

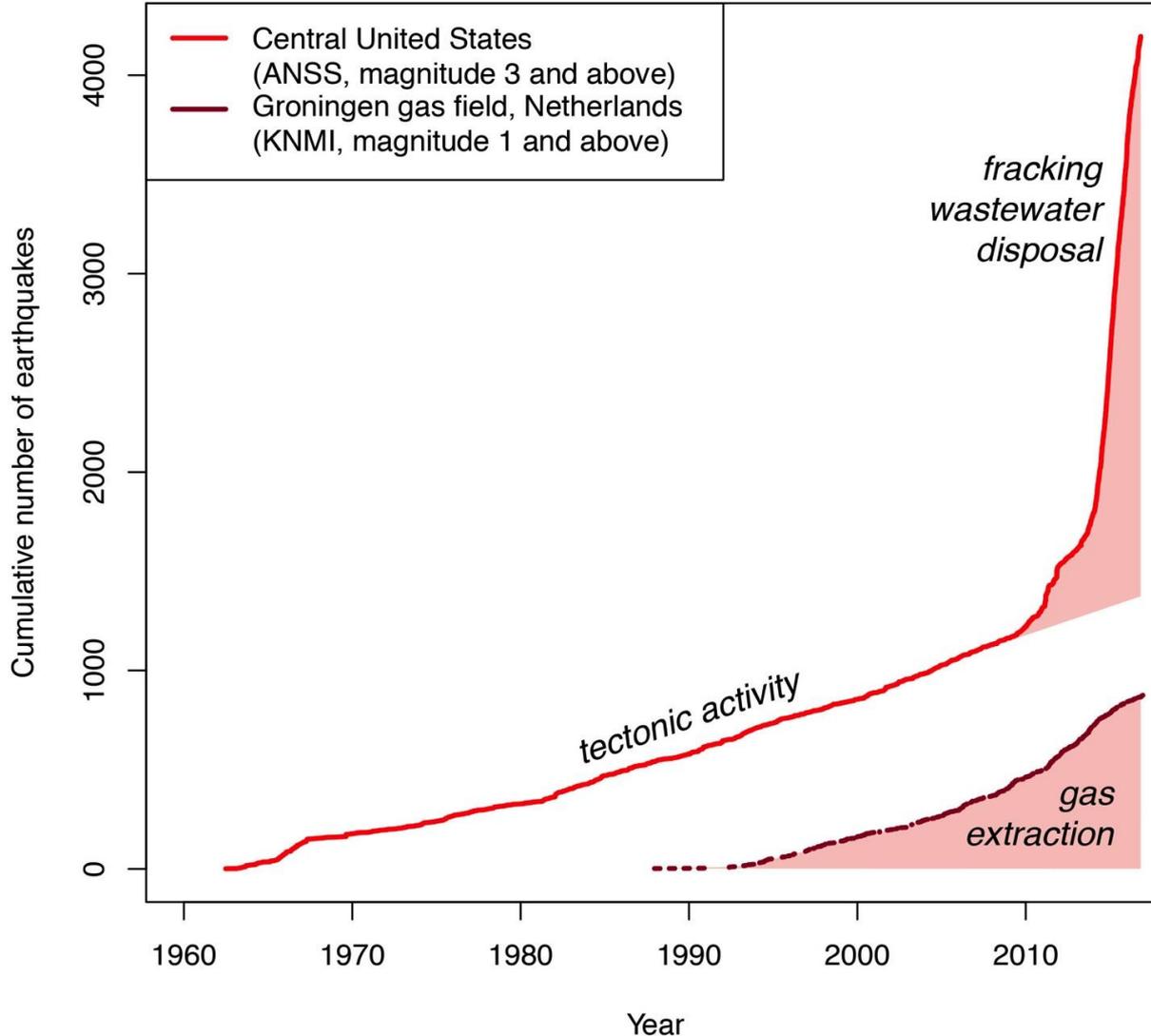
Induced seismicity risk mitigation: An actuarial approach

A. Mignan (ETH Zurich)

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

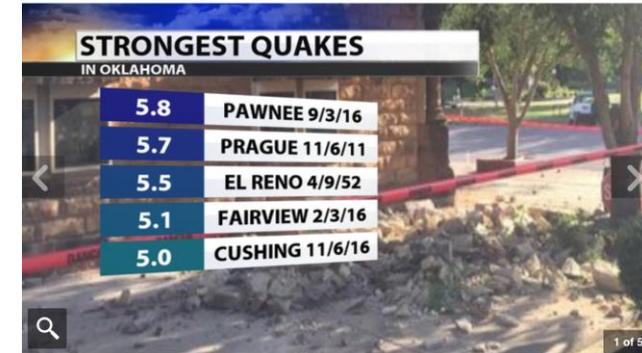
*SCCER-SoE Annual Conference 2017
14 September 2017, Birmensdorf*

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

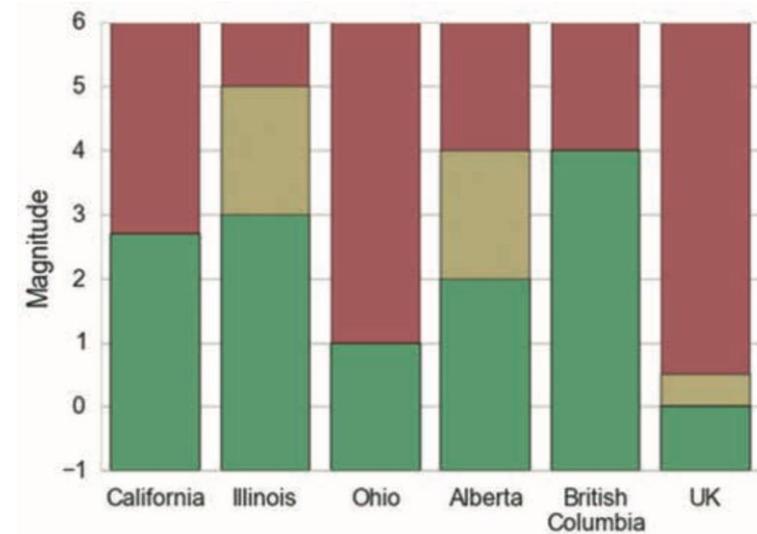


A condemned and shored-up cafe. Photo: Graham Dockery

source: Dutch News

Traffic-Light Systems (TLS) as a solution

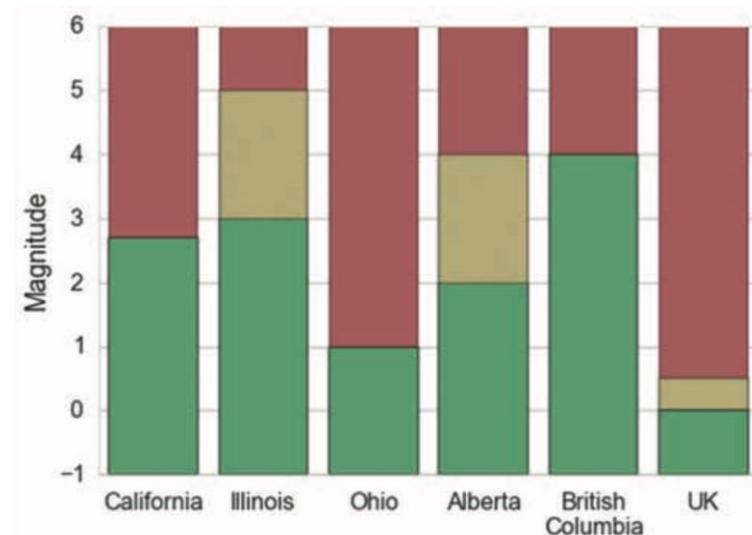
- ✓ Consists in minimizing induced seismicity based on:
 - **Decision variable** (e.g., earthquake magnitude, peak ground velocity)
 - **Threshold value** above which actions are taken (e.g., reduction or stopping of injection)
- ✓ Tools **still inherently heuristic & mostly based on expert elicitation**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

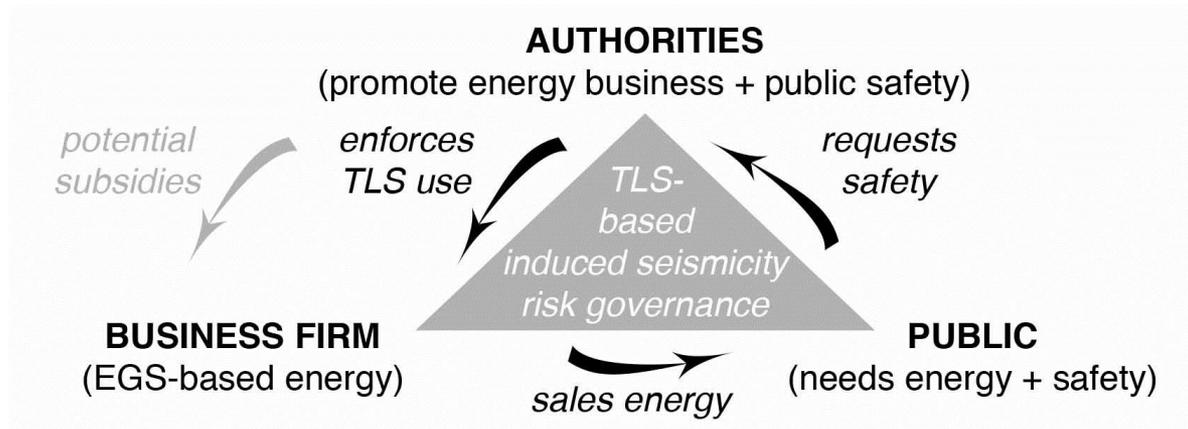
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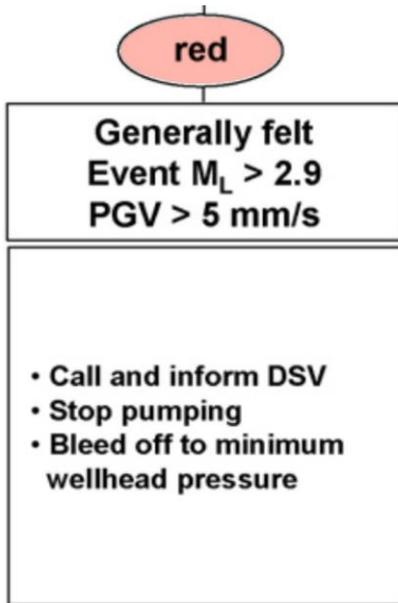


