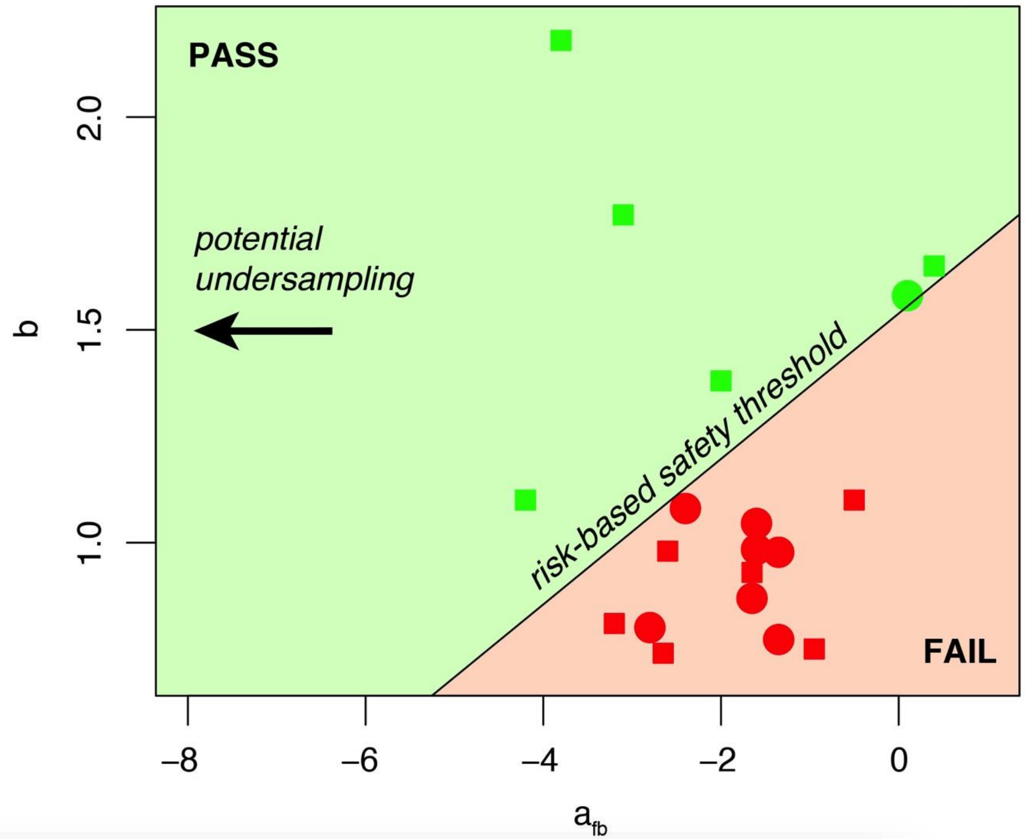
- ✓ Let us define a **risk-based safety norm**
  - ➢ Fixed to **Pr(fatality) = Y = 10^{-6}**
  - ➢ Risk of earthquake damage assumed to be insured
- ✓ Can be **mapped into magnitude space**
  - ➢ Poisson process with Pr(≥m_{saf}) = 1-exp N(≥m_{saf})
  - ➢ Total number N **obtained by integrating rate model**
- ✓ **Closed-form** means
  - ➢ Almost instantaneous computation
  - ➢ **Robust & transparent**

modified from Mignan et al. (in rev., Sci. Rep.)
(for V=10,000m³, 4km depth, d=0km from borehole)



$$\Pr(m \geq m_{saf}) = 1 - \exp\{-10^{a_{fb} - b m_{saf}}[V(t_{shut-in}) + \tau \dot{V}(t_{shut-in})]\} = Y$$

Developing a TLS based on the rate-model (2/2)

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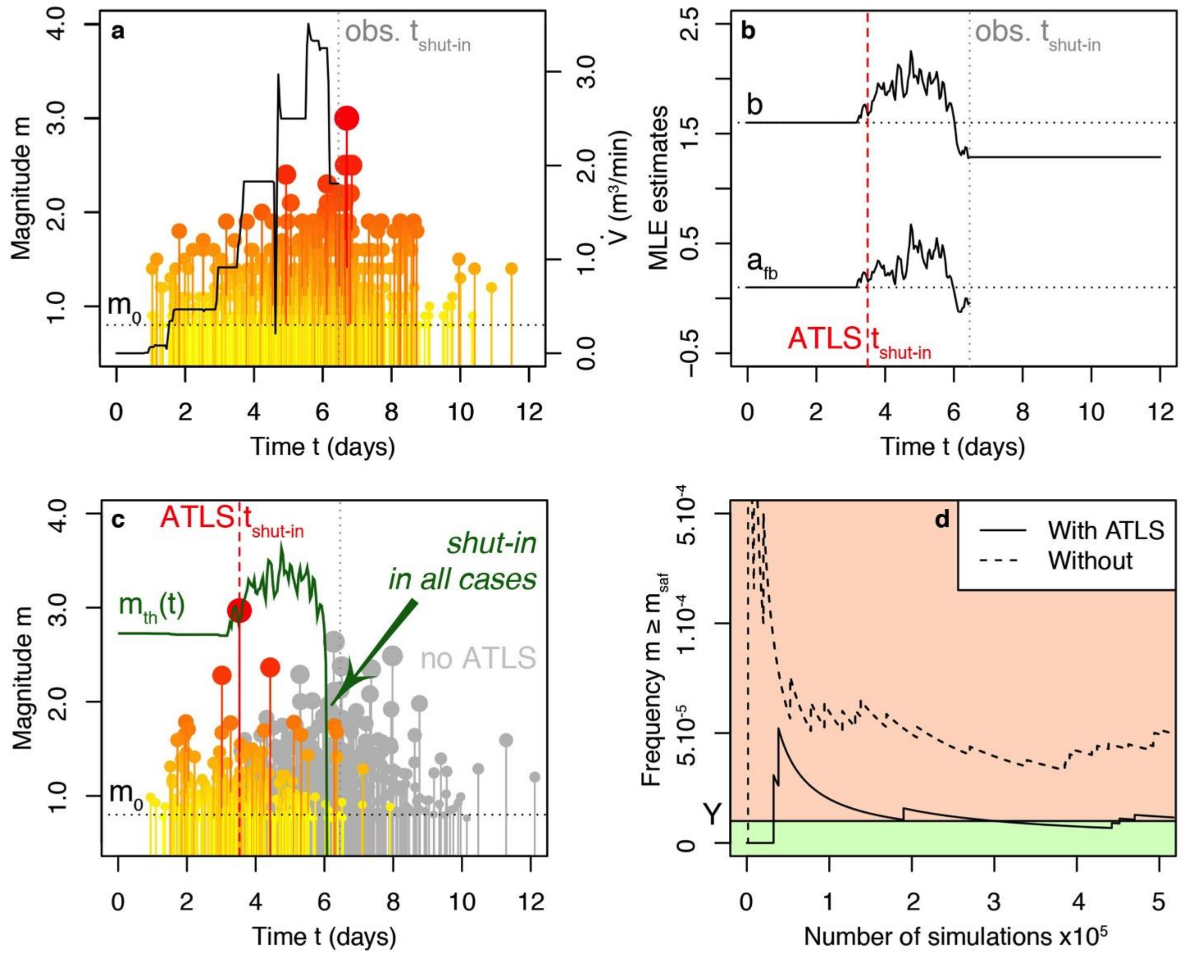
source: Mignan et al. (in rev., Sci. Rep.)

