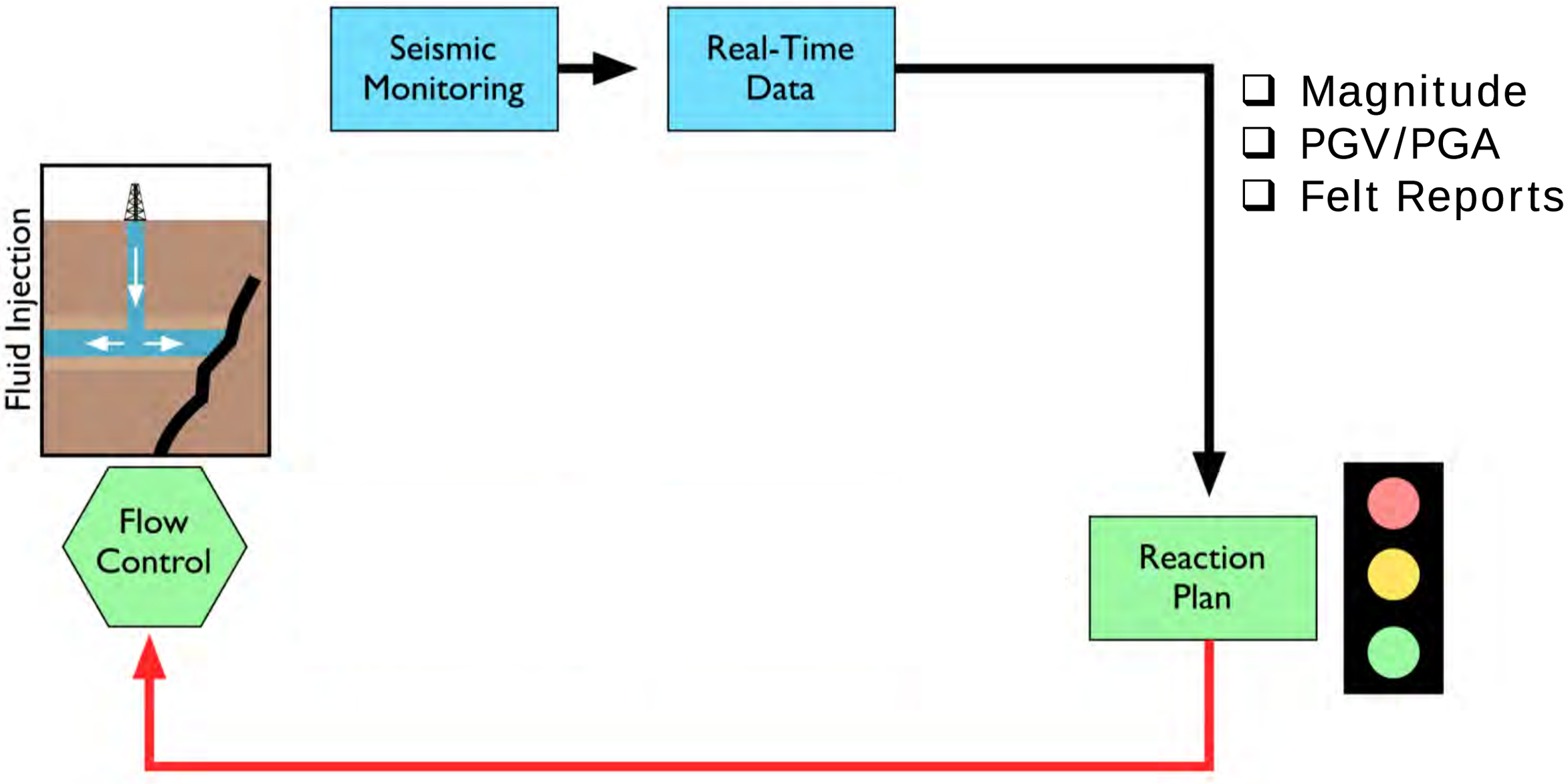
Testing advanced traffic light systems for the management of induced seismicity

Prof. Dr. Stefan Wiemer

With major contributions from:
Arnaud Mignan, Marco Broccardo and many others

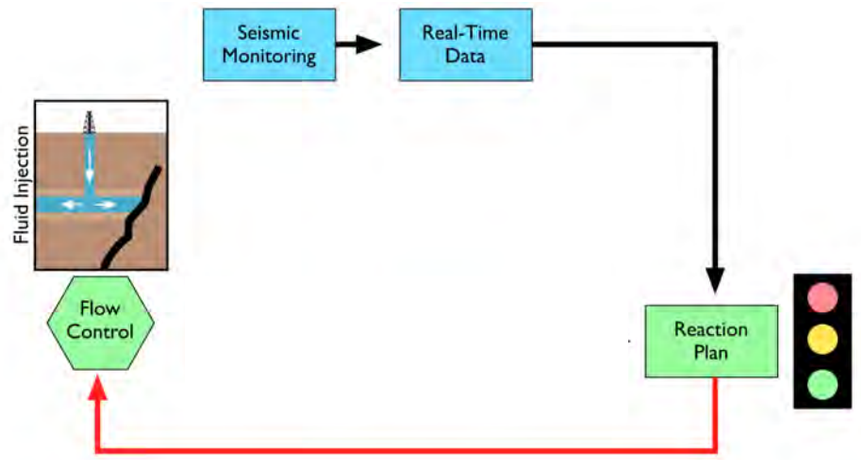
ETH-Zurich, Swiss Seismological Service (SED), Switzerland

Traffic Light Protocols for managing induced seismicity are very useful, and proven technology!



Grigoli et al. (2017)

Simple, useful – but not very smart:



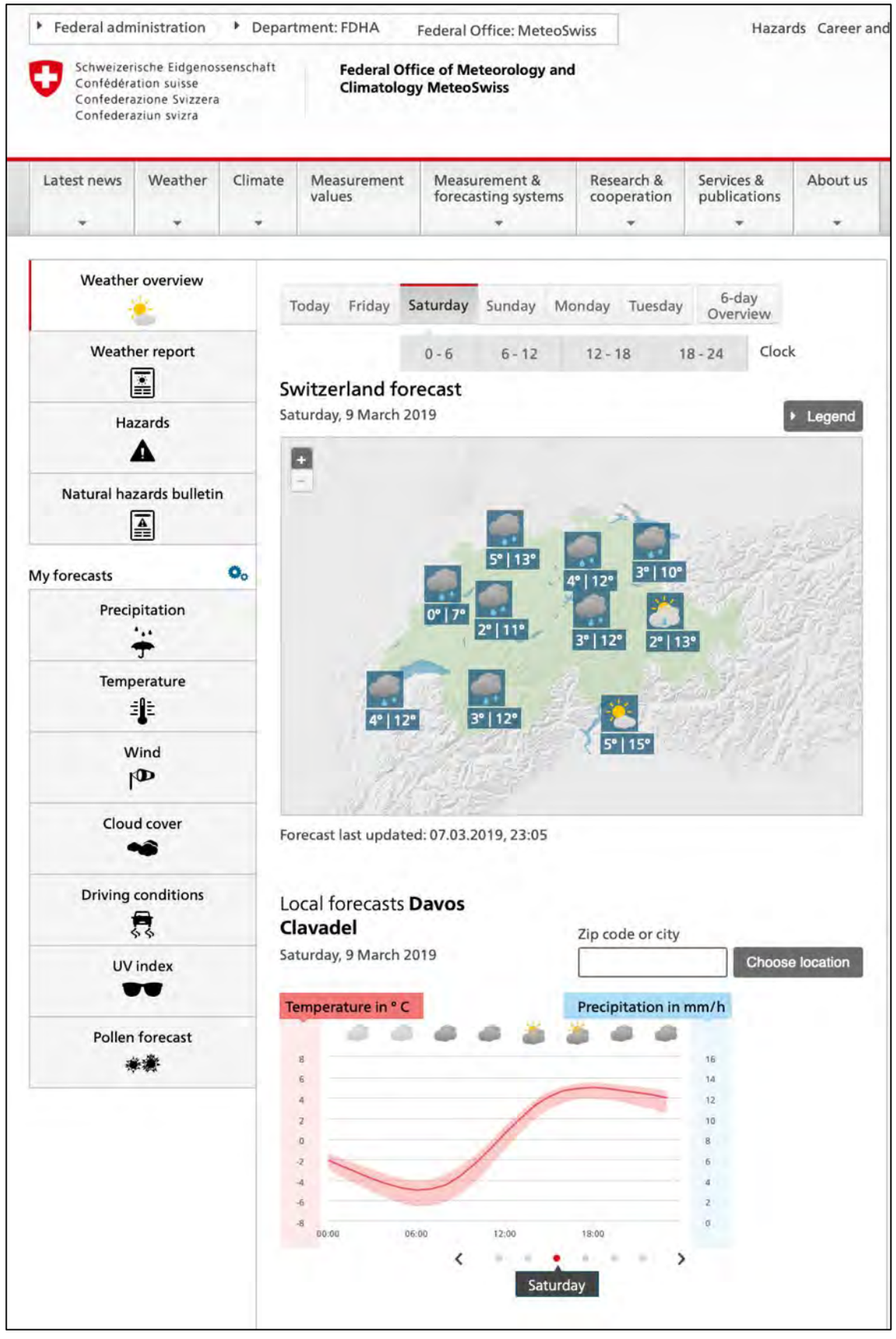
- No underlying physical/reservoir model
- Limited use for real-time reservoir optimization
- No benefit from better monitoring‘
- Threshold set ‘heuristically’ and a somewhat random success rate.
- No integration of knowledge on geology, site response, ground motion prediction, build vulnerability, exposure ...