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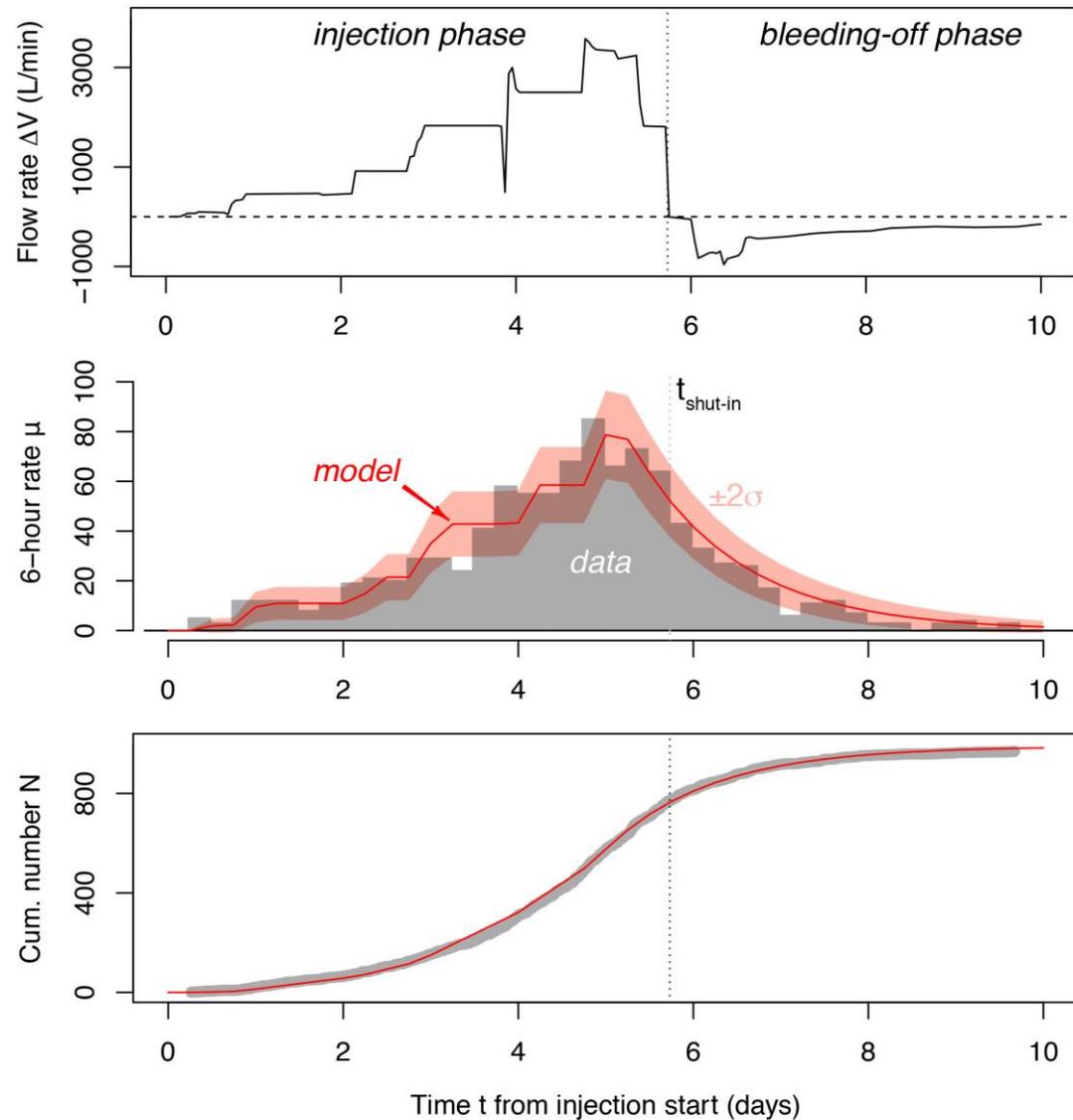
- ✓ One of the goals of T4.1 “*Risk, safety & public acceptance*” is to propose an **actuarial approach** to this problem in the scope of a **TLS-based induced seismicity risk governance** framework



A closer look at what happened in Basel, 2006



TLS source:
Häring et al. (2008)

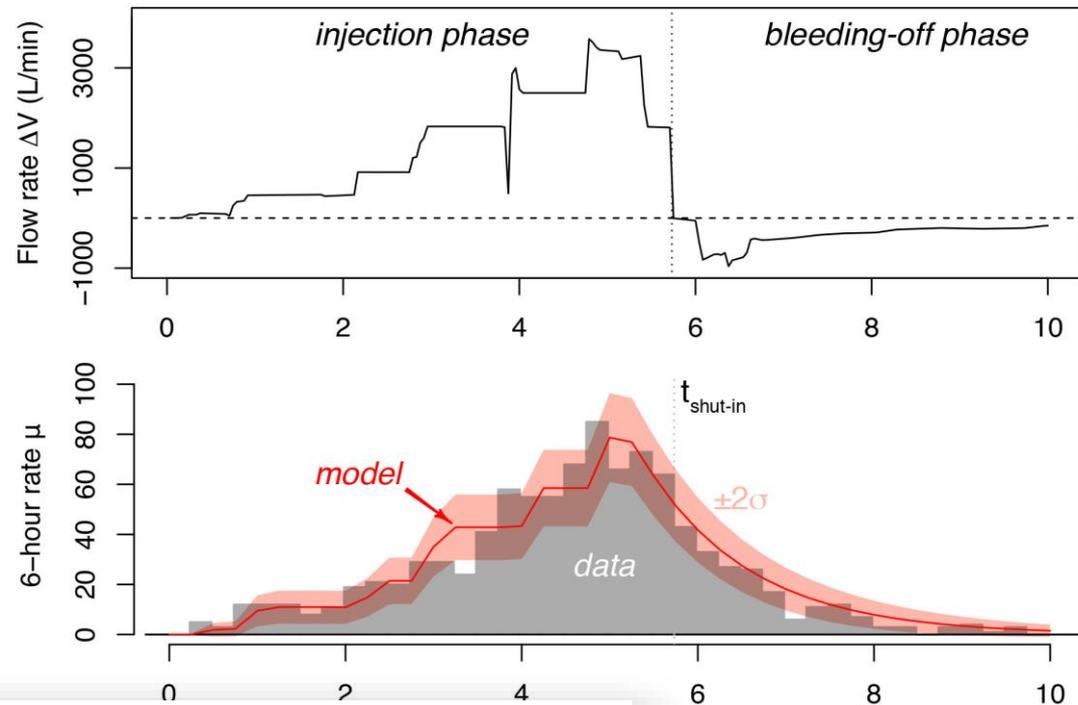


2006 Basel EGS data sources:
Häring et al. (2008);
Kraft & Deichmann (2014)

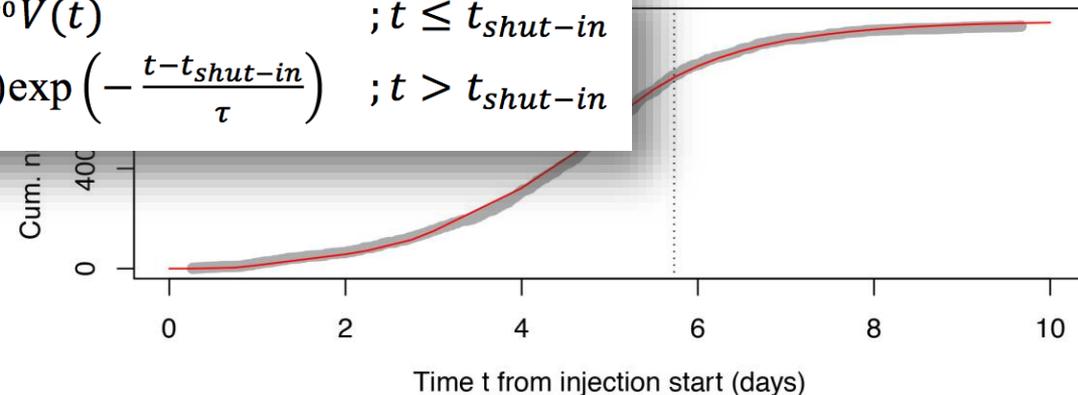
source: modified from Mignan (2016)

Induced seismicity rate model

- ✓ Linear relationship between flow rate $\Delta V(t)$ and induced seismicity rate $\lambda(t)$
- ✓ Overall activity or “underground feedback” represented by a_{fb}
- ✓ Normal diffusion in post-injection phase with mean relaxation time τ