a. Simulation of 2006 Basel time series
   - ➢ Stochastic process based on rate model

b. Temporal evolution of (a_{fb},b)
   - ➢ Risk evolves with time
   - ➢ **Adaptive TLS** (ATLS)

c. TLS definition
   - ➢ **Stop injecting above m_{th}**

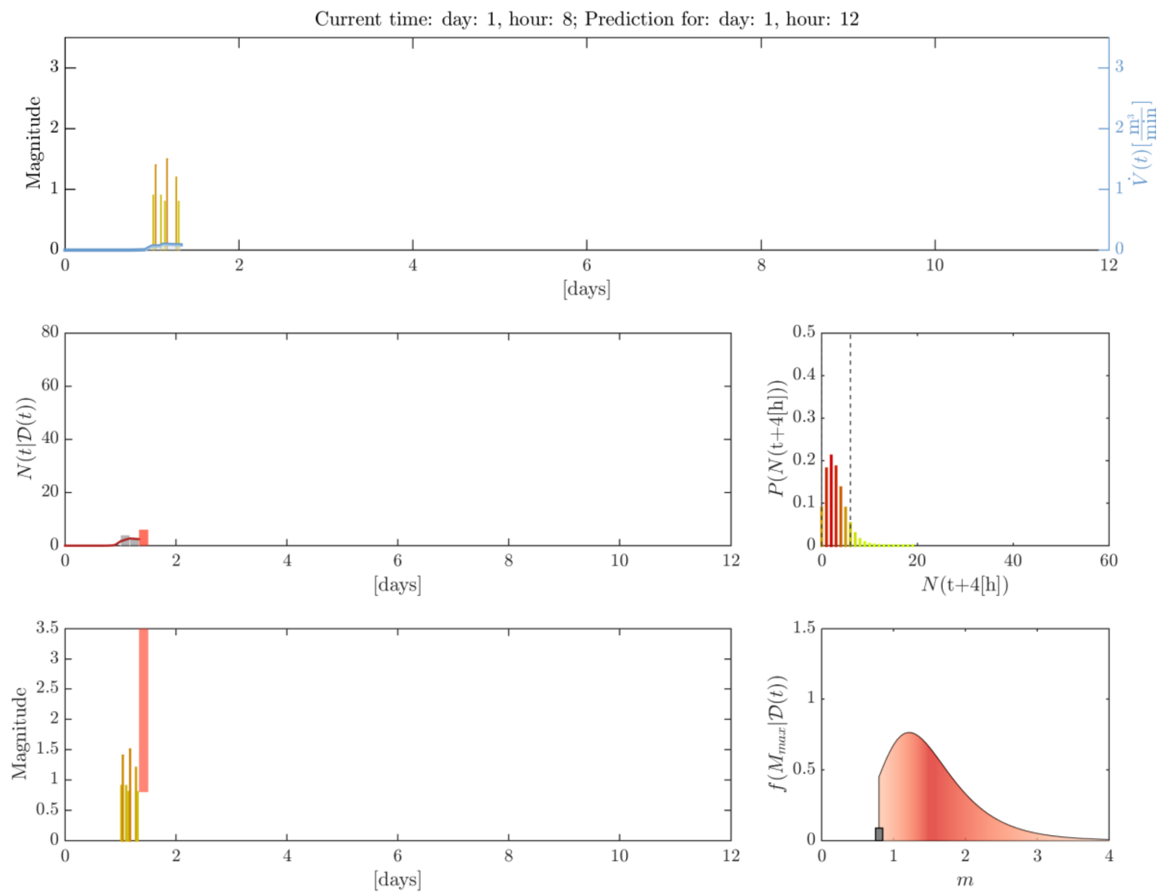
d. TLS validation
   - ➢ Over millions of simulations, we observe that the safety norm is respected in average



$$m_{th} = \frac{1}{b}\log_{10}\left[Y - 10^{a_{fb} - b m_{saf}} \tau \dot{V}(t_{shut-in})\right] + m_{saf}$$

Hierarchical Bayesian forecasting

- ✓ Bayesian online updating, including uncertainty quantification
- ✓ Predicts both the number of events & the expected maximum magnitude
- ✓ See SCCER-SoE T4.1 poster by *Broccardo et al.*



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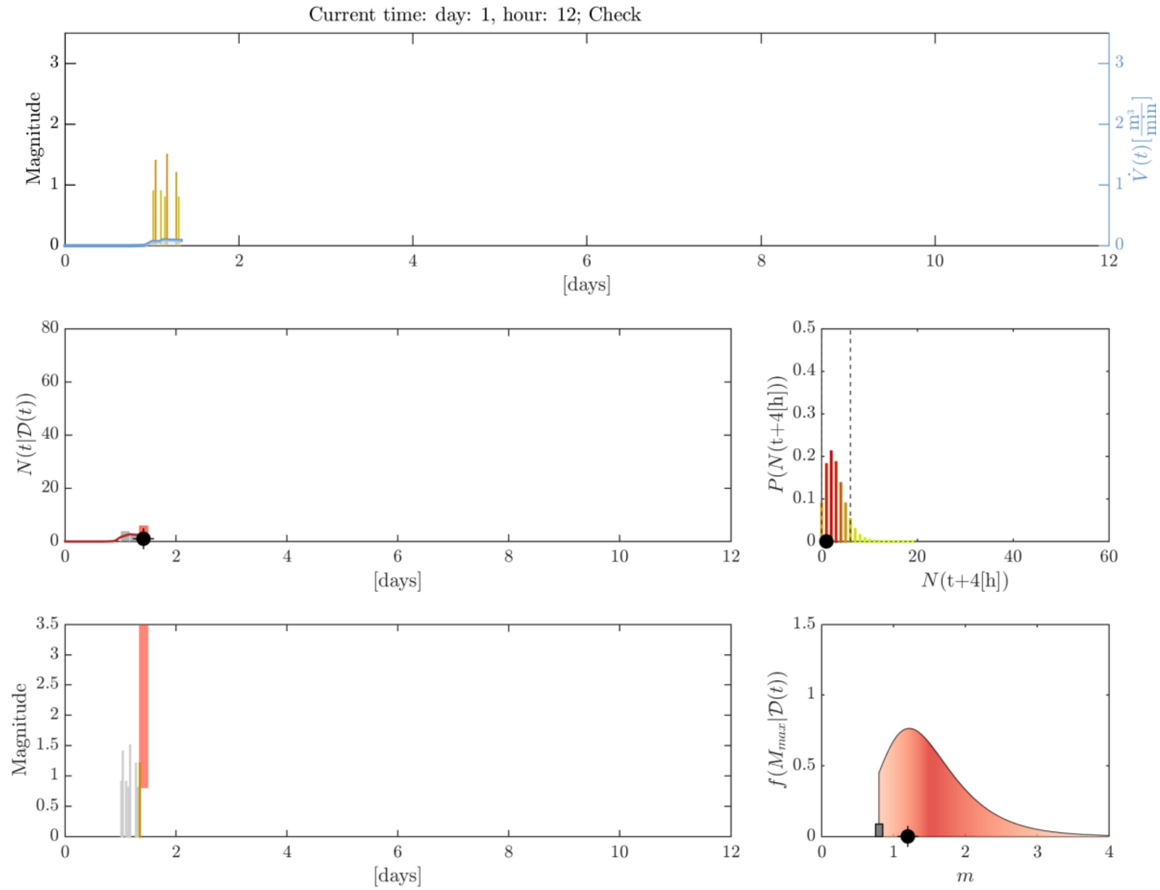