The weather analogue: A TLS means that you take an umbrella if you see cloud emerging.

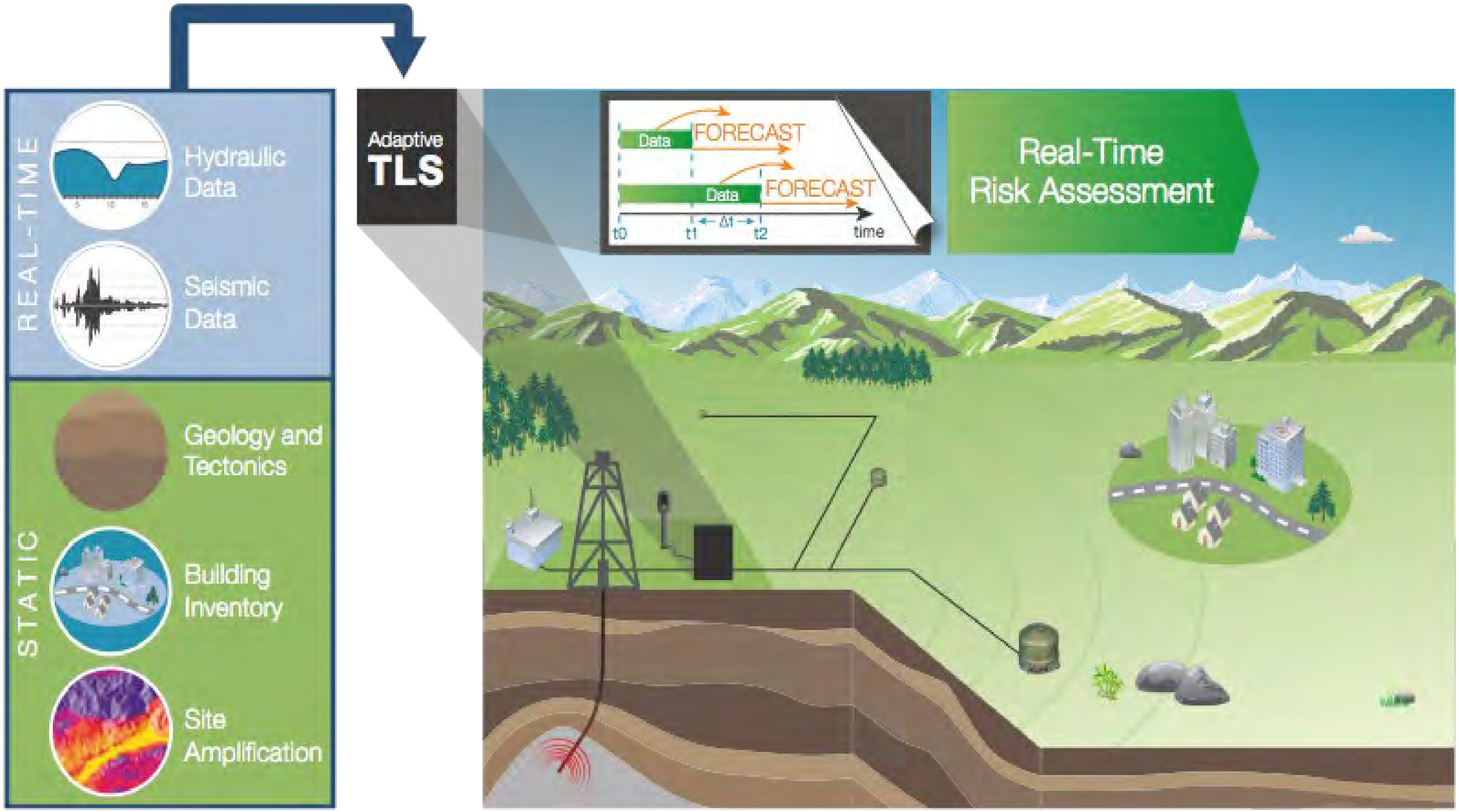
Useful for the short term & simple and robust. But not robust against surprises nor for longer forecast horizons.

Beyond cloud viewing

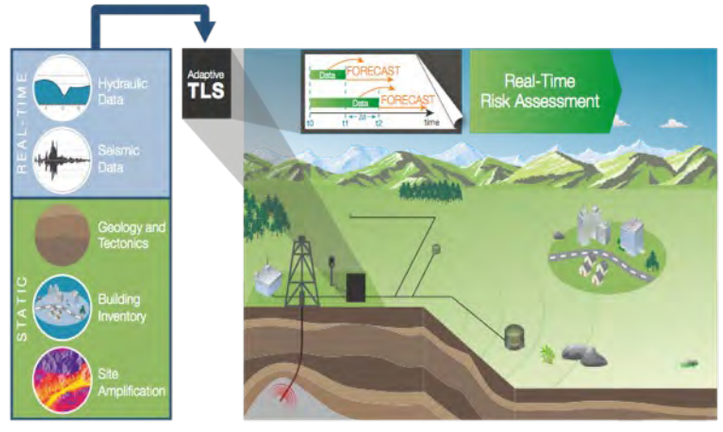
- If you plan your next weekend trip, you will check a forecast.
- A forecast will take a **lot of data**, and various **models** to give you the best estimate of what will happen in the next days...
- And you would expect that:
  - Models are tested, validated.
  - As new data arrives, models are updated.



Enter “Adaptive, data-driven Traffic Light Systems (ATLS)”



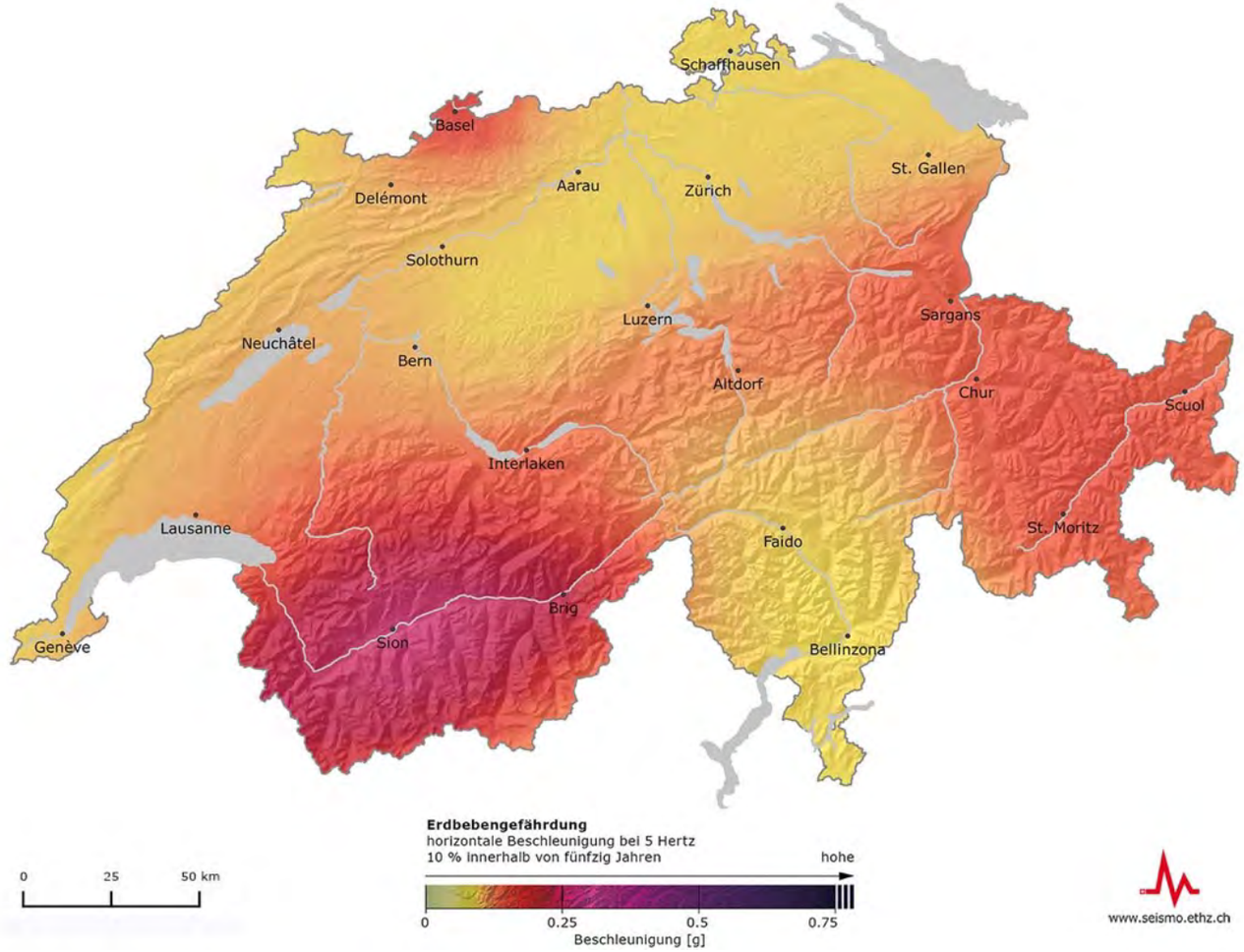
“Adaptive, data-driven Traffic Light Systems (ATLS)”



- ATLS are dynamically updated, forward-looking and fully probabilistic models that forecast the future seismicity and reservoir evolution based on a range of relevant key parameters (eq., K P, T, …).
- Are probabilistic, and consider also ‘low probability-high consequence events’.
- Integrate in risk space (GMPE, exposure vulnerability)
- Integrate prior knowledge and real-time data in a Bayesian sense
- Achieve robustness through ensemble forecasting and dynamic weighting of models based on real-time performance.

Why risk?