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

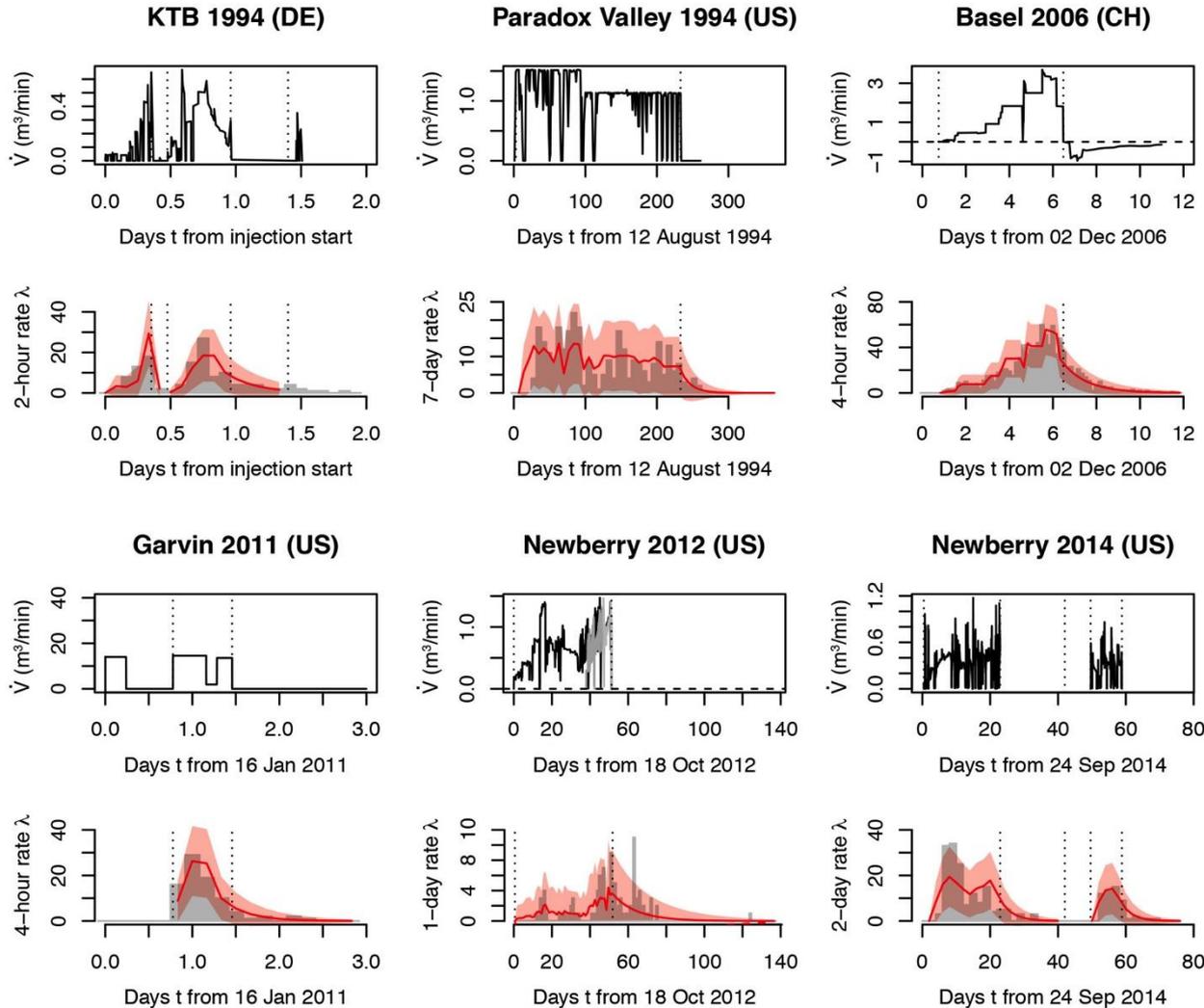


2006 Basel EGS data sources:
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Time t from injection start (days)

source: modified from Mignan (2016)

Deep fluid injections around the world



✓ **Simple model fits reasonably well** most of the sequences (based on MLE & KS test)

✓ **High variability of underground feedback**

- $-2.8 \leq a_{fb} \leq 0.1 \text{ m}^{-3}$
- $0.8 \leq b \leq 1.6$
- $0.2 \leq \tau \leq 20 \text{ days}$

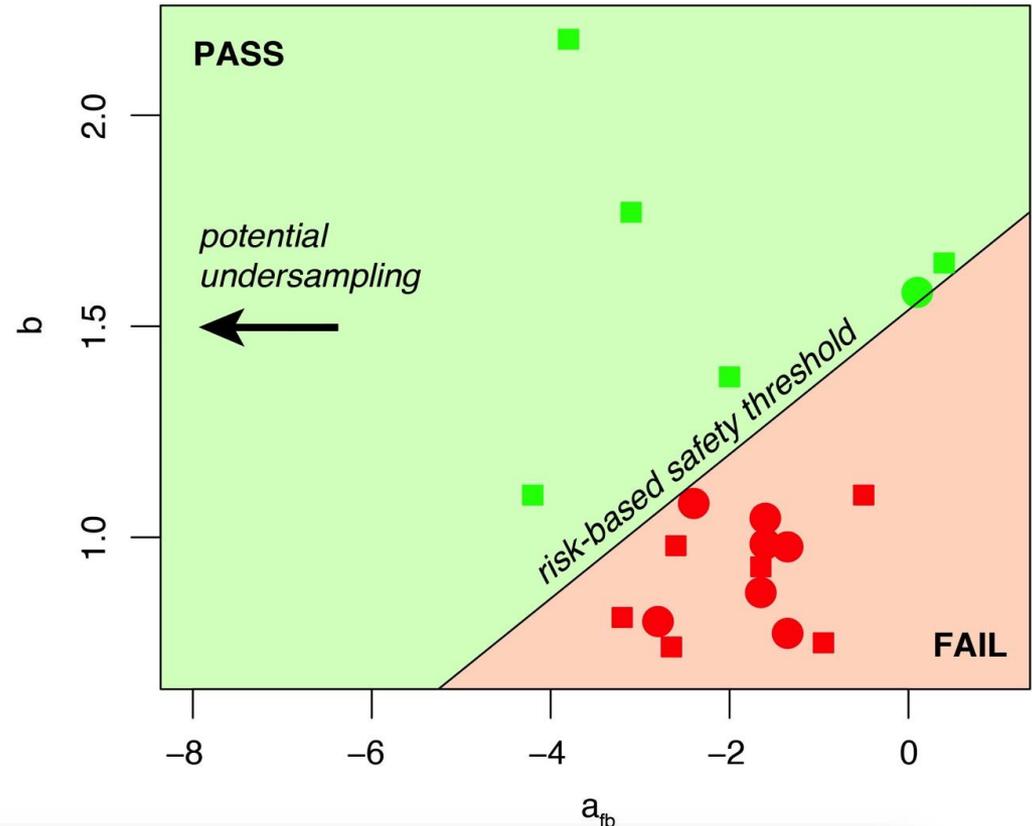
✓ **Second-order deviations from model still to be understood**

- Missing on-site data?
- Second-order physics?

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

- ✓ 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 $\Pr(\geq m_{saf}) = 1 - \exp N(\geq m_{saf})$
 - 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 $V=10,000\text{m}^3$, 4km depth, $d=0\text{km}$ from borehole)



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

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

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)

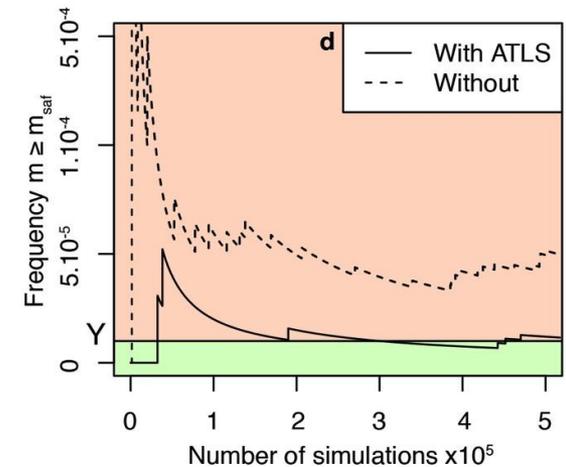
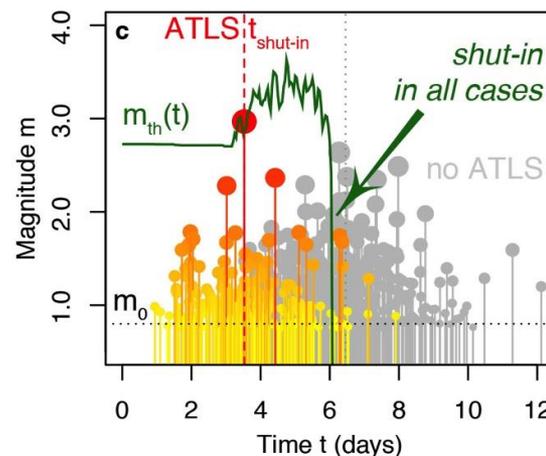
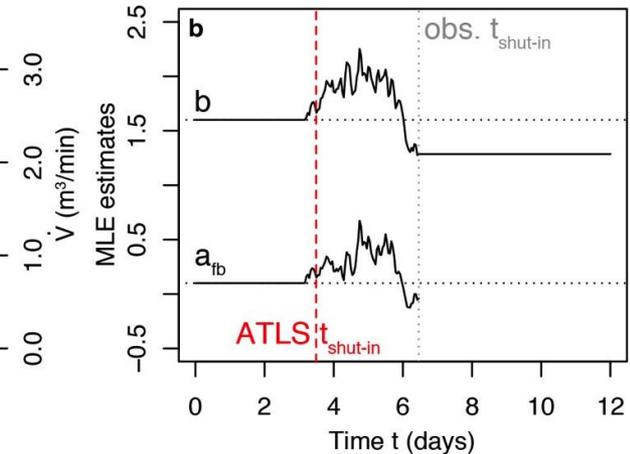
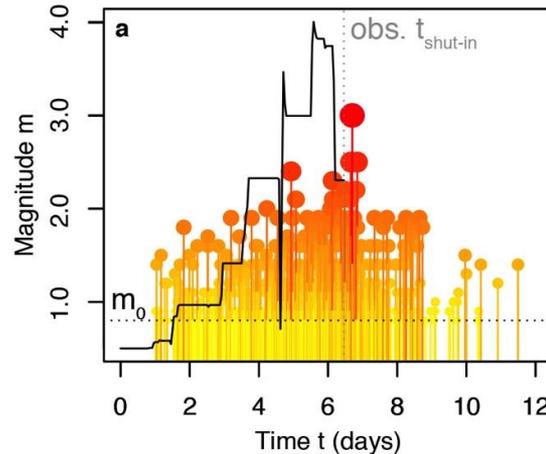
- Risk evolves with time
- **Adaptive TLS (ATLS)**