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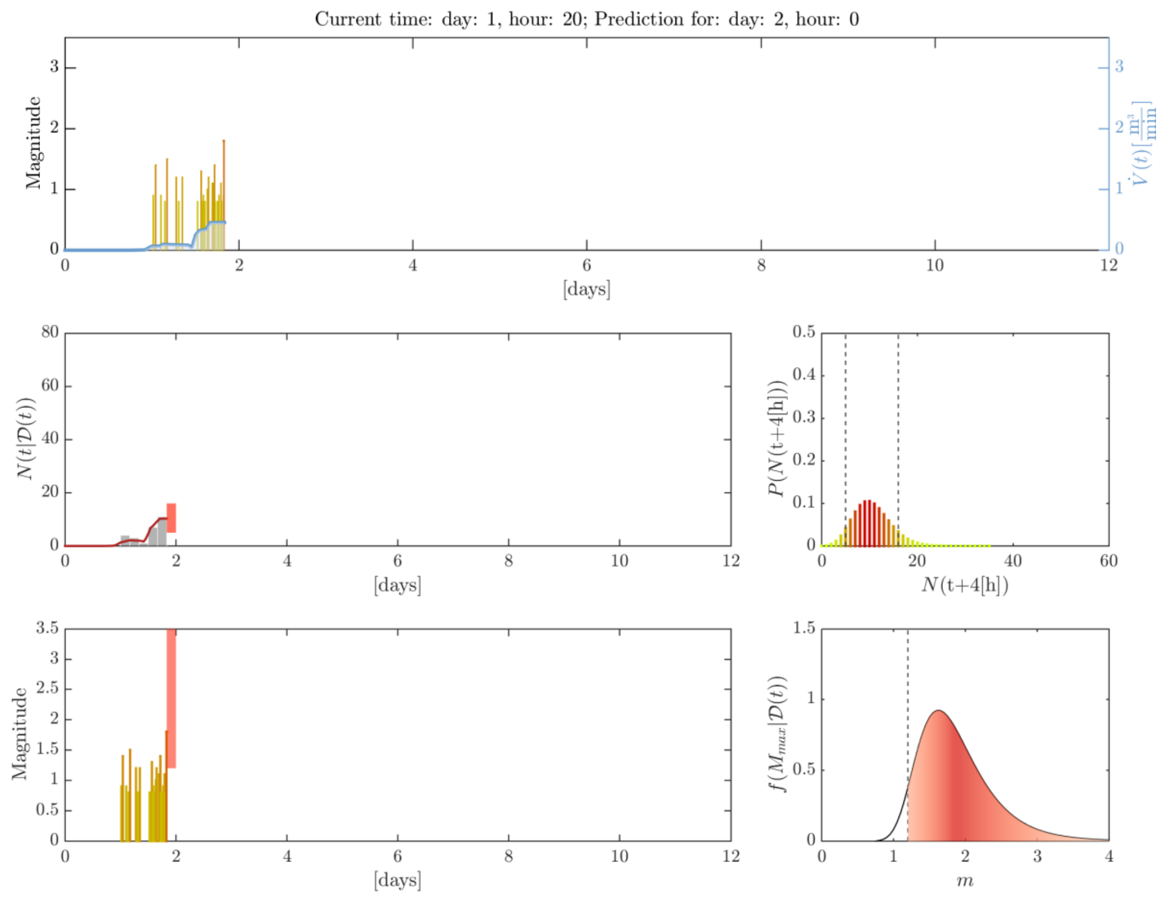

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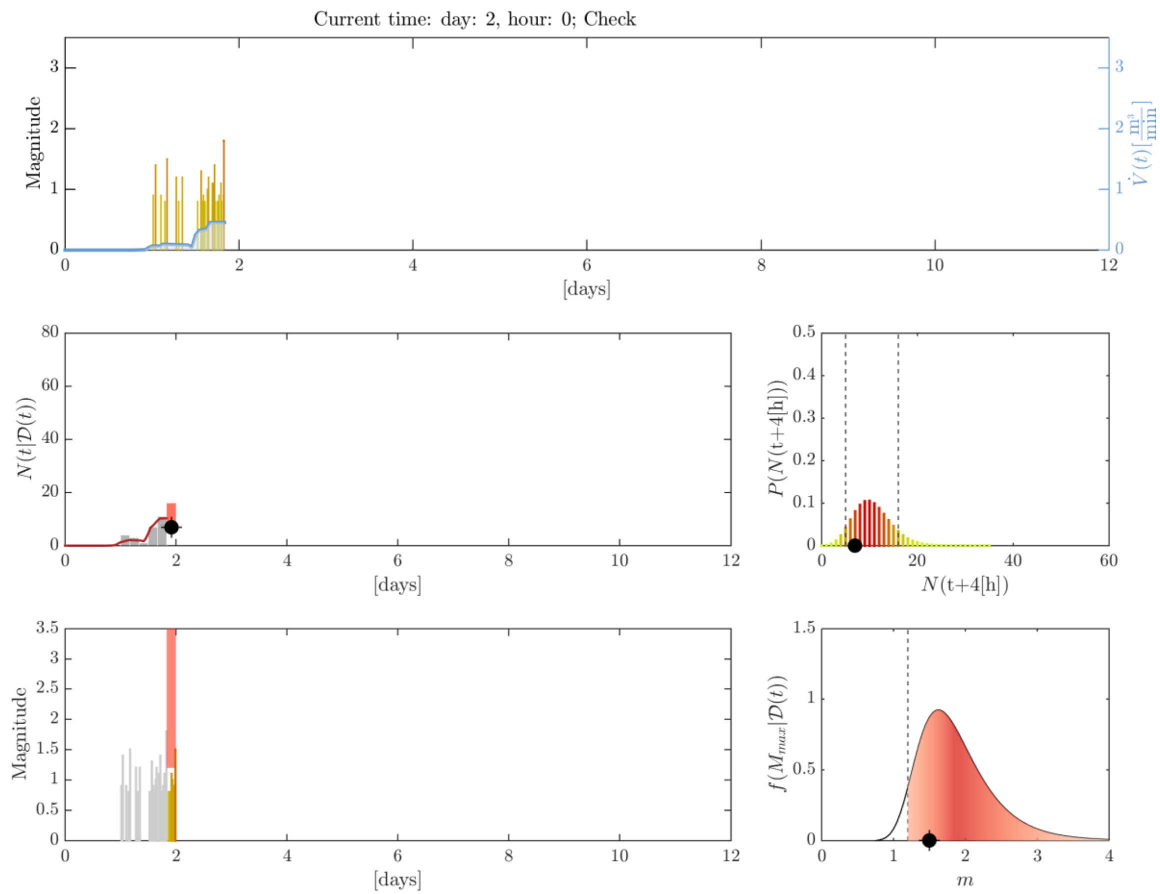