- People, companies, governments usually take risk based decisions.
- Risk integrates all our knowledge on a process, also considering uncertainties, in a structured, transparent, reproducible way.
- This map of rock reference hazard is, well, quite useless.... Because my personal risk varies dramatically depending on the soil type, the building I am in and with time.



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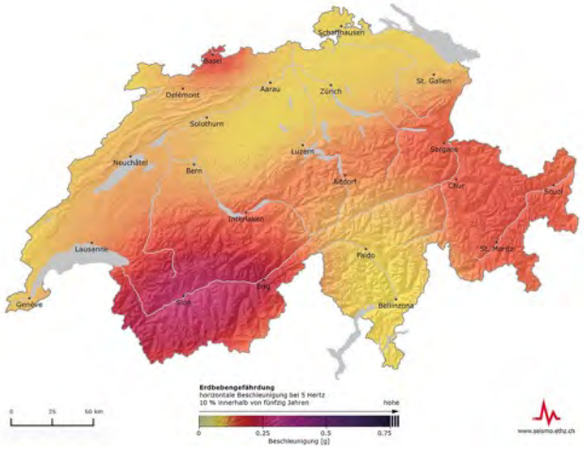
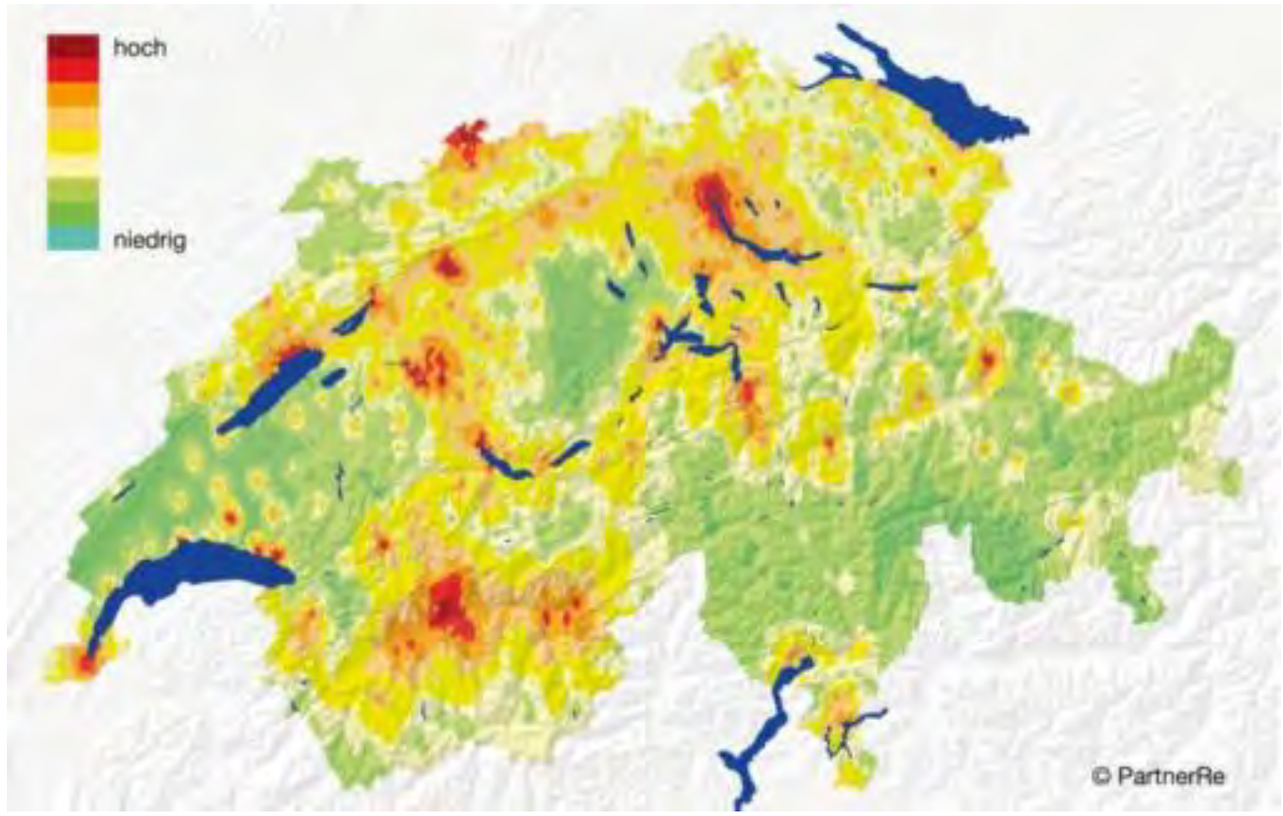
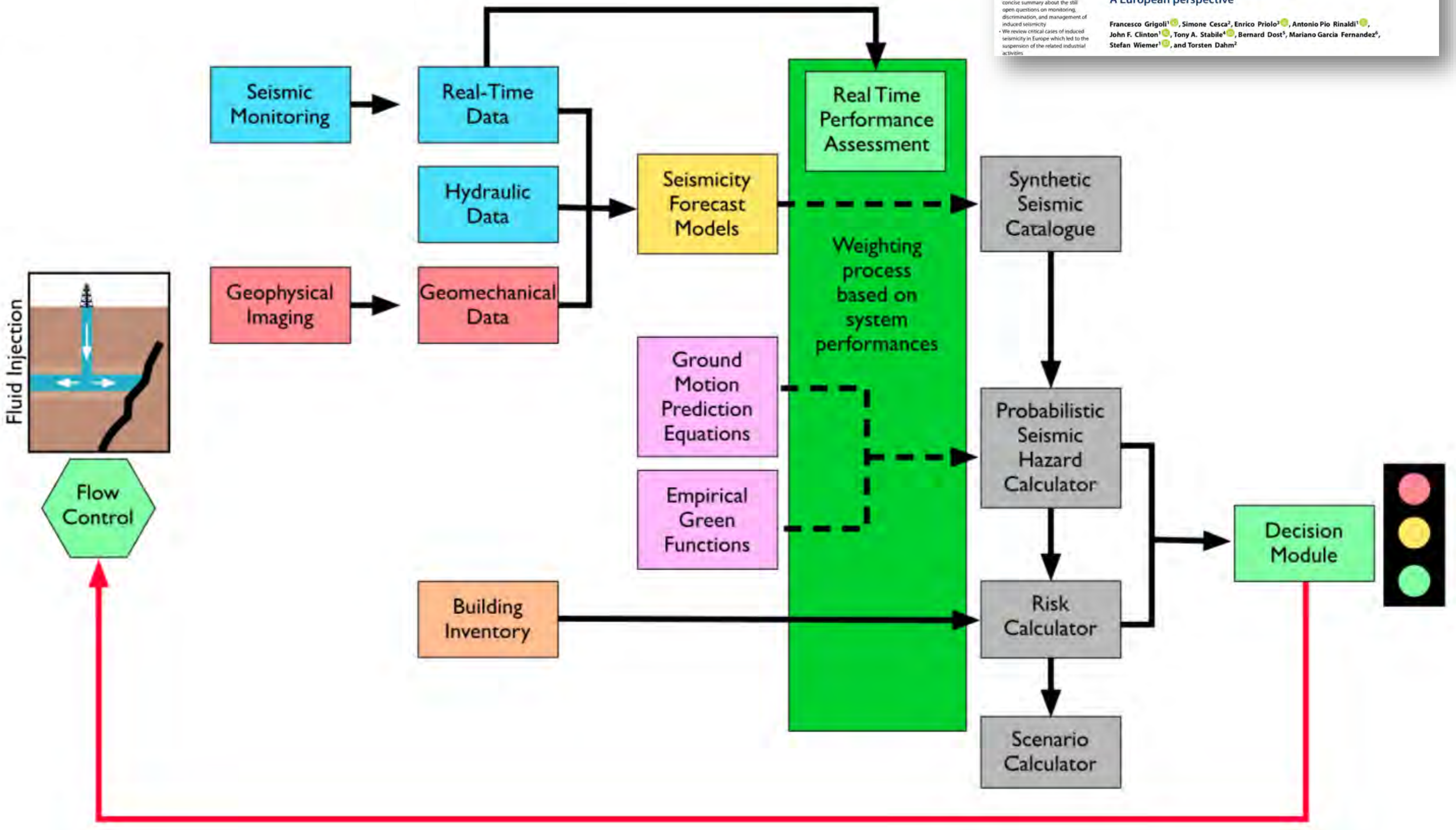