c. TLS definition

- **Stop injecting above m_{th}**

d. TLS validation

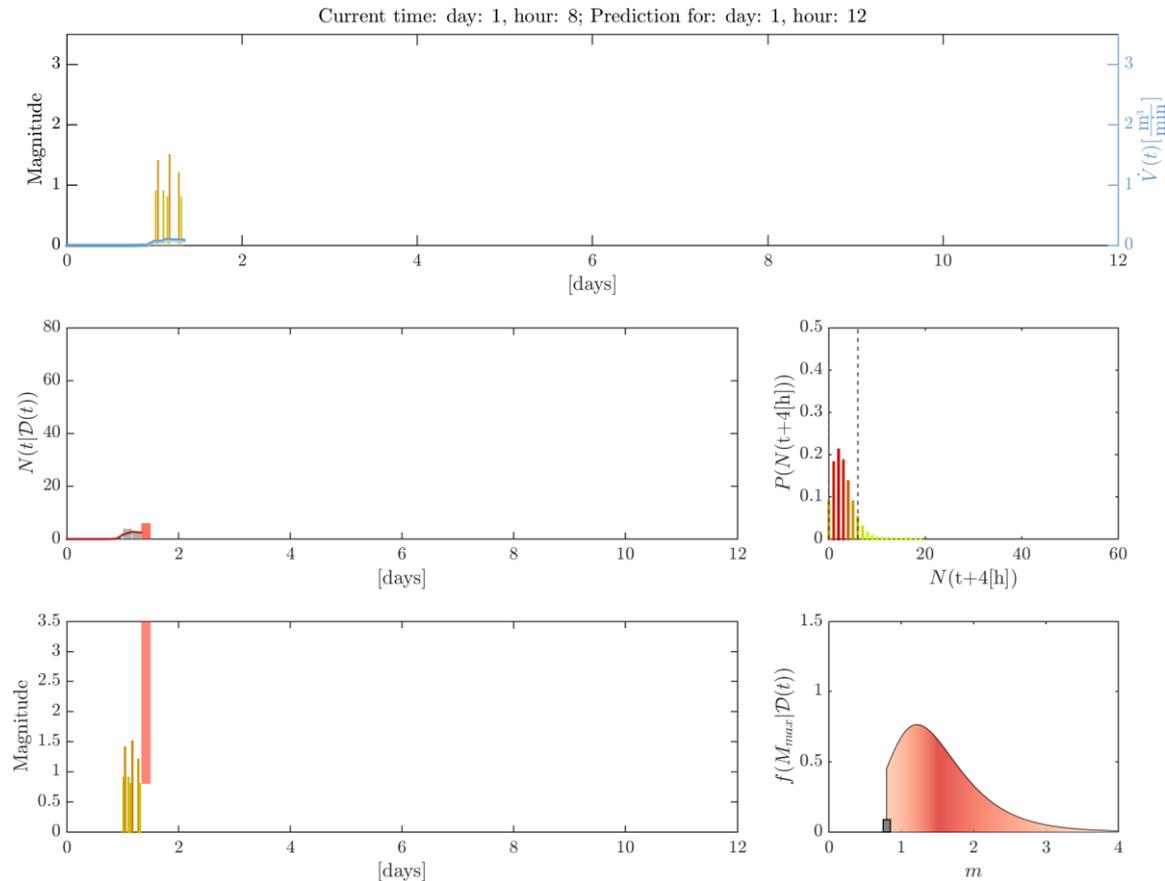
- Over millions of simulations, we observe that the safety norm is respected in average