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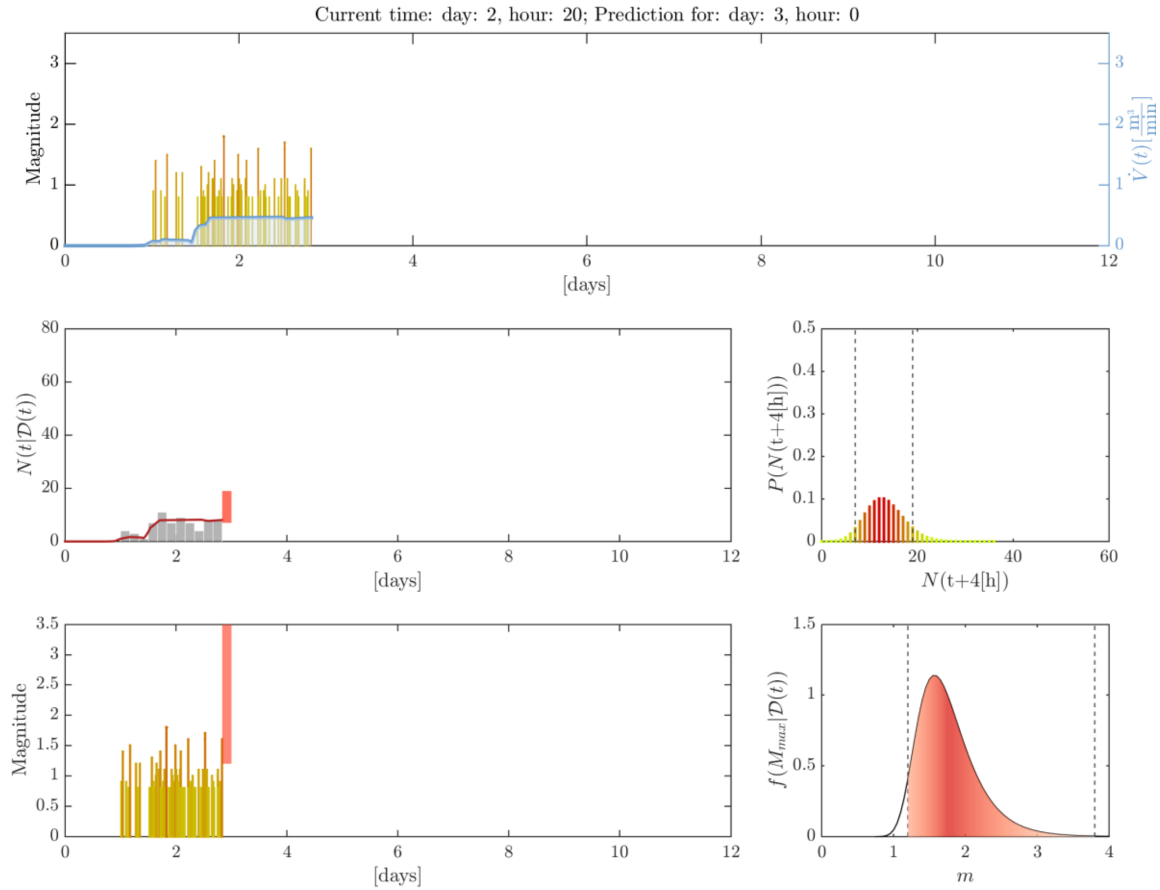

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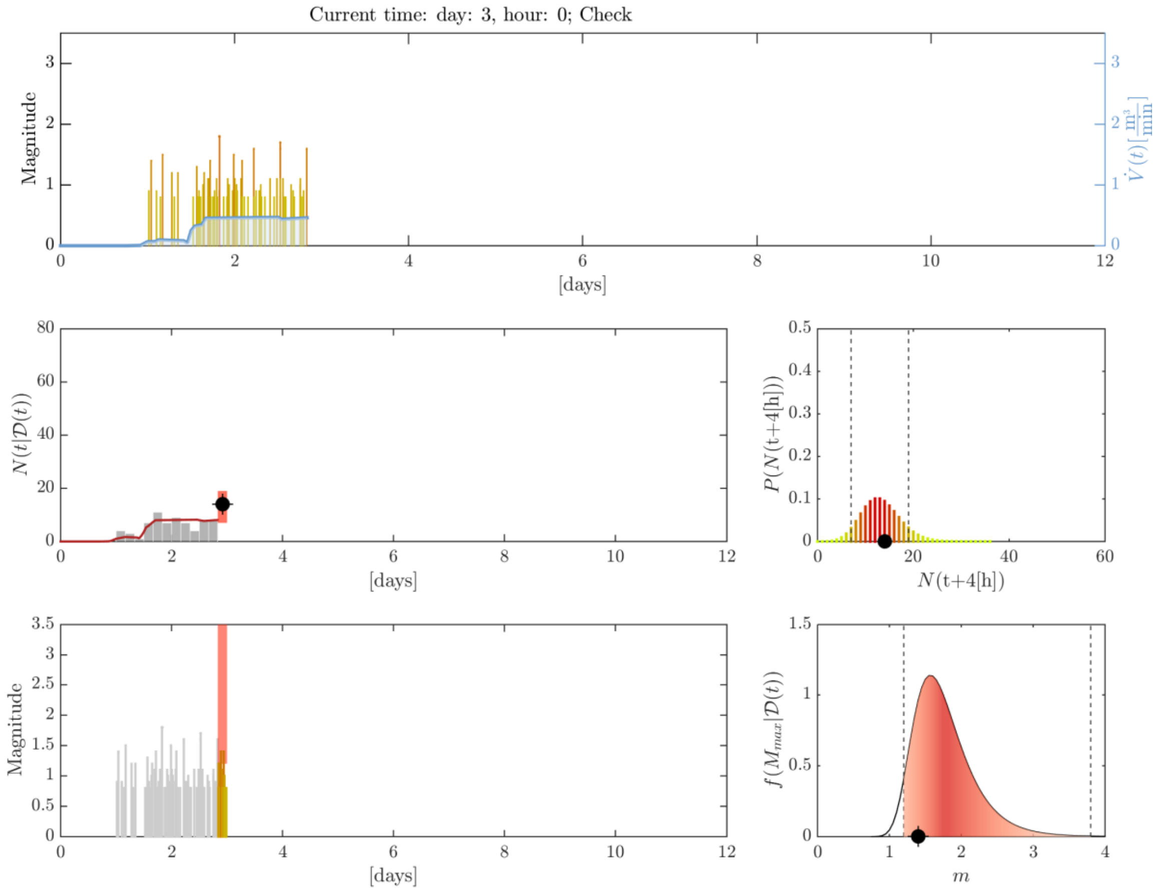