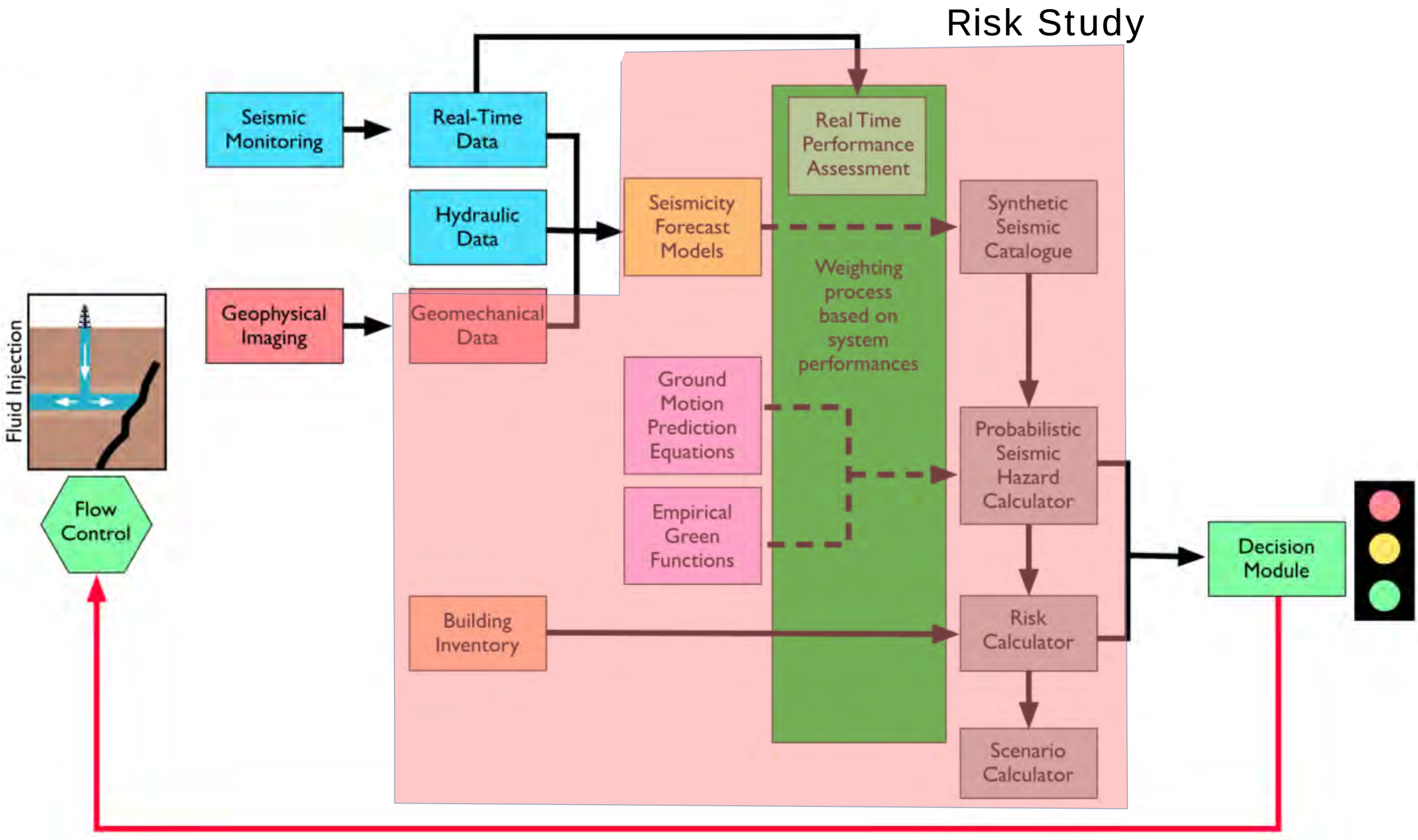


Adaptive Traffic Light System (ATLS)



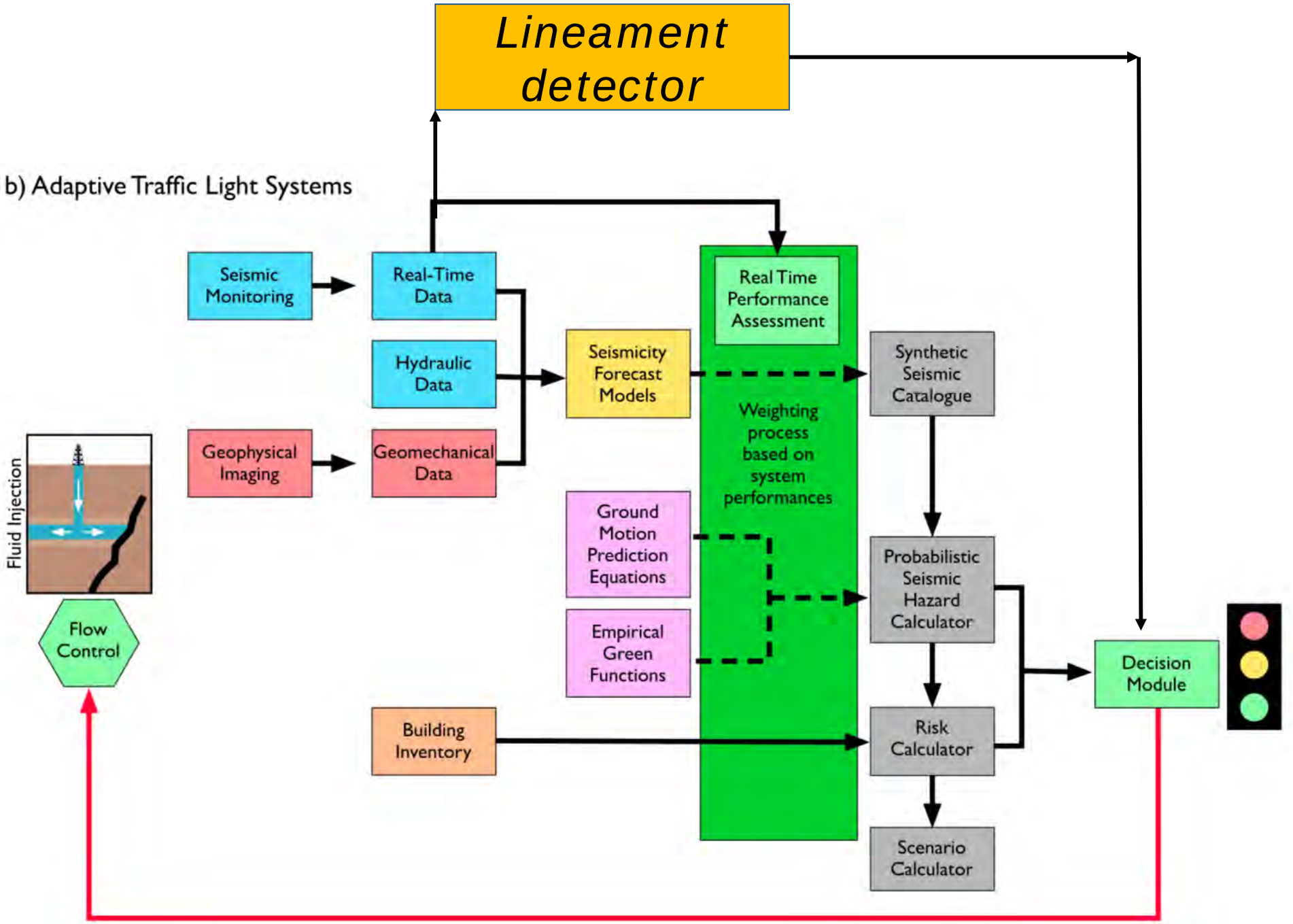
Grigoli et al. (2017)

ATLS = a dynamically update risk study



Grigoli et al. (2017)

What I learned the last days...



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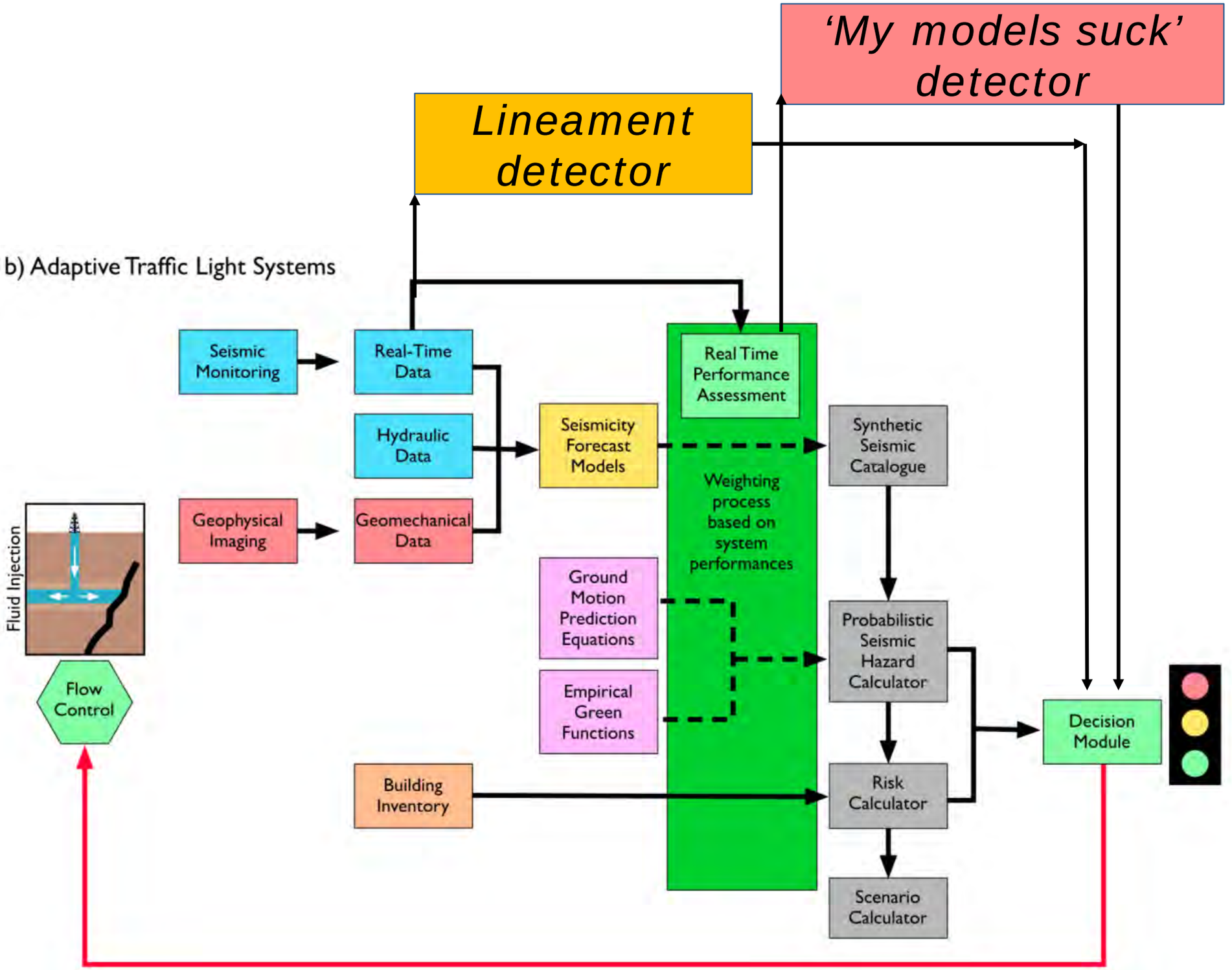