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

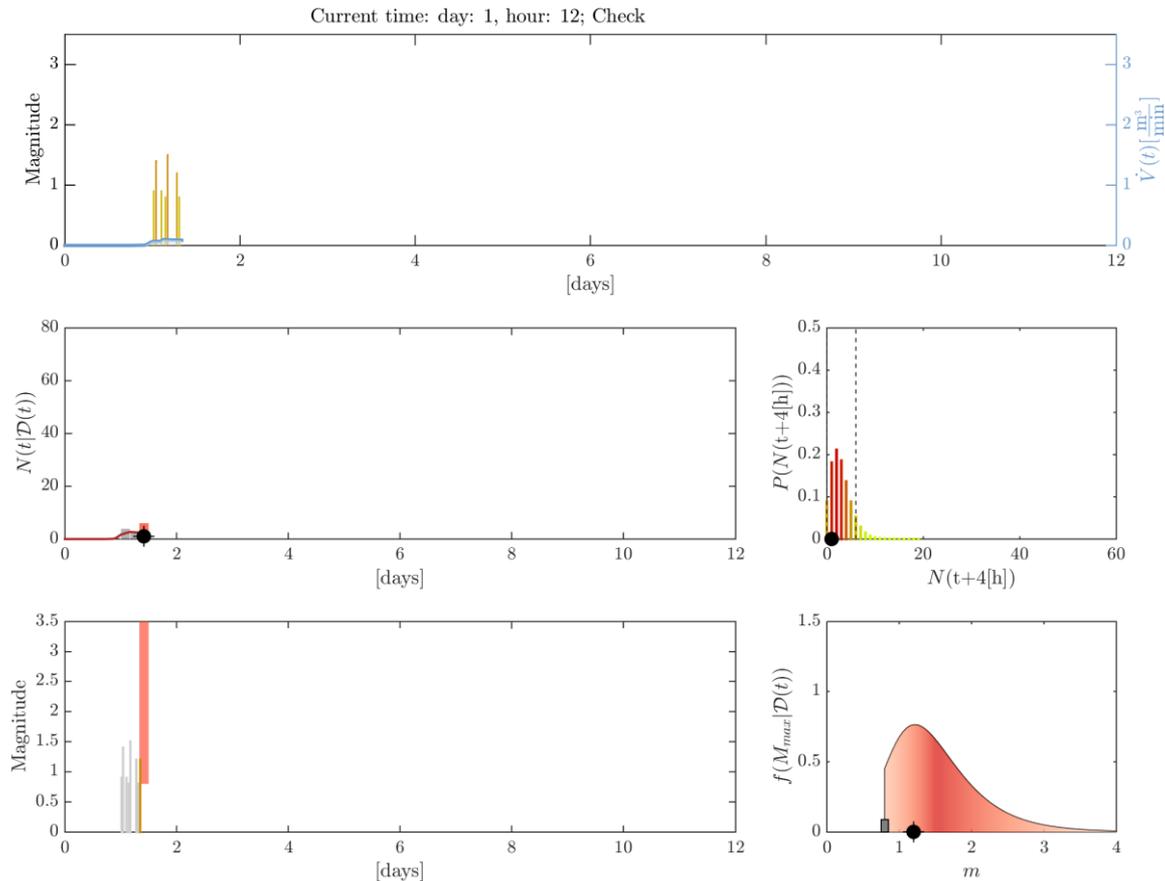
Hierarchical Bayesian forecasting

- ✓ 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.*



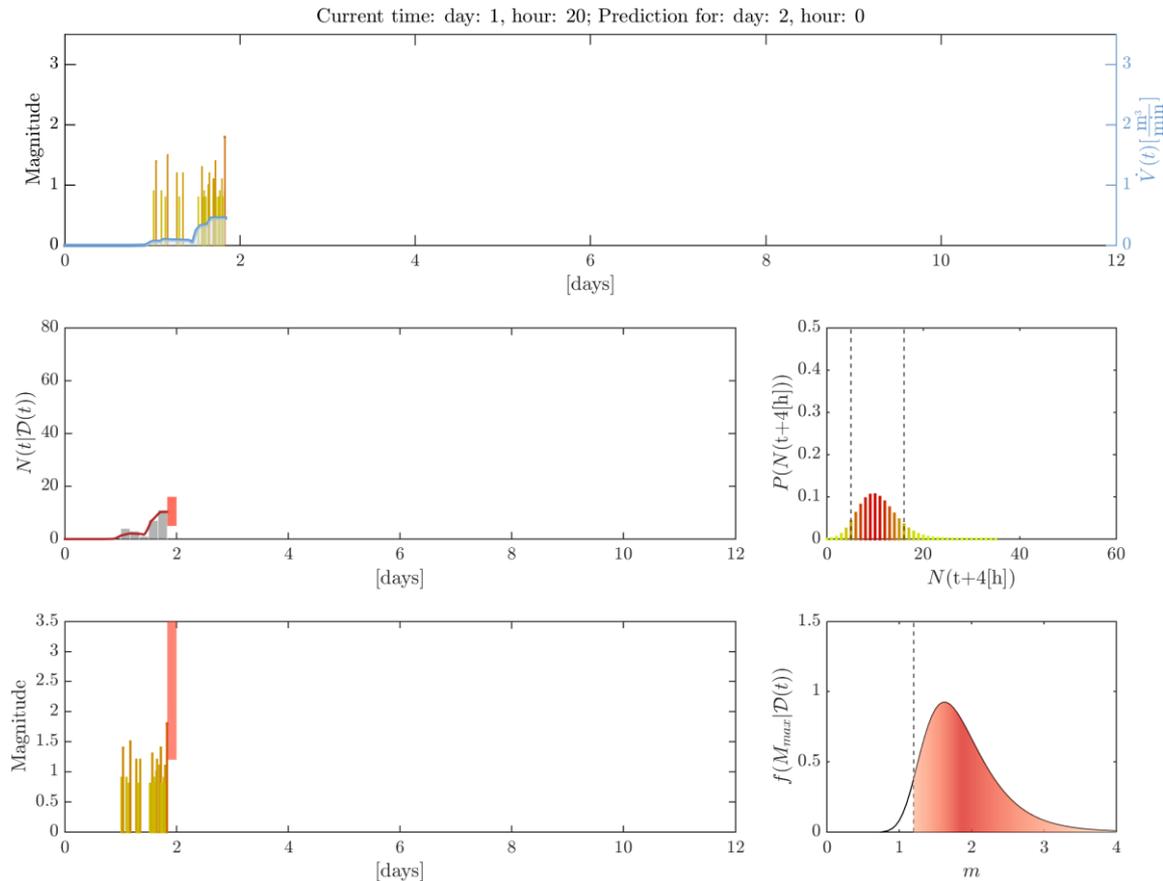
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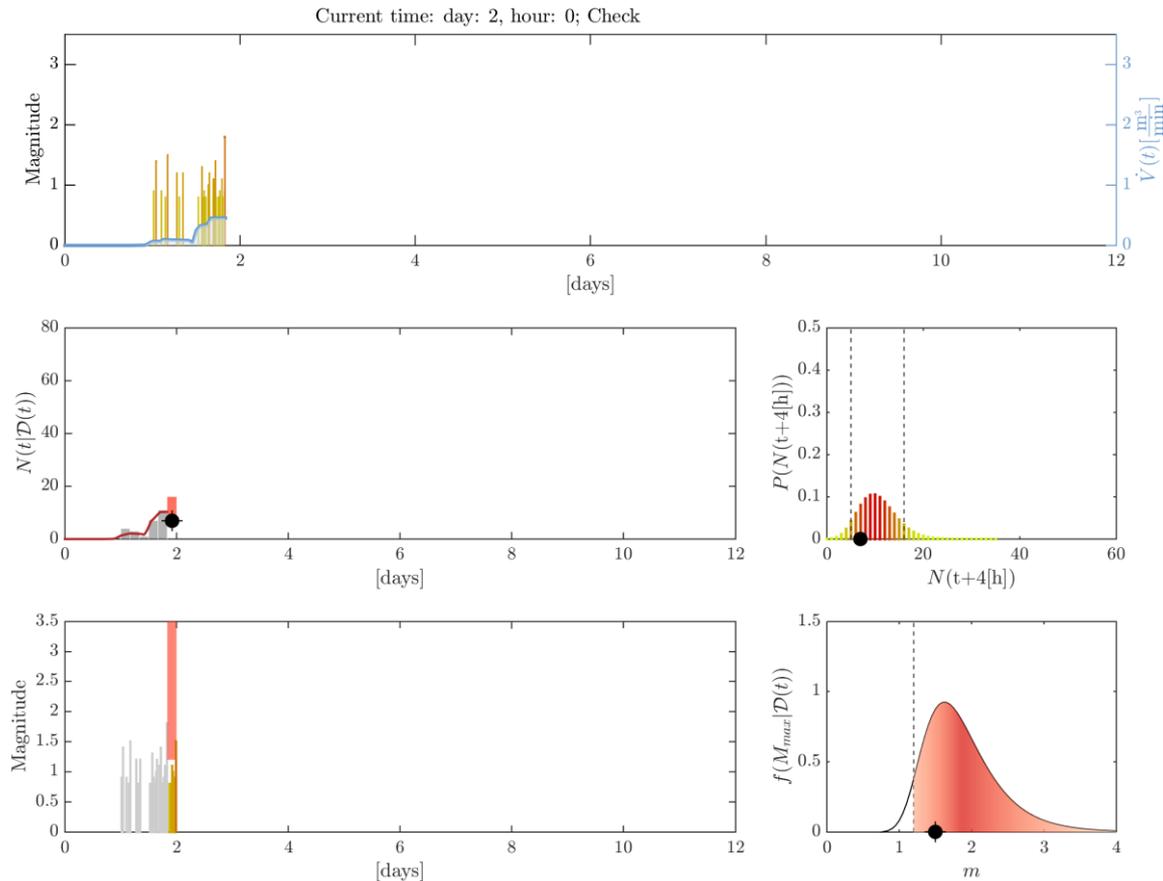