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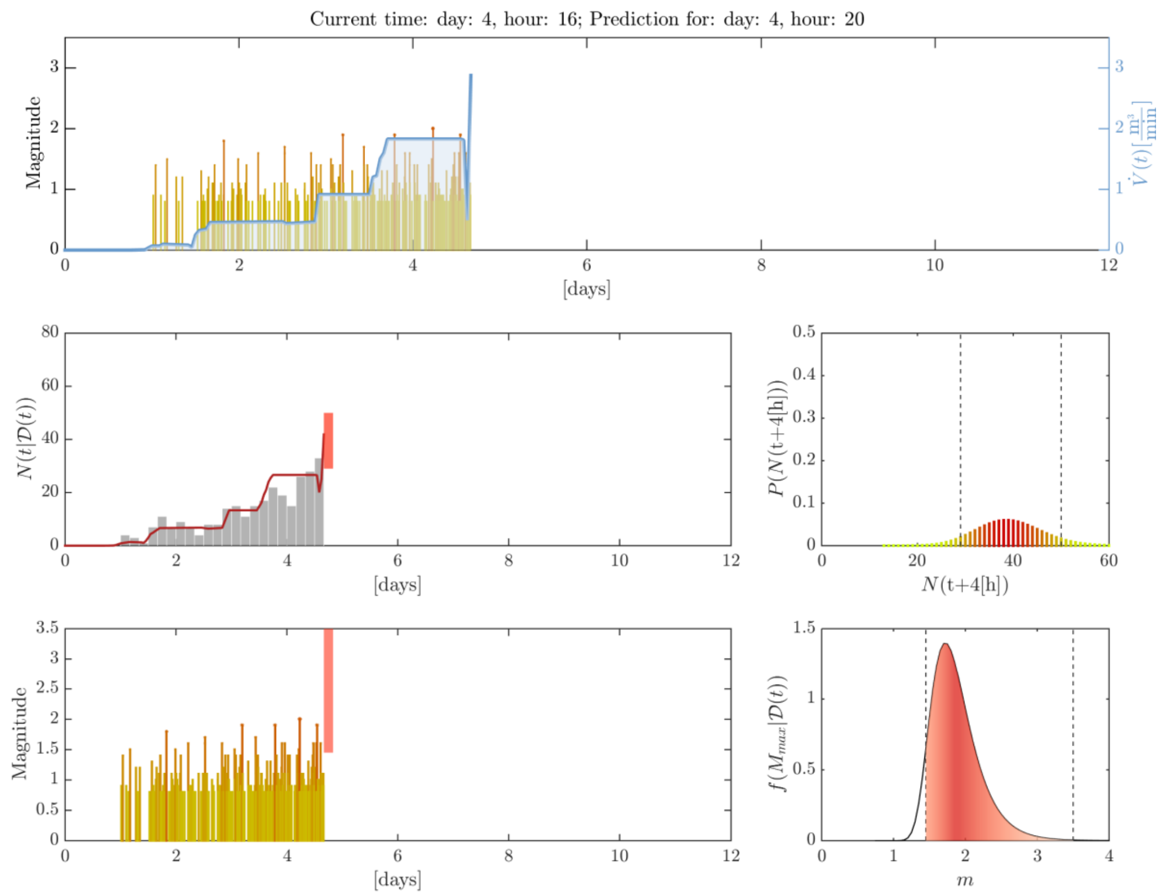

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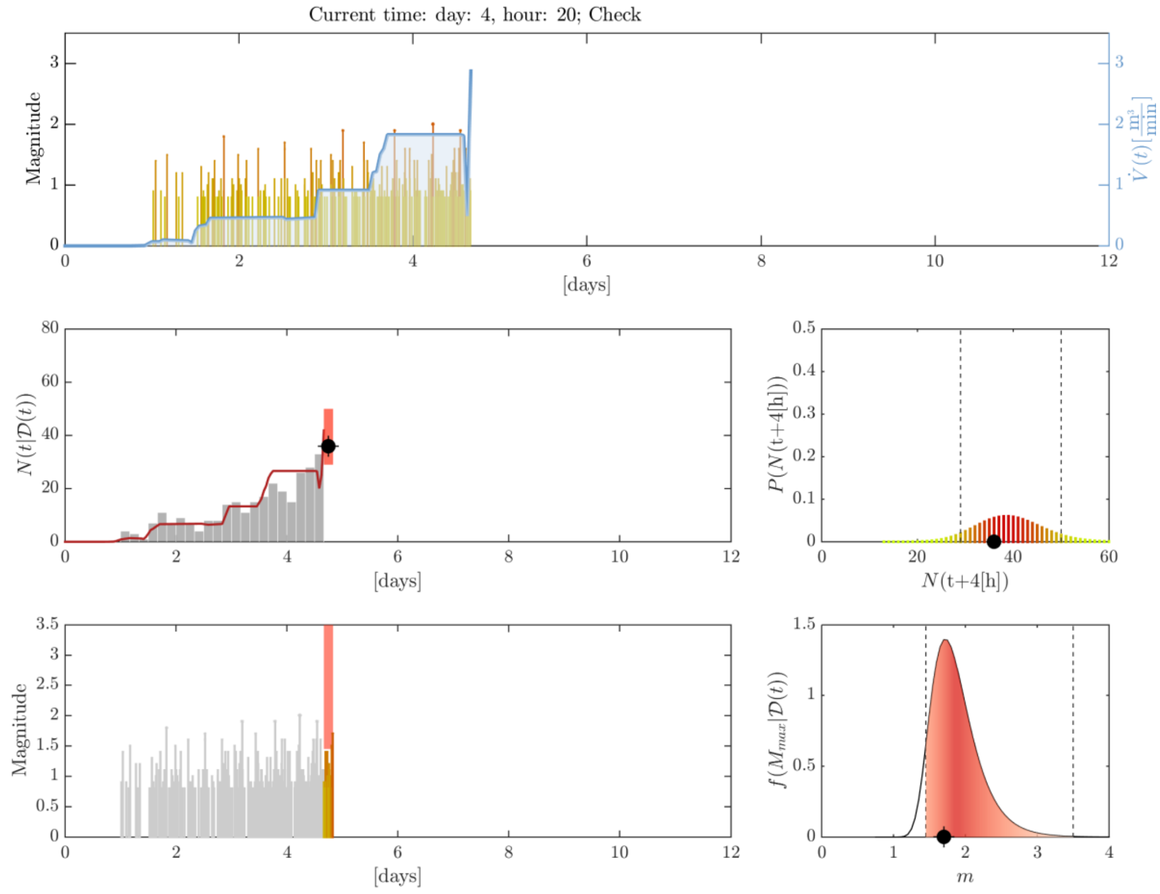