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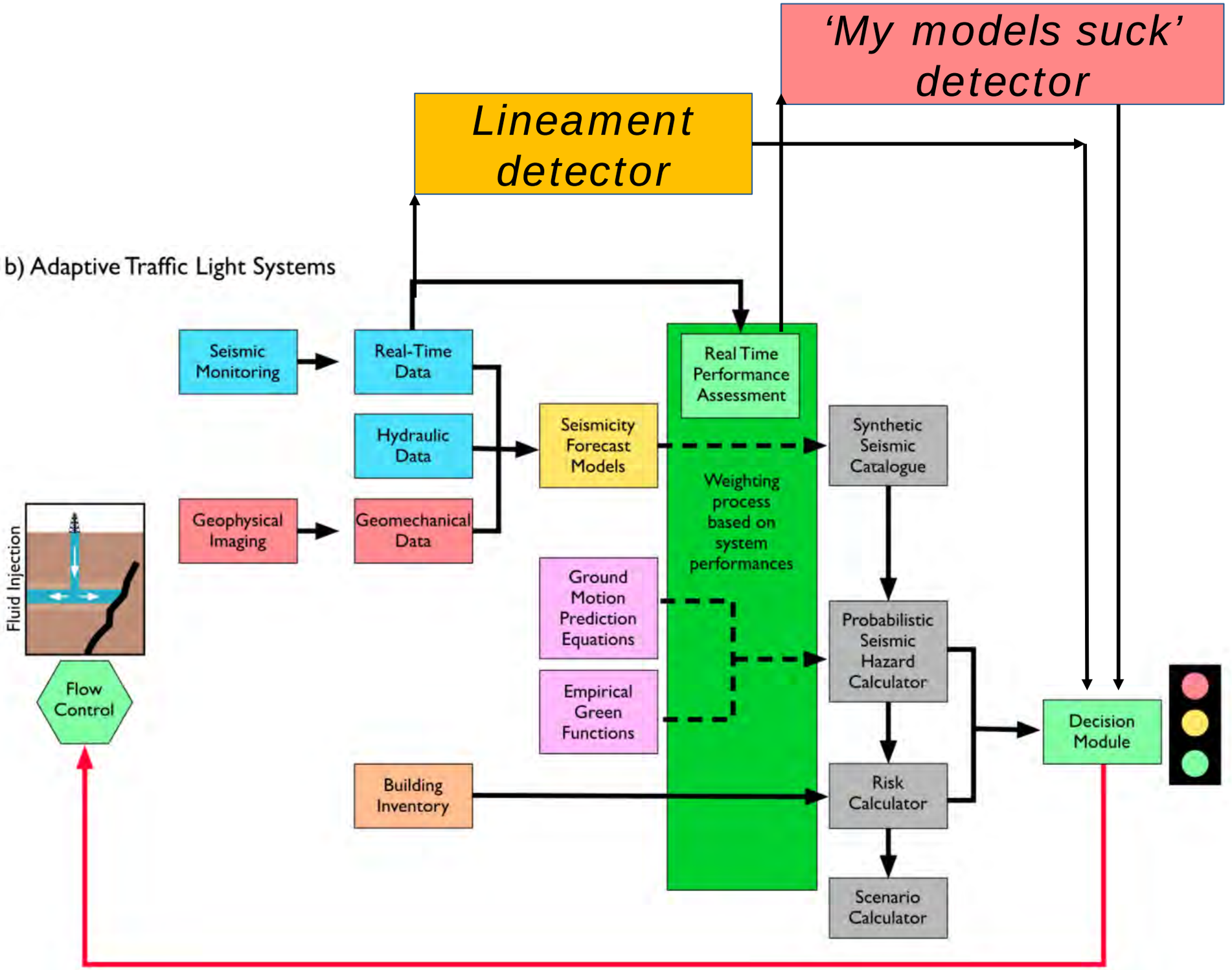
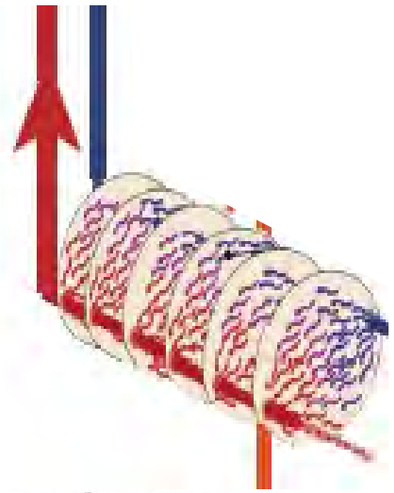