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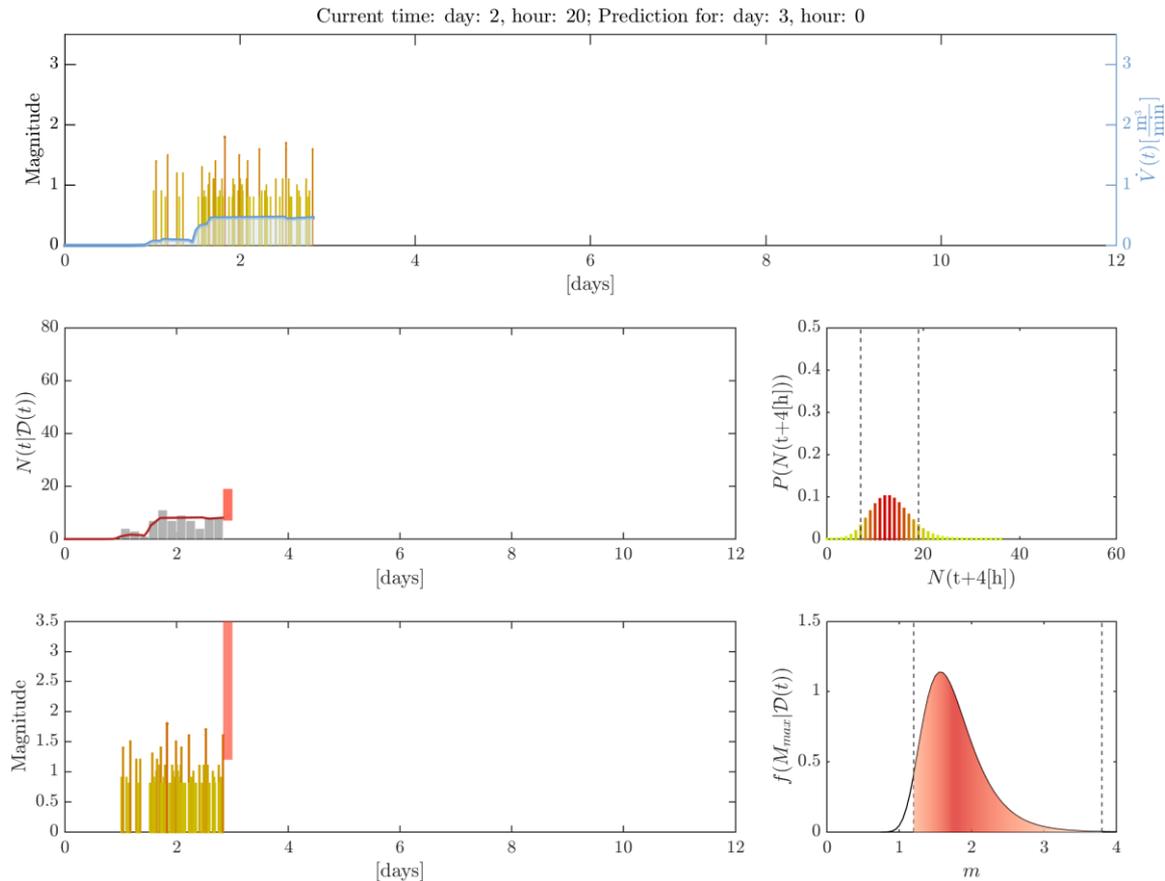
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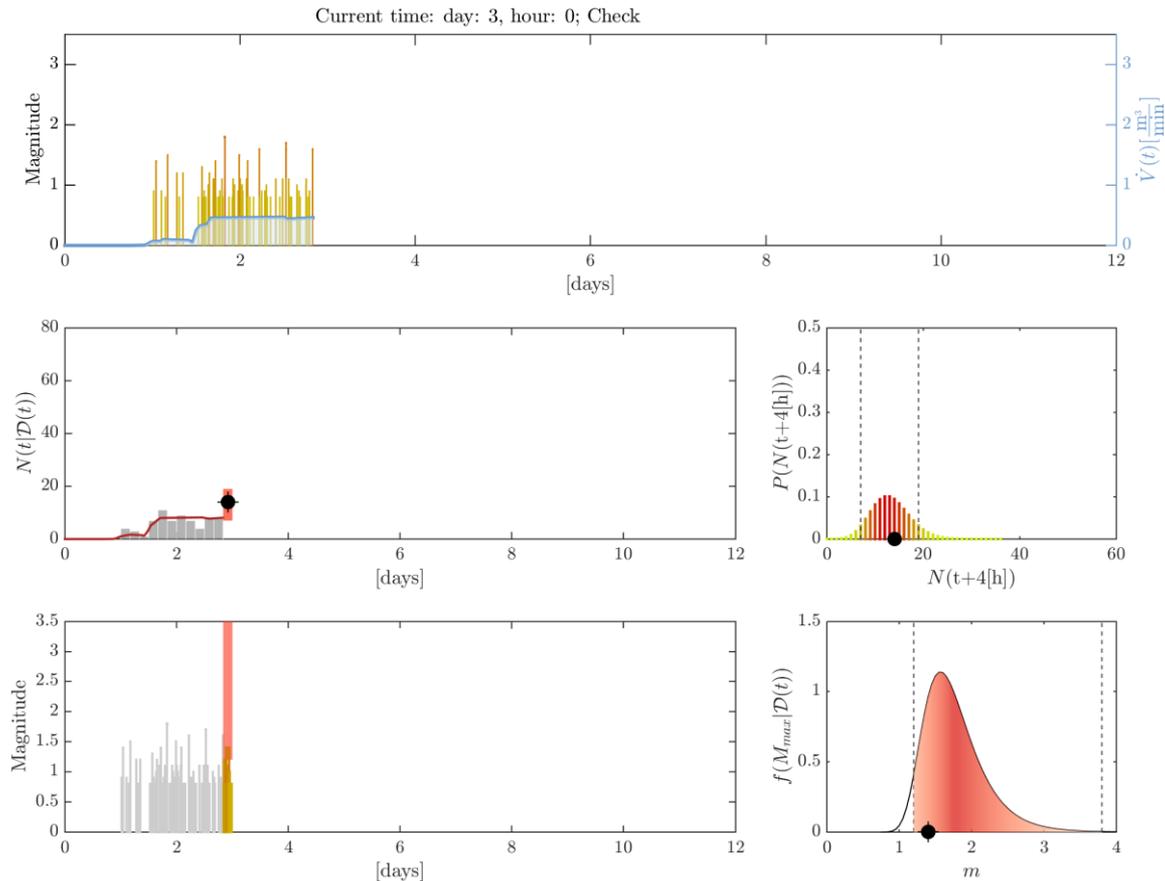
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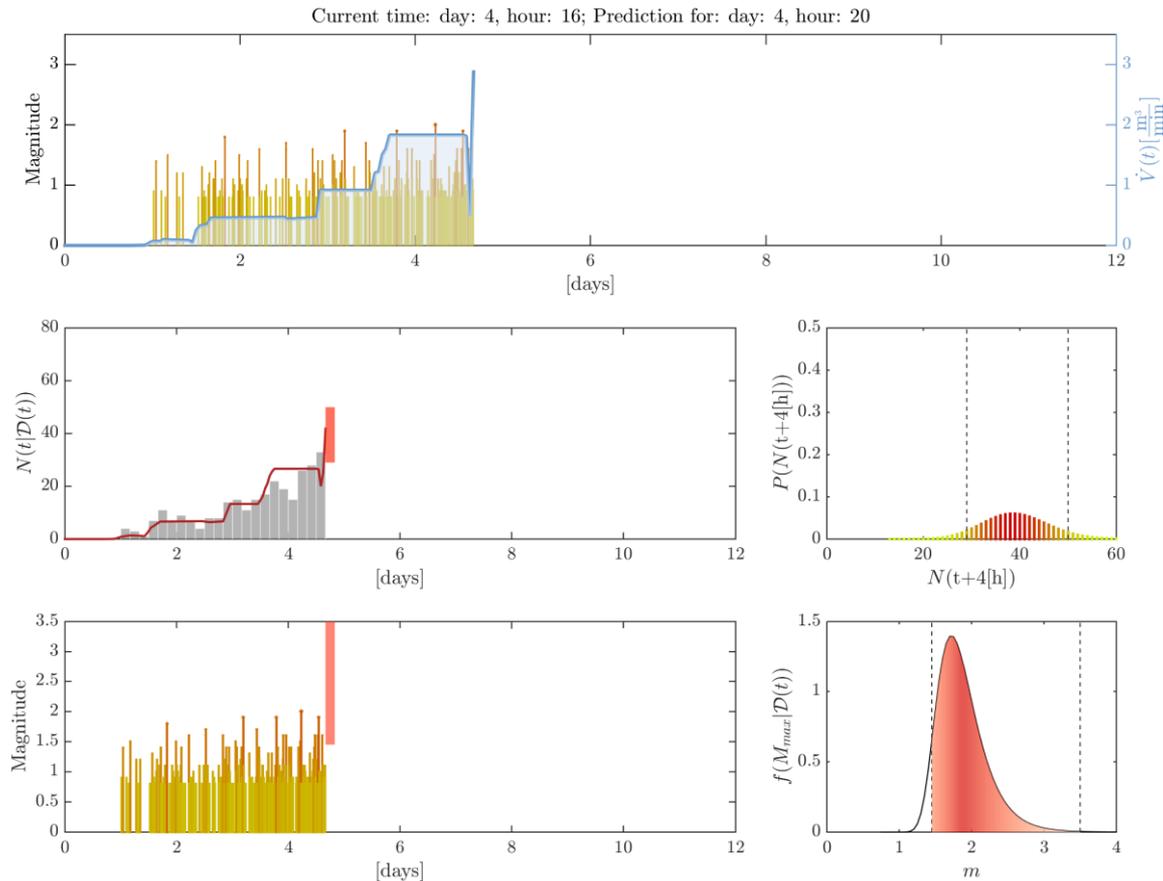
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source: *Broccardo et al. (submitted)*