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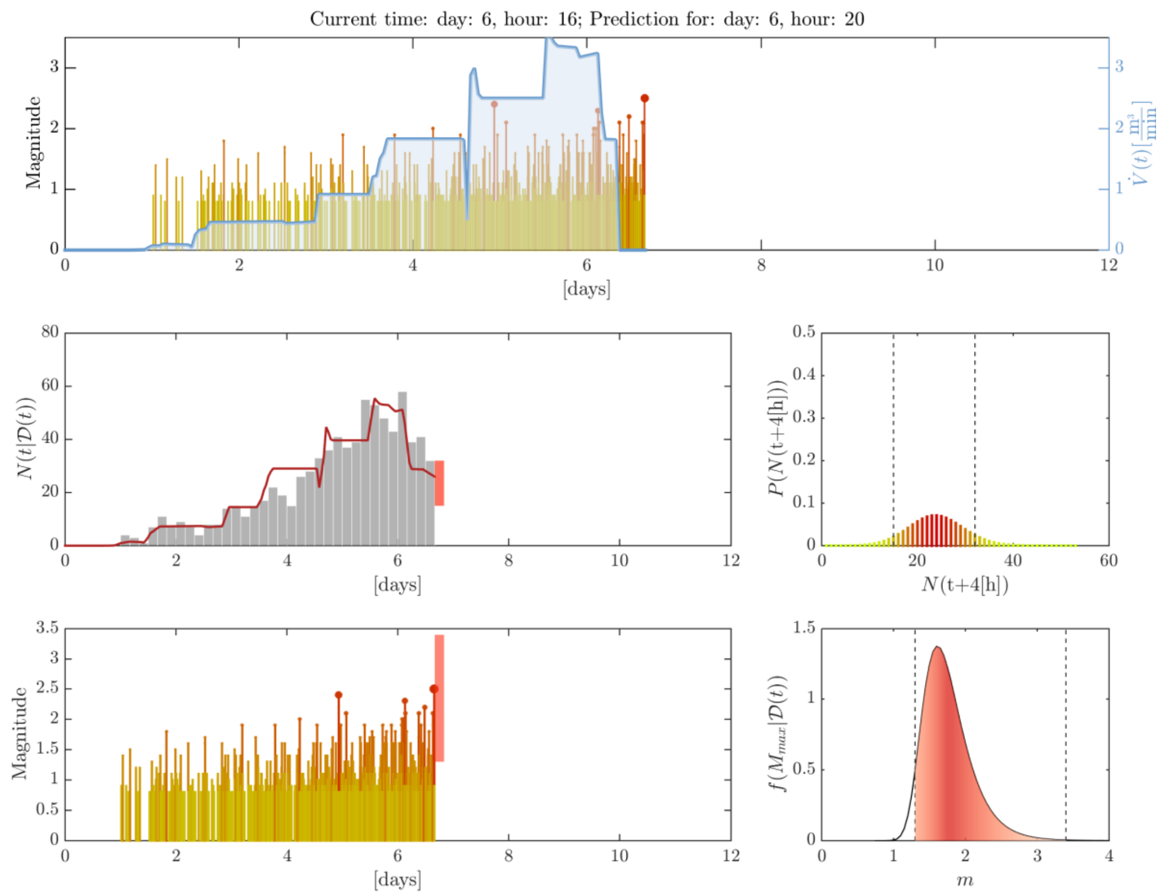

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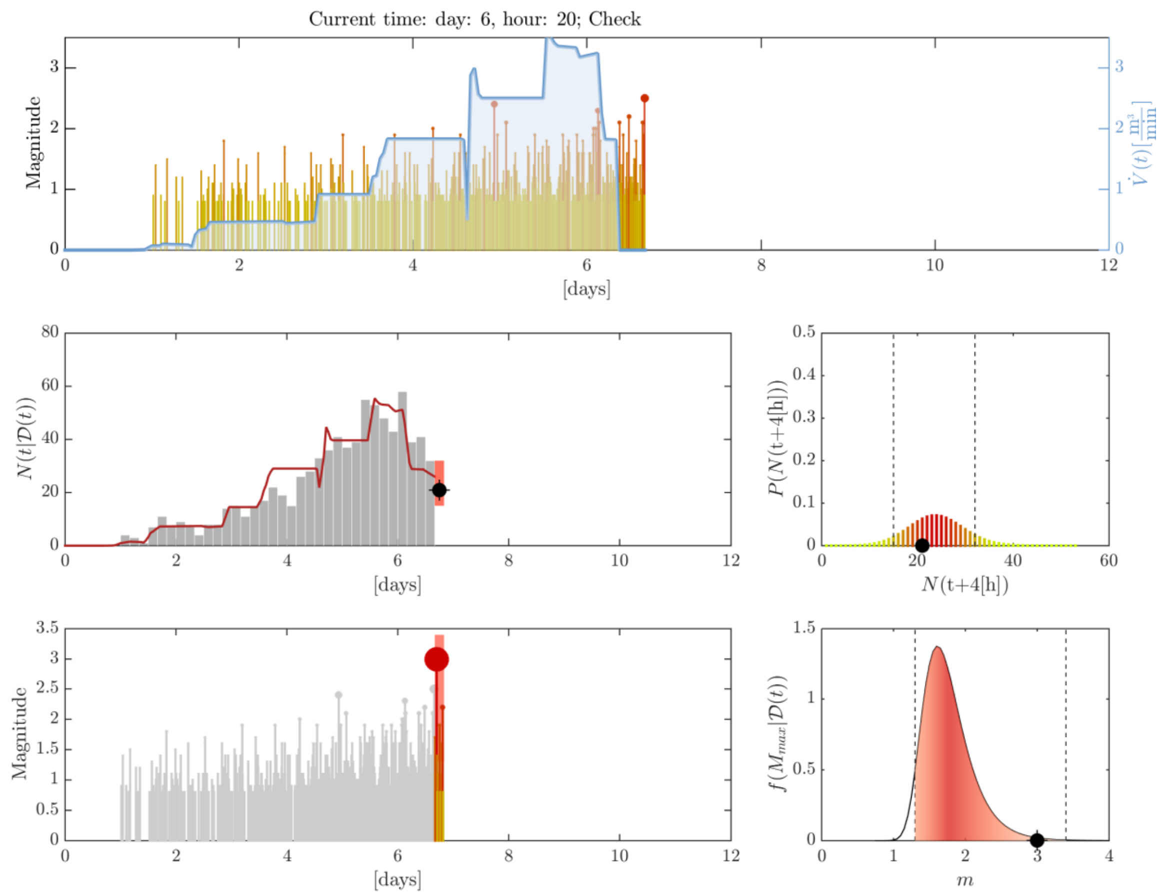

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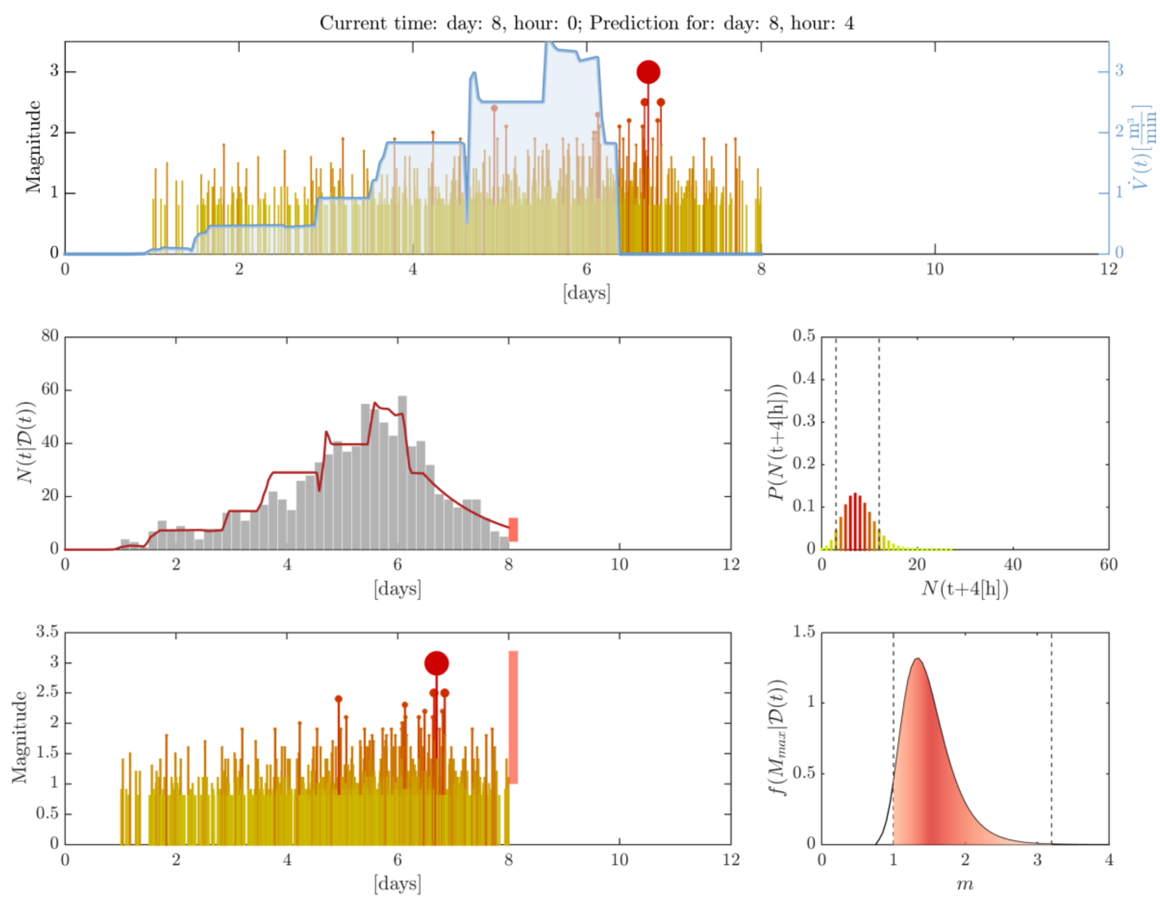