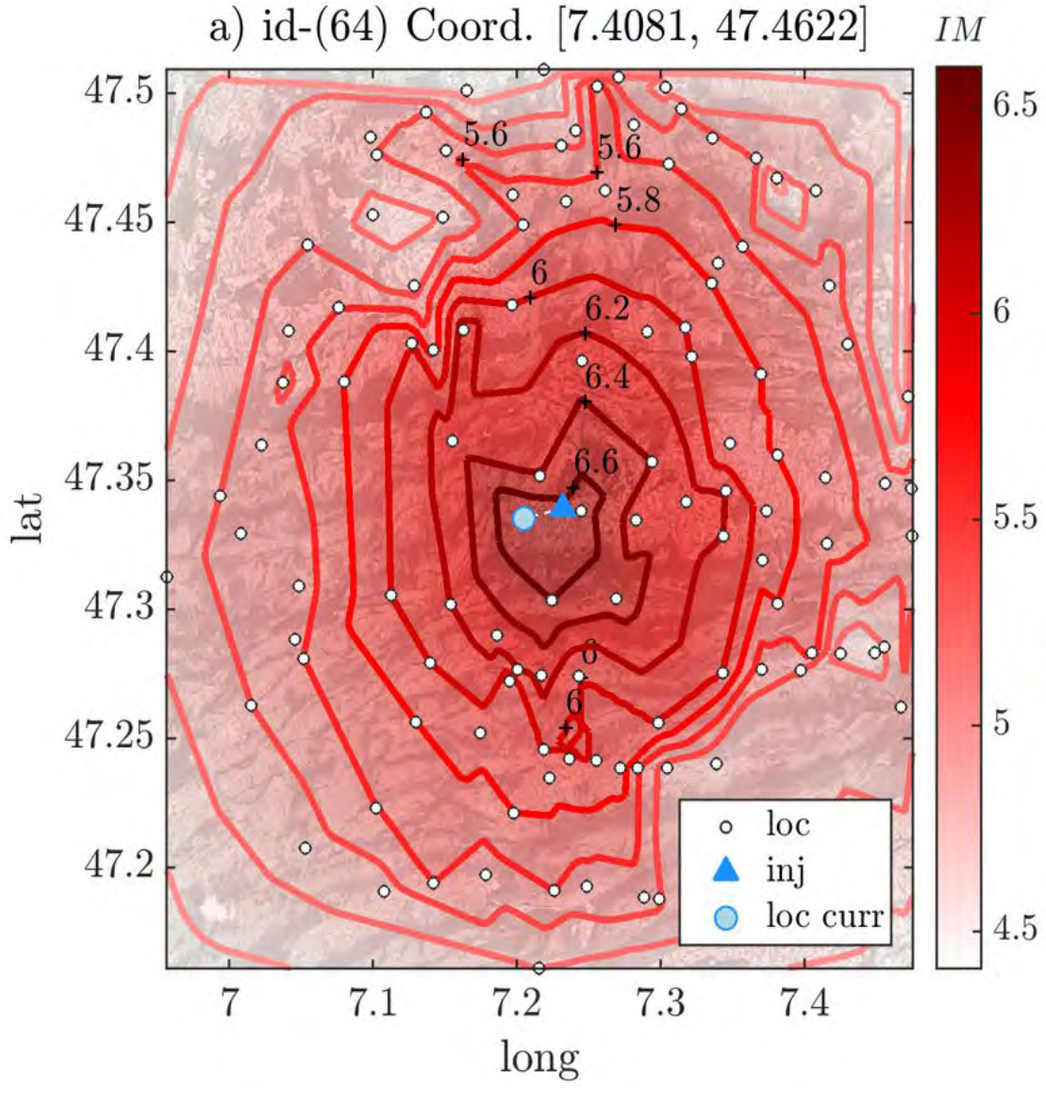
Natural or induced probabilities

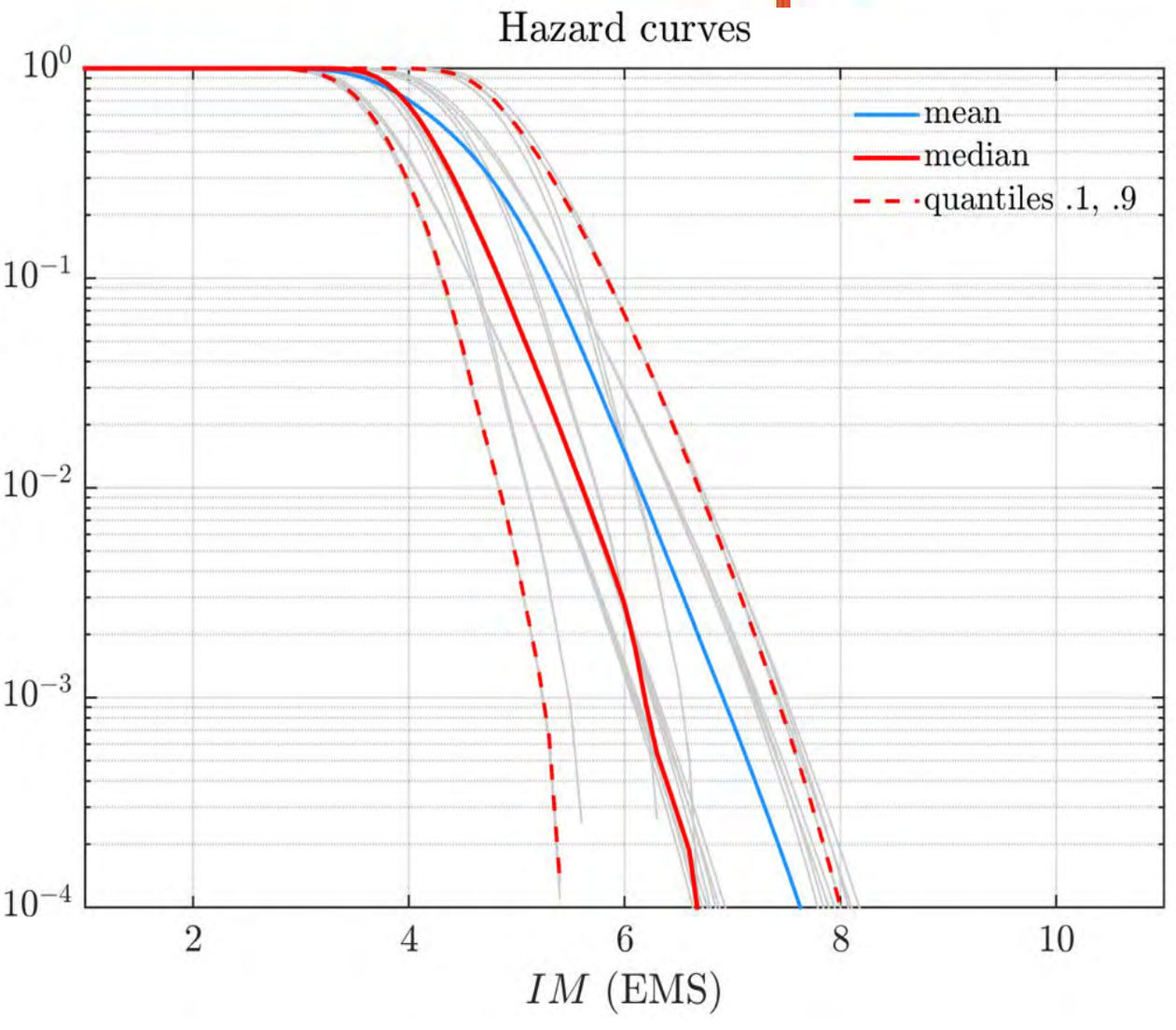
Grigoli et al. (2017)

What does a risk study or ATLS output?

1. Hazard maps and hazard curves – interesting … But what is acceptable?

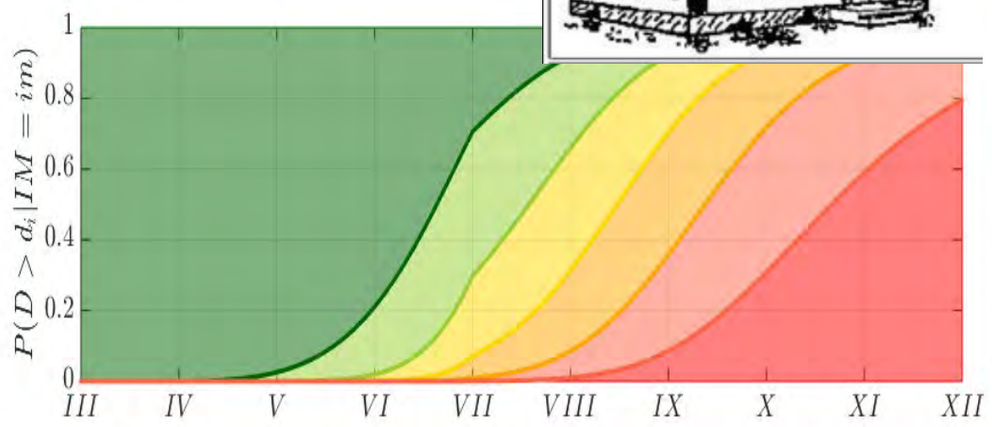




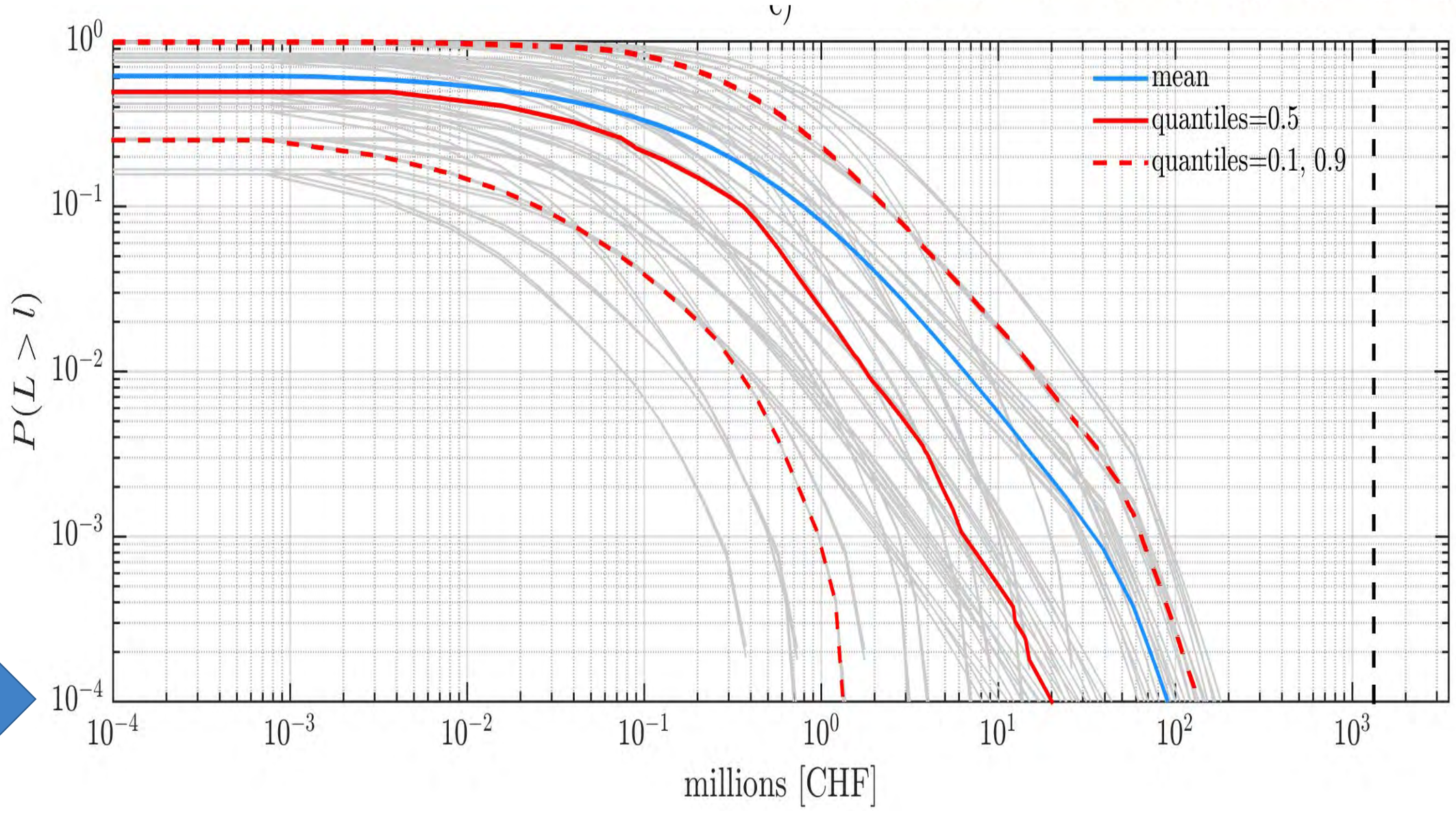


What does a risk study or ATLS output?