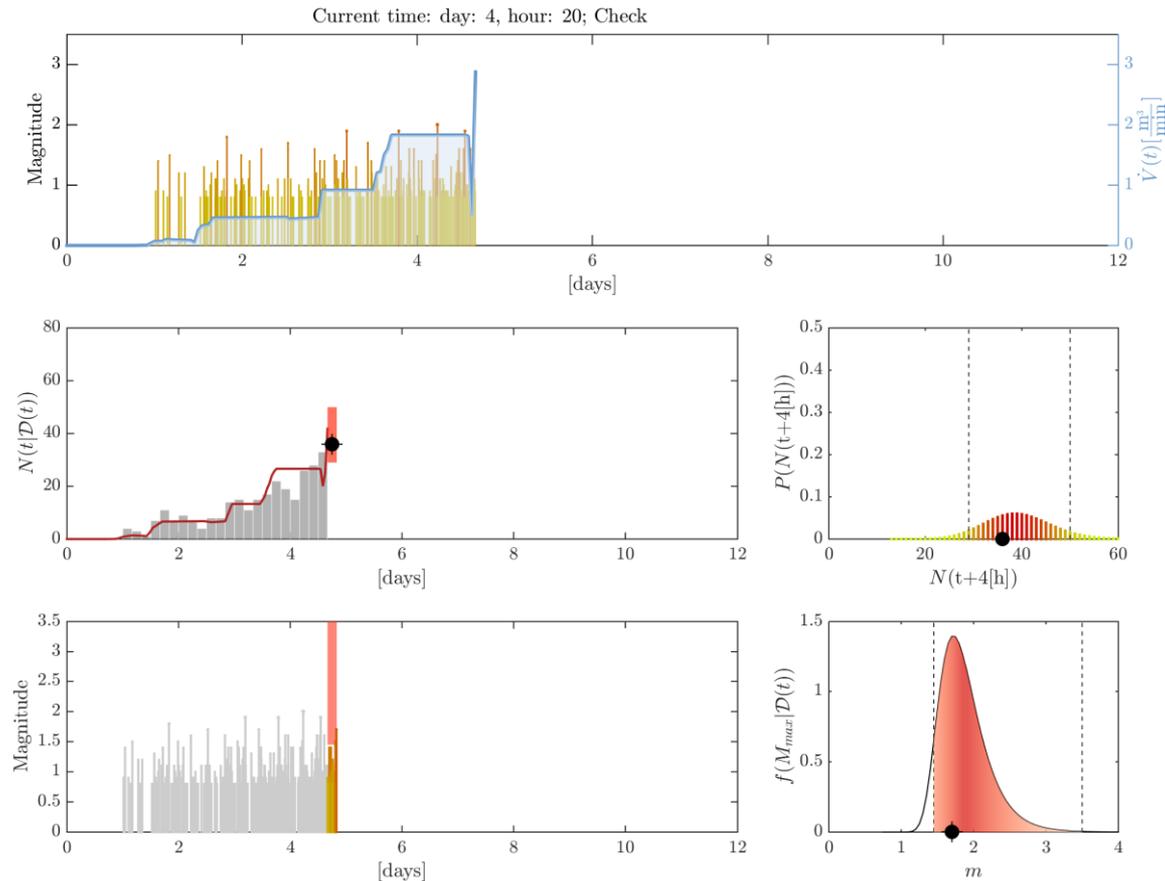
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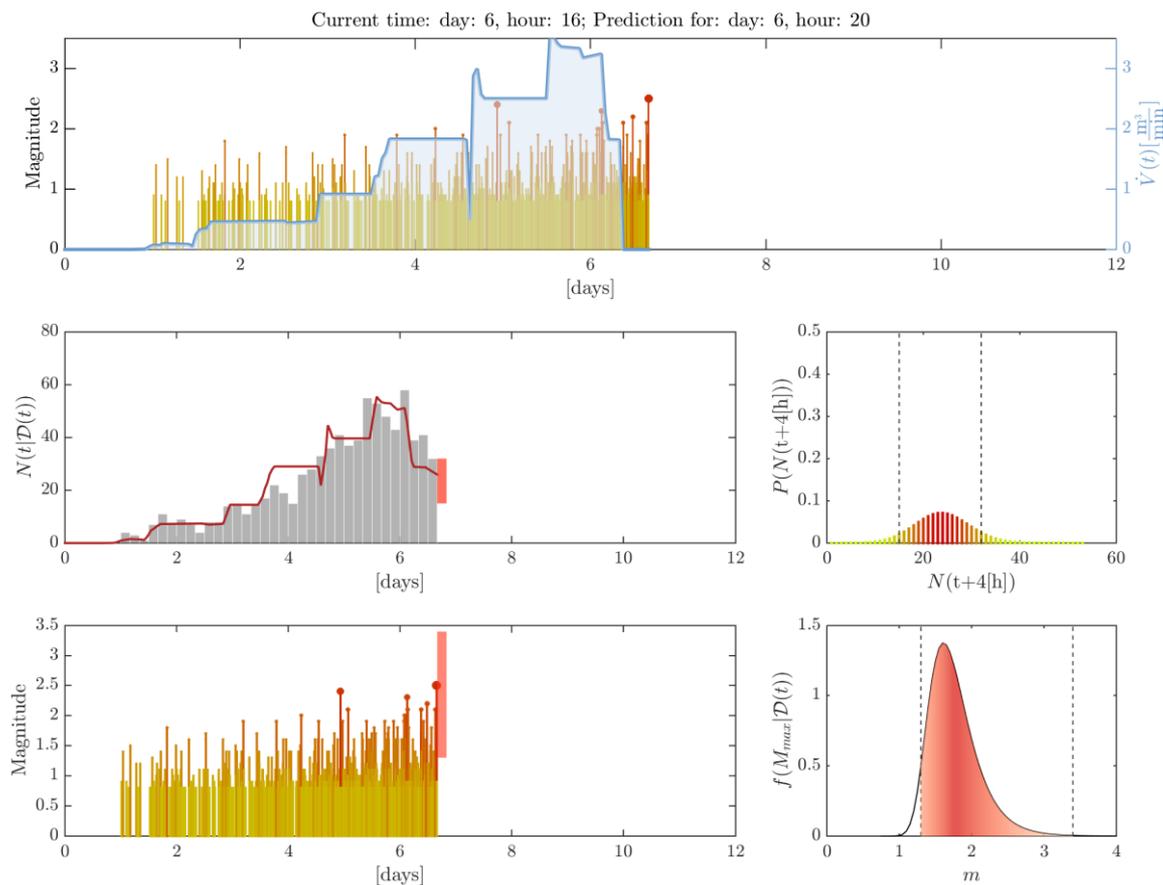
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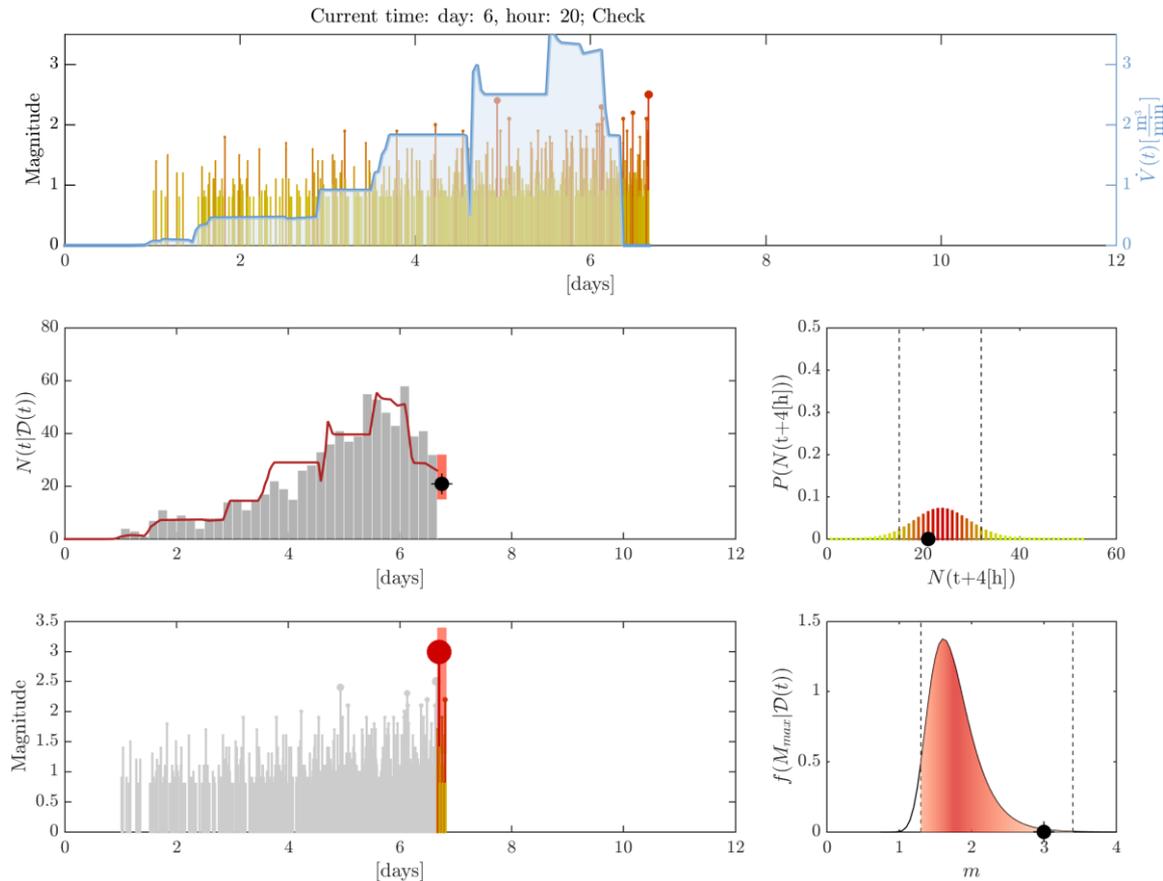
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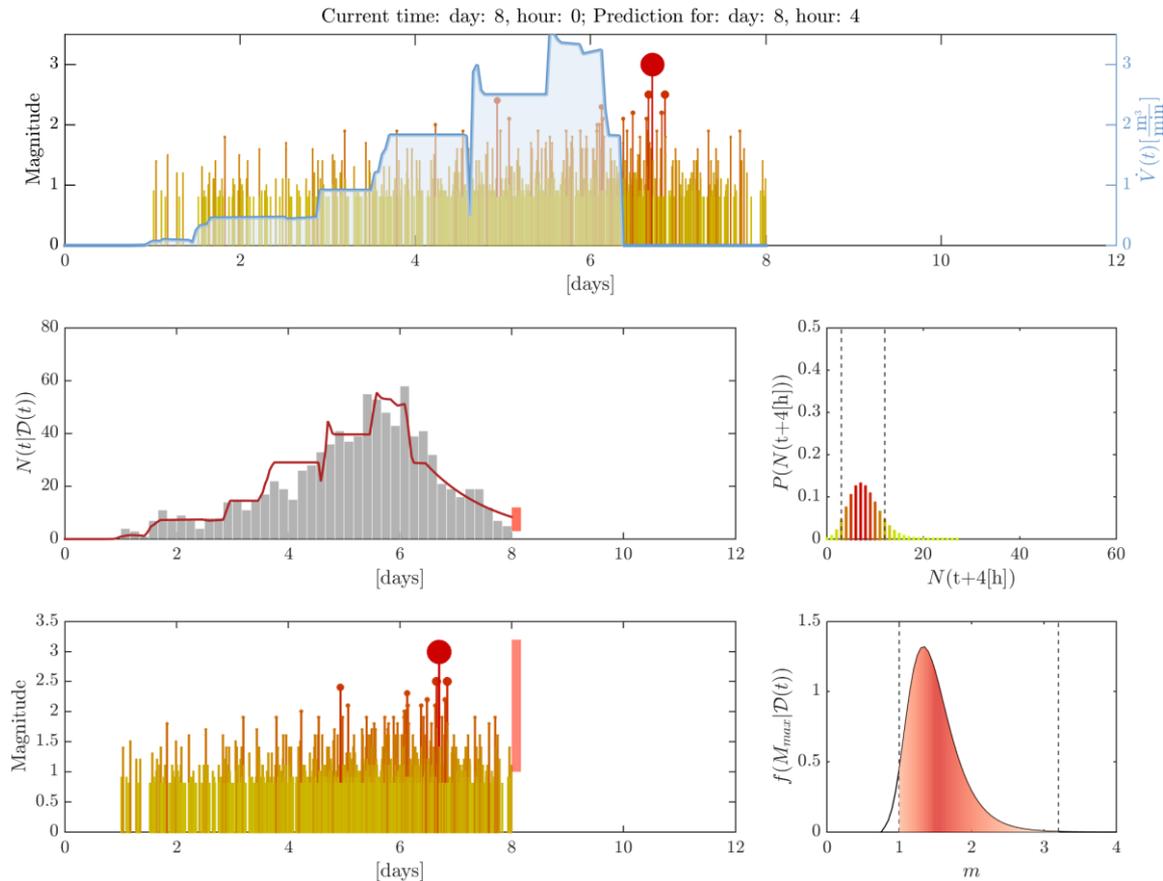
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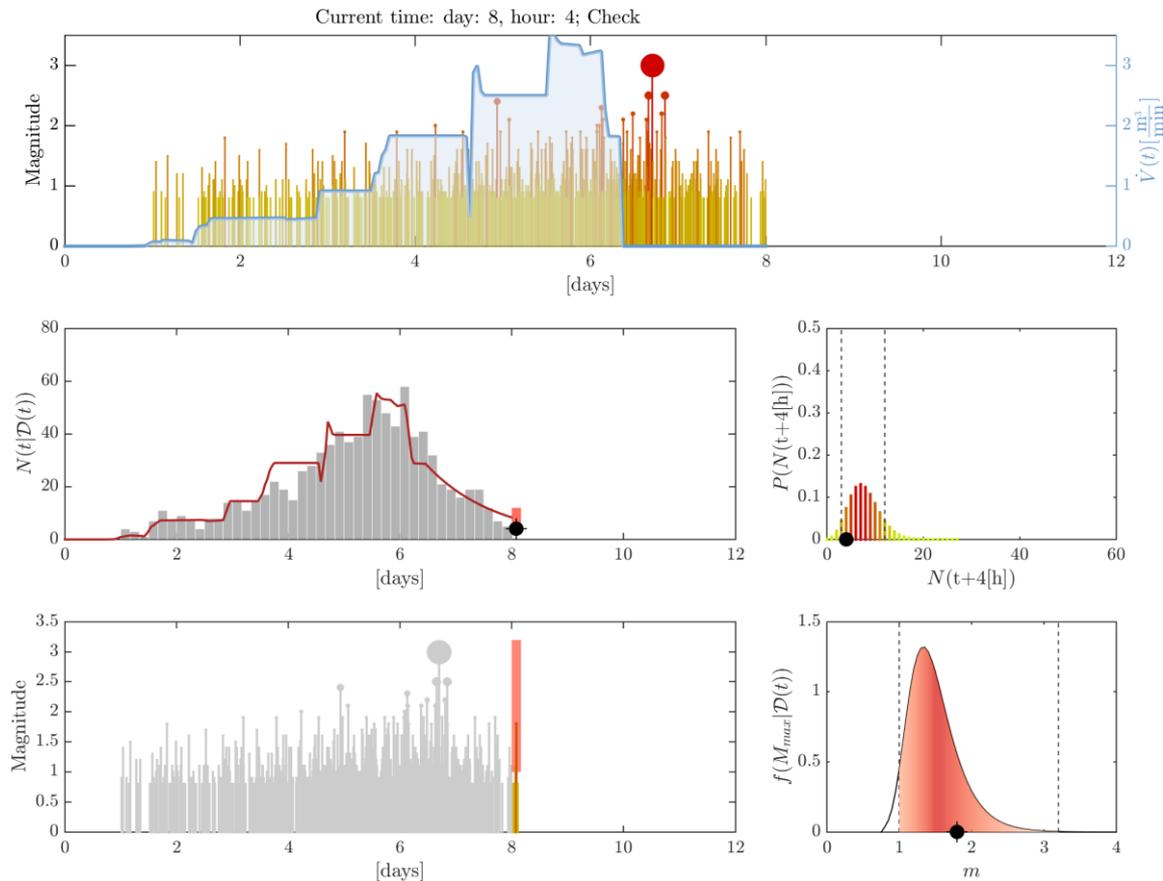
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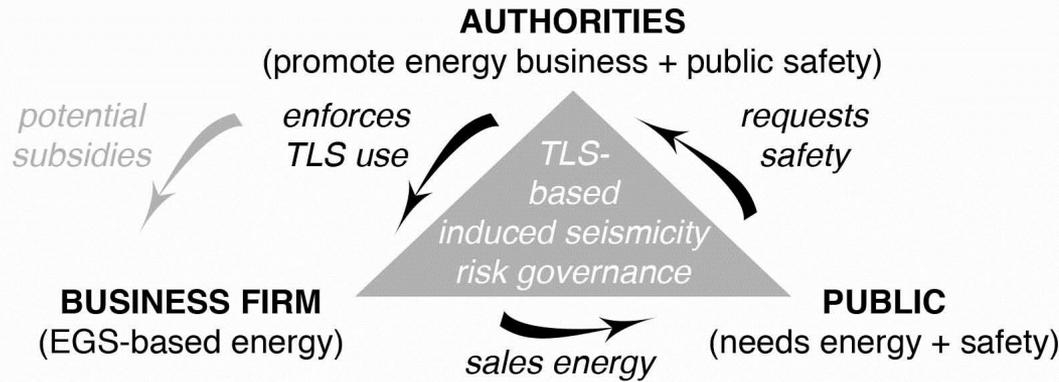