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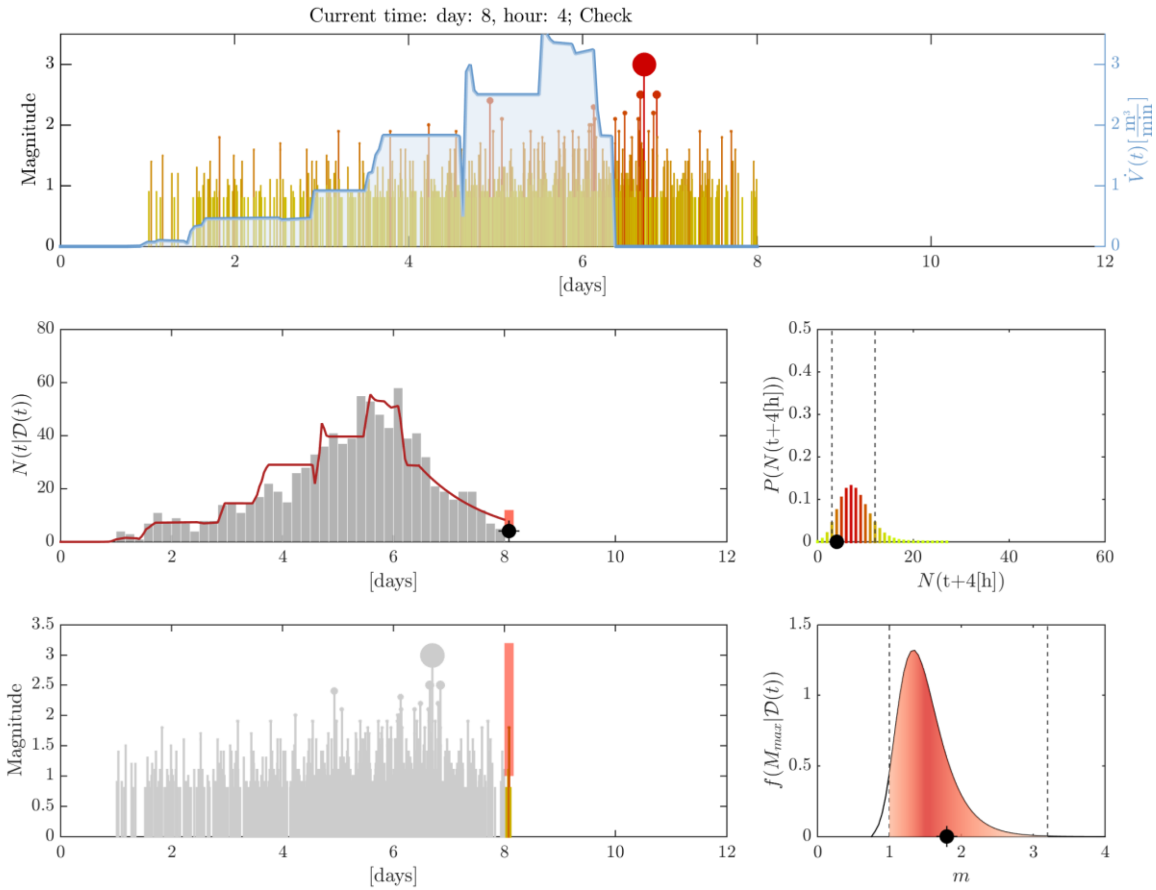

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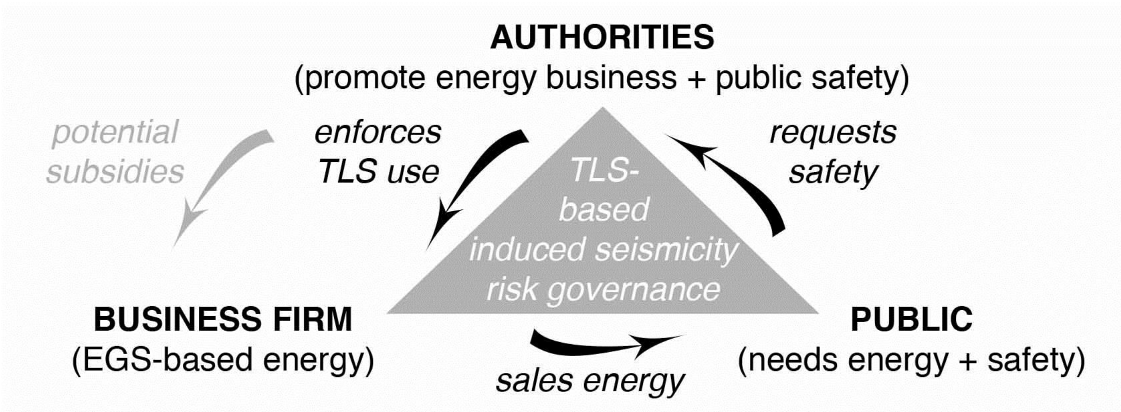
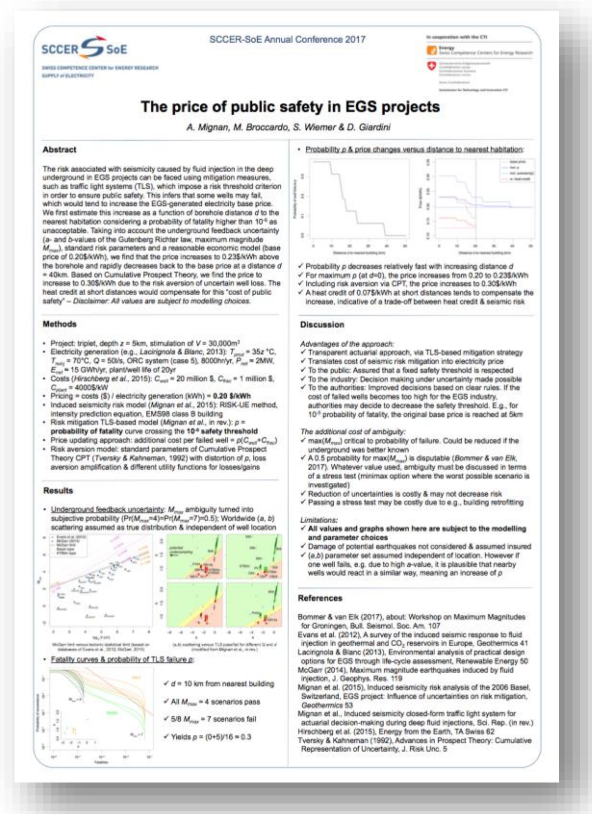
Next steps