1. Risk maps and risk curves –> how much insurance do you need (and what does it costs)



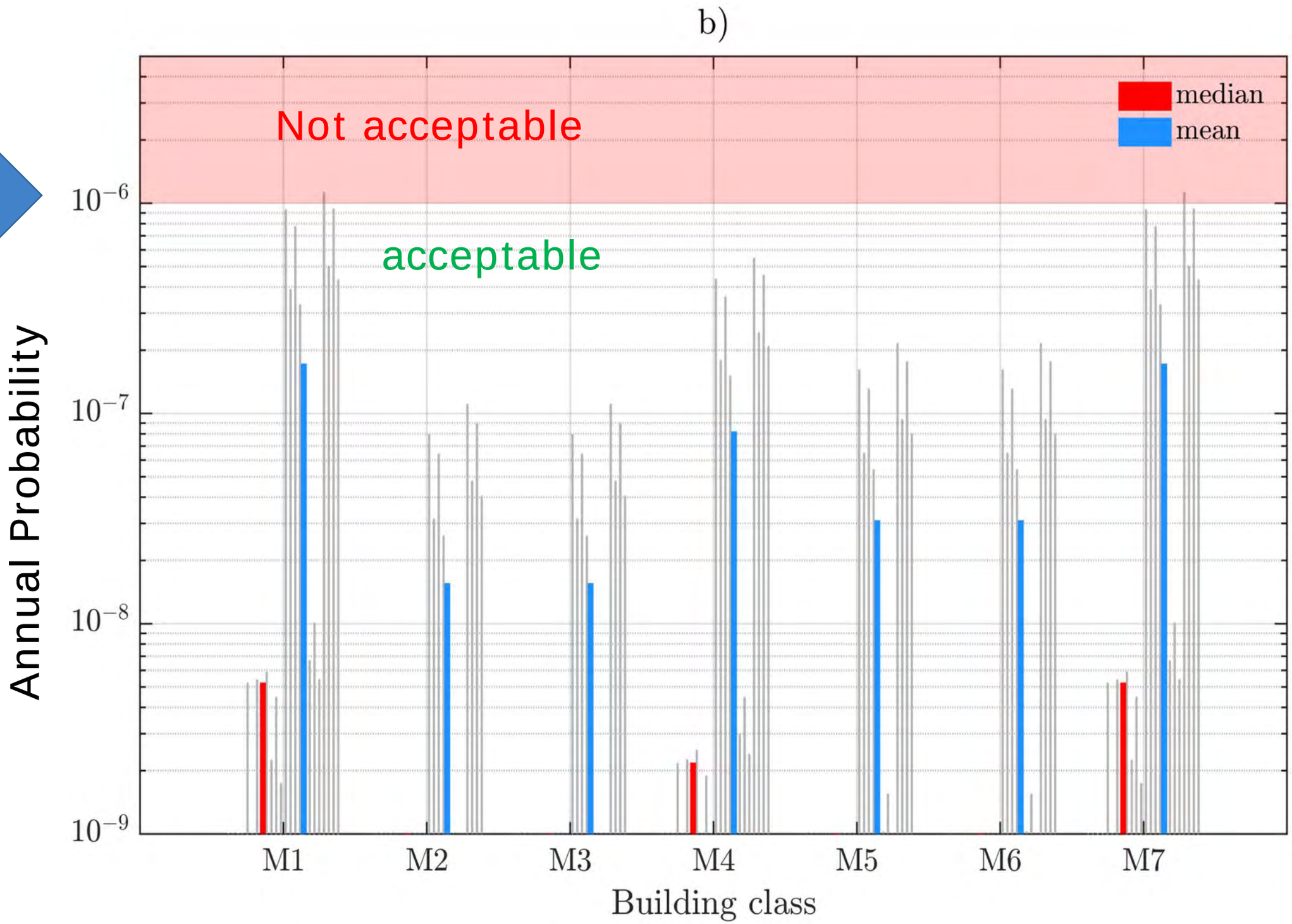
c)



Used in CH

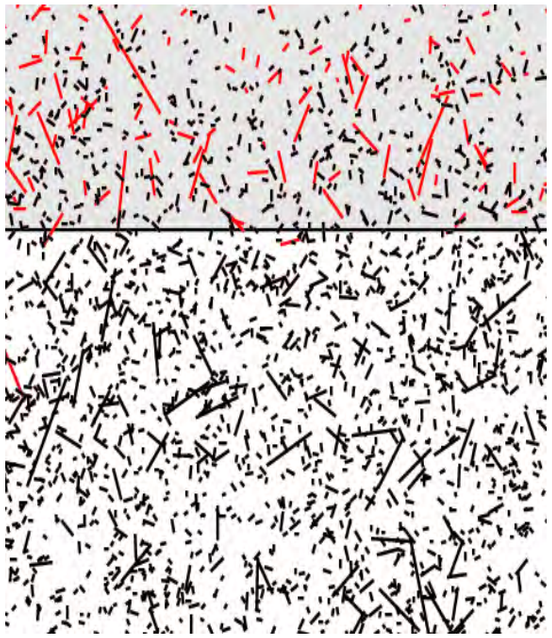
Risk thresholds – how much danger to people is permitted?

Used in CH/NL



The simplest (and most widely used) model for induced seismicity:

- The induced earthquakes per volume injected are **a site-specific constant.**
- Basic statistics: more volume injected → more volume/faults affected → higher chance of eqs.
- When injection stops, an exponential decay starts (new parameter: **tau**)

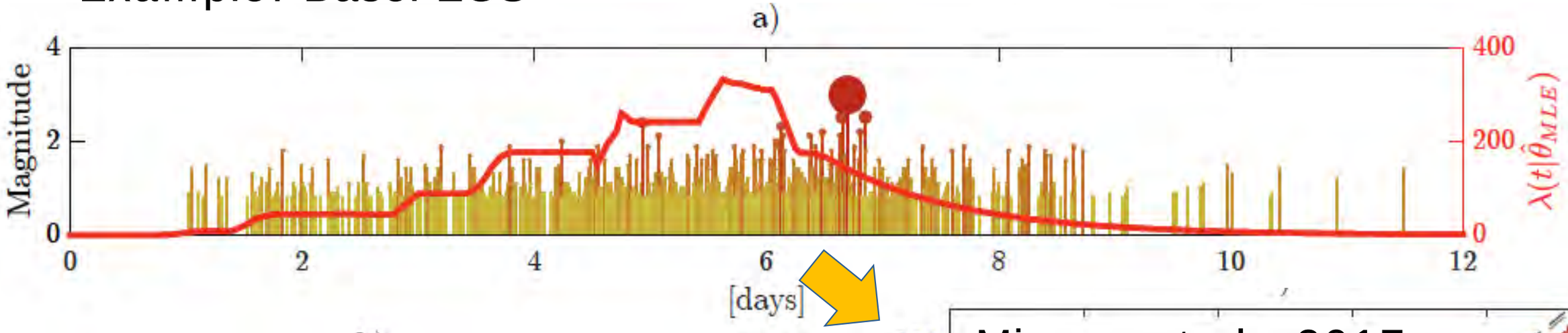


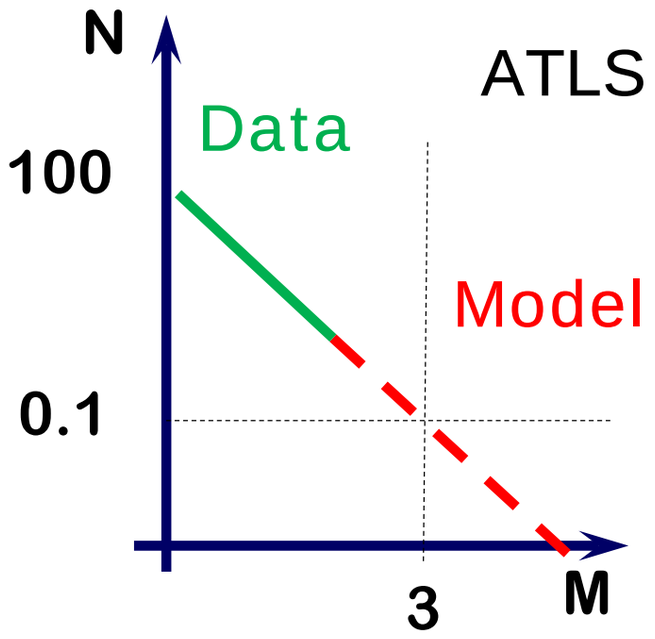
Fault density and criticality matter

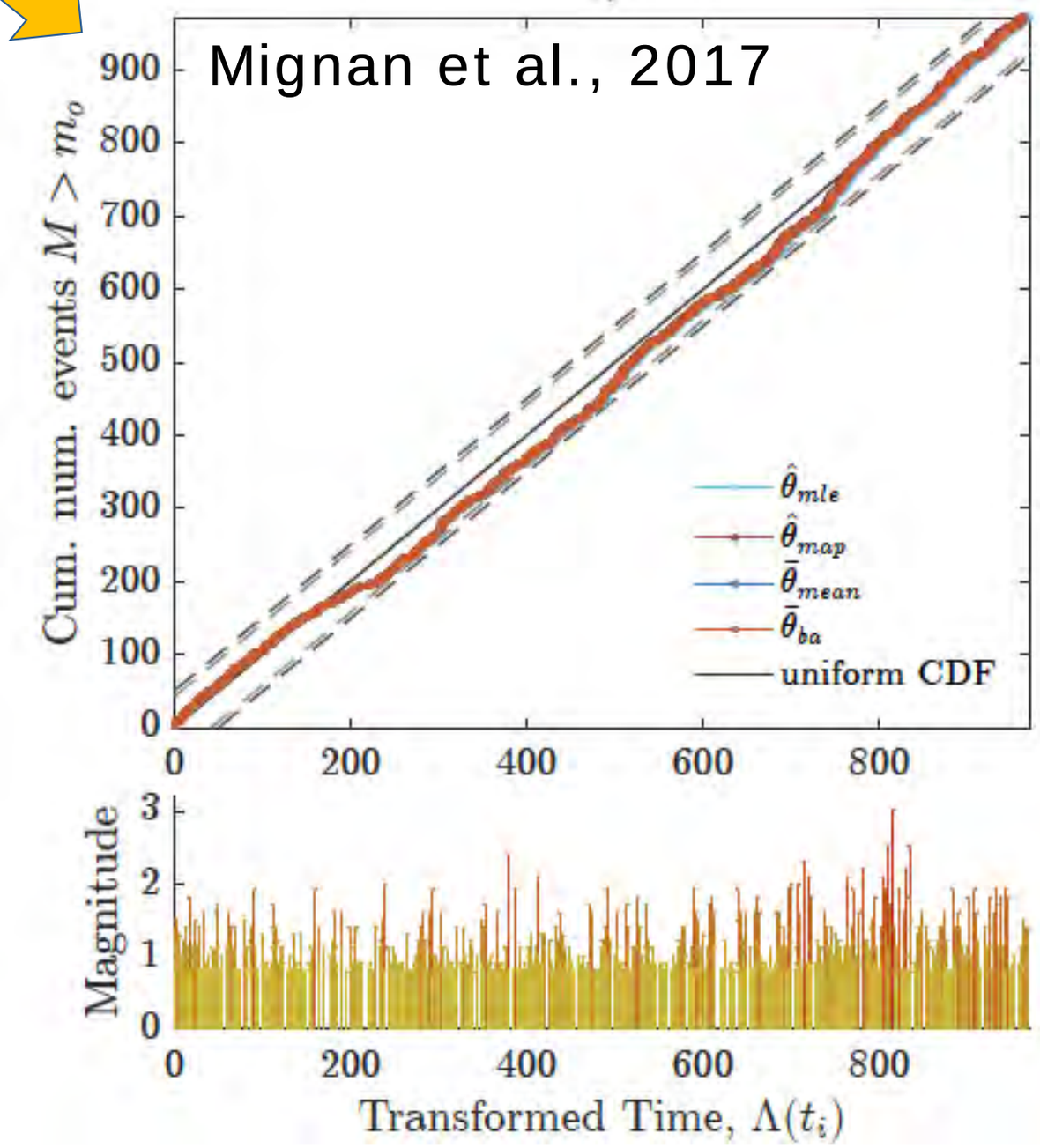
$$\lambda(t,\, m \geq m_0;\theta) = \begin{cases} 10^{a_{fb}-bm_0}\dot{V}(t) & ;\, t \leq t_{shut-in} \\ 10^{a_{fb}-bm_0}\dot{V}(t_{shut-in})\exp\left(-\dfrac{t-t_{shut-in}}{\tau}\right) & ;\, t > t_{shut-in} \end{cases}$$