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Next steps



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 - Seismic risk turned into increased price/kWh
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The price of public safety in EGS projects
A. Mignan, M. Broccardo, S. Wiemer & D. Giardini

Abstract
The risk associated with seismicity caused by fluid injection in the deep underground in EGS projects can be fixed using mitigation measures, such as traffic light systems (TLS), which impose a risk threshold criterion in order to ensure public safety. This infra that some wells may fail, which would tend to increase the EGS-generated electricity base price. We first estimate this increase as a function of borehole distance to the nearest habitation considering a probability of fatality higher than 10⁻⁴ as unacceptable. Taking into account the underground feedback uncertainty (α- and β-values of the Gutenberg Richter law, maximum magnitude M_{max} , standard risk parameters and a reasonable economic model (base price of 0.28\$/kWh), we find that the price increases to 0.23\$/kWh above the borehole and rapidly decreases back to the base price at a distance of ~4km. Based on Cumulative Prospect Theory, we find the price to increase to 0.30\$/kWh due to the risk aversion of uncertain well loss. The heat credit at short distances would compensate for this ‘cost of public safety’ – Disclaimer: All values are subject to modeling choices.

Methods

- Project: triplet, depth $z = 5km$, stimulation of $V = 50,000m^3$
- Electricity generation (e.g., Lacioglu & Blanc, 2013): $T_{res} = 35^\circ C$, $\rho_{res} = 787 kg/m^3$, $Q = 50kWh$, CRC system (case 5), $8000m^3/hr$, $M_{max} = 2M$, $C_{min} = 15,000m^3$, standard well $d_w = 20W$
- Costs (Mitschberger et al., 2015): $C_{min} = 20$ million \$, $C_{max} = 1$ million \$, $C_{avg} = 4000kWh$
- Pricing = costs (\$) / electricity generation (kWh) = 0.28 \$/kWh
- Inducer seismicity risk model (Mignan et al., 2015): 10k-USE method, intensity predictor equation, EM508 class B building.
- Risk mitigation TLS-based model (Mignan et al., in prep): $p =$ probability of fatality curve crossing the 10⁻⁴ safety threshold
- Price updating approach: additional cost per failed well = $p(C_{min}/C_{max})$
- Risk aversion model: standard parameters of Cumulative Prospect Theory CPT (Tversky & Kahneman, 1992) with distribution of p , loss aversion amplification & different utility functions for losses/gains

Results

- Underground feedback uncertainty: M_{max} ambiguity turned into subjective probability $p(M_{max} = 4.0/M_{max} = 7.0)$; β -Werte (e.g.) scattering assumed as true distribution & independent of well location
- Fatality curves & probability of TLS failure:
 - ✓ $d = 10$ km from nearest building
 - ✓ All $M_{max} = 4$ scenarios pass
 - ✓ 5/8 $M_{max} = 7$ scenarios fail
 - ✓ Yields $p = (0.5/16) = 0.3$

Advantages of the approach:

- ✓ Translates cost of seismic risk mitigation into electricity price
- ✓ To the public: Assured that a fixed safety threshold is respected
- ✓ To the industry: Decision making under uncertainty made possible
- ✓ To the authorities: Improved decisions based on clear rules. If the cost of failed wells becomes too high for the EGS industry, authorities may decide to decrease the safety threshold. E.g. for 10⁻⁴ probability of fatality, the original base price is reached at 5km

The additional cost of ambiguity:

- ✓ $\max(M_{max})$ critical to probability of failure. Could be reduced if the underground was better known
- ✓ A 0.5 probability for $\max(M_{max})$ is disputable (Bommer & van Elk, 2017). Whatever value used, ambiguity must be discussed in terms of a stress test (minimax option where the worst possible scenario is investigated)
- ✓ Reduction of uncertainties is costly & may not decrease risk
- ✓ Passing a stress test may be costly due to e.g., building retrofitting

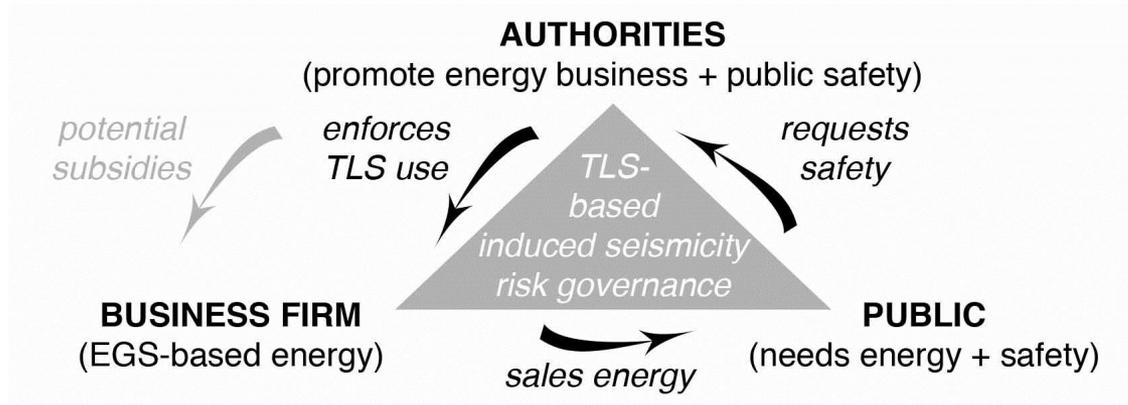
Limitations:

- All values and graphs shown here are subject to the modeling and parameter choices
- Damage of potential earthquakes not considered & assumed insured
- (α, β) parameter set assumed independent of location. However if one well fails, e.g. due to high-α-values, it is plausible that nearby wells would react in a similar way, meaning an increase of p

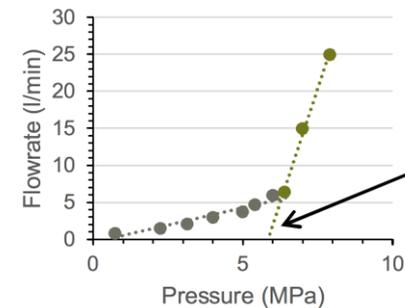
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 Mignan et al. (2015), Induced seismicity risk analysis of the 2006 Basel, Switzerland, EGS project: influence of uncertainties on risk mitigation, Geothermics 53
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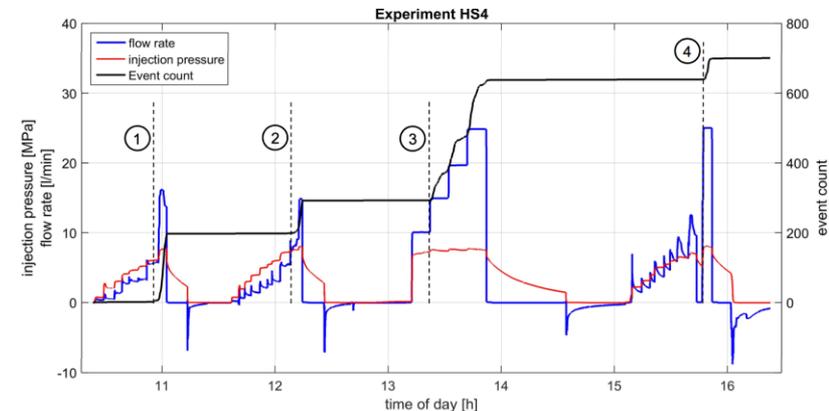
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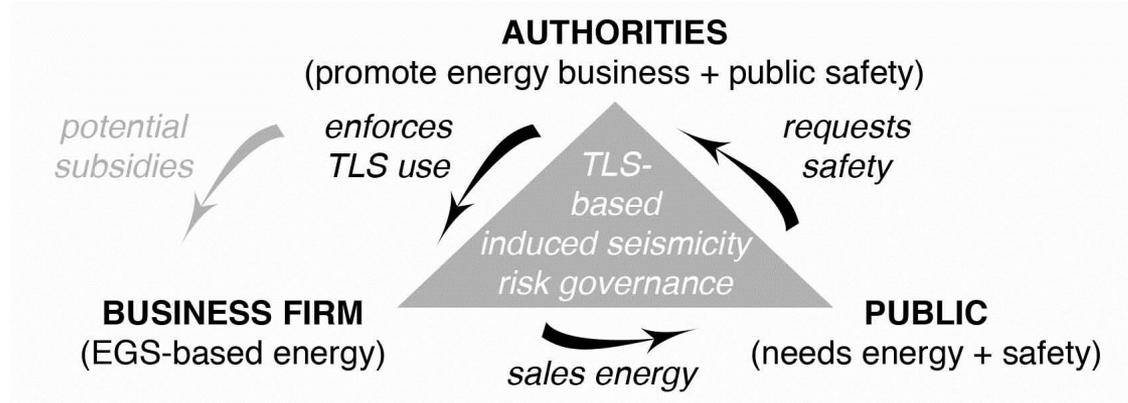
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Courtesy of the DUG Lab Team



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- ✓ **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*