- ✓ Consider the impact of a TLS on the EGS business (see poster "***The price of public safety in EGS projects***")
  - ➢ Seismic risk turned into increased price/kWh
  - ➢ Decision-making under uncertainty to quantify stakeholders' behaviour
- ✓ Improved **physical model of induced seismicity**
  - ➢ Changes of injectivity; pressure minimum threshold? (insights from **DUG-Lab**)
  - ➢ Could provide smarter strategies, e.g., modifying injection profile instead of brutal stop
- ✓ TLS in **legislations & public acceptance** (**SoE-CREST JA**)



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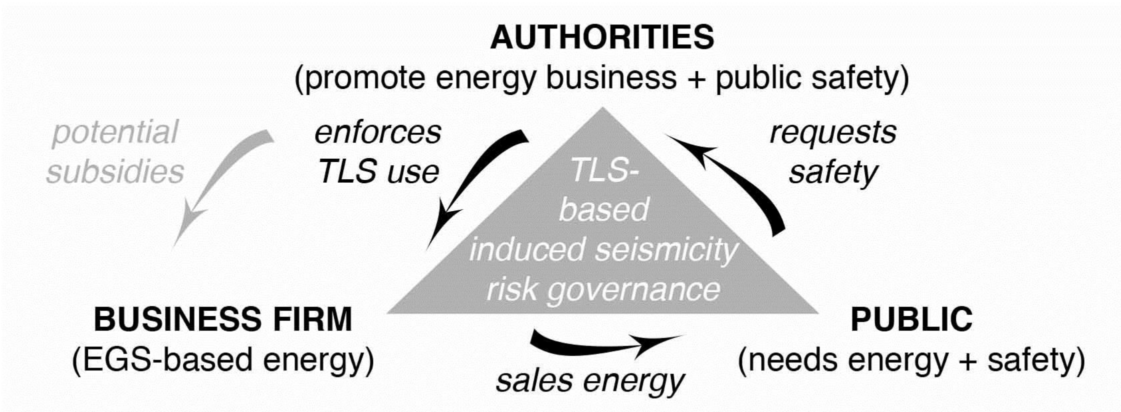

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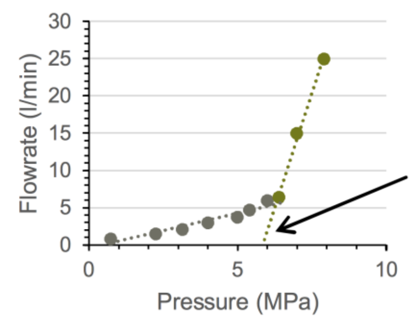
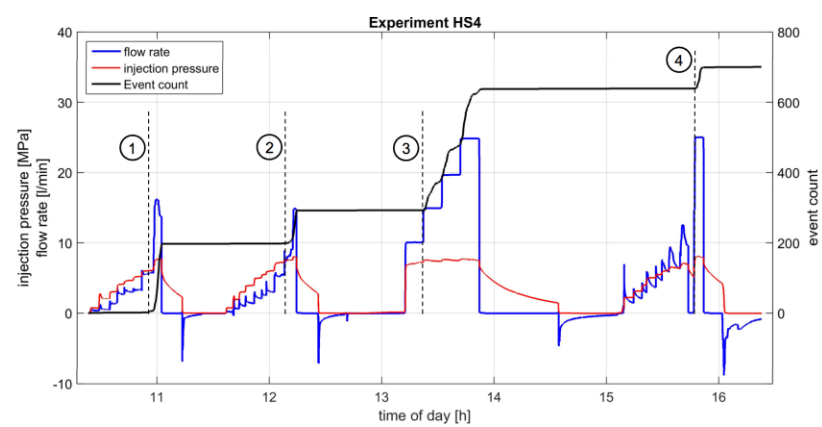


Courtesy of the DUG Lab Team



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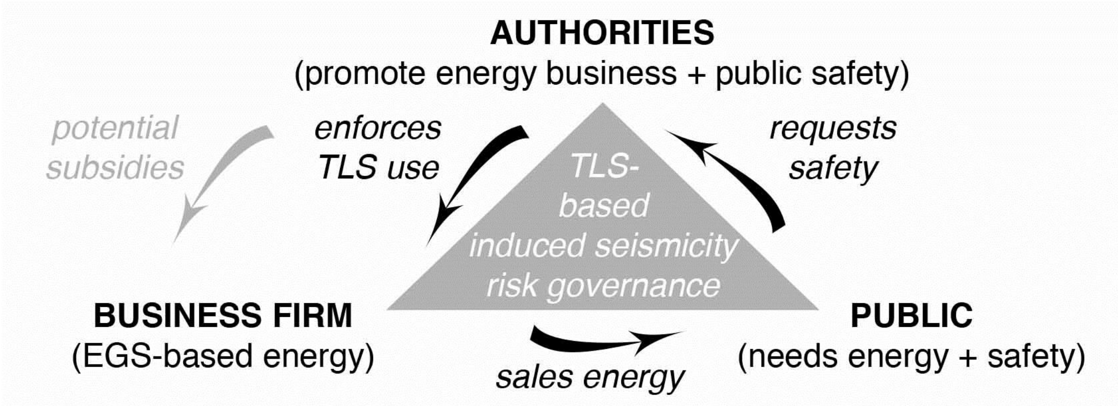

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References

- **On induced seismicity risk analysis** (for magnitude-risk mapping)
  - Mignan, A., D. Landtwing, P. Kastli, B. Mena, S. Wiemer (2015), Induced seismicity risk analysis of the 2006 Basel, Switzerland, Enhanced Geothermal System project: Influence of uncertainties on risk mitigation, *Geothermics* 53

- **On induced seismicity modelling & forecasting**
  - Mignan, A. (2016), Static behaviour of induced seismicity, *Nonlin. Processes Geophys.* 23
  - Broccardo, M., A. Mignan, S. Wiemer, B. Stojadinovic, D. Giardini (subm.), Hierarchical Bayesian modeling of fluid-induced seismicity, *Geophys. Res. Lett.*

- **On traffic light systems & safety norms**
  - Mignan, A., M. Broccardo, S. Wiemer, D. Giardini (in rev.), Induced seismicity closed-form traffic light system for actuarial decision-making during deep fluid injection, *Sci. Rep.*

- **SCCER SoE posters**
  - Broccardo, M., A. Mignan, B. Stojadinovic, S. Wiemer, D. Giardini, *Hierarchical Bayesian modelling for fluid-induced seismicity*
  - Mignan, A., M. Broccardo, S. Wiemer, D. Giardini, *The price of public safety in EGS projects*