- Model works often surprisingly well (→ Mignan et al., 2017)
- Identical to tectonic earthquakes - if you replace volume injected with **strain.**

Example: Basel EGS

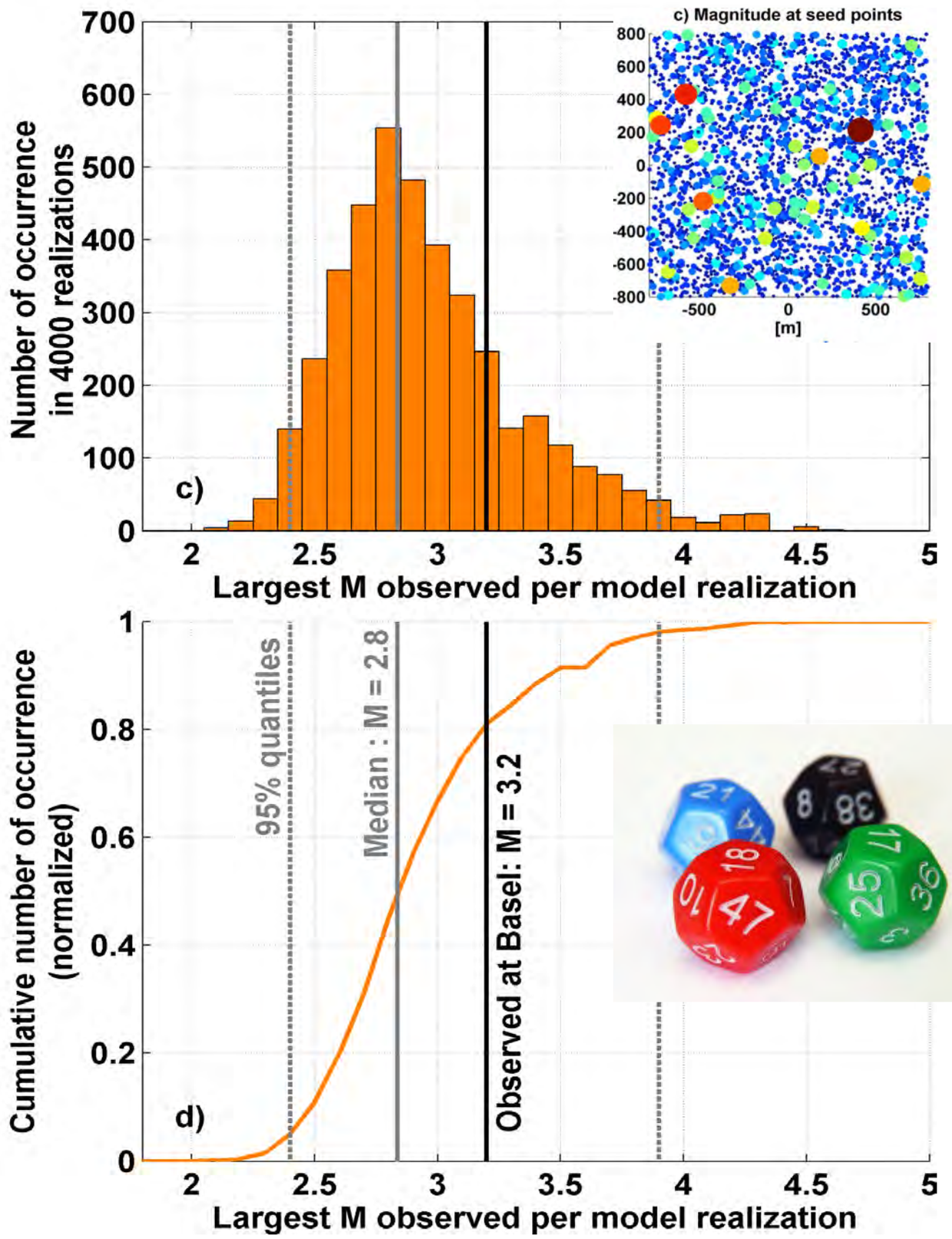






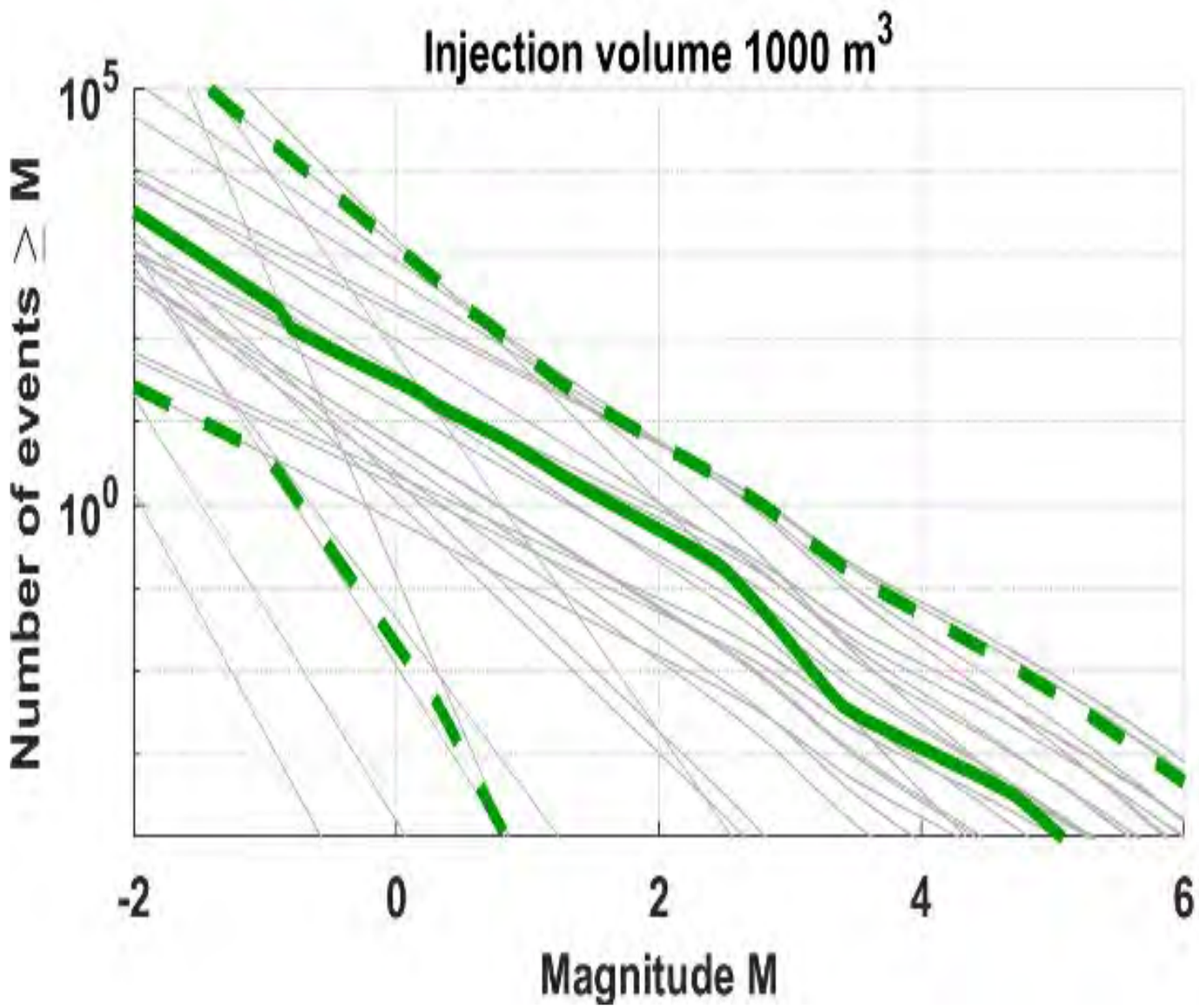
A conservative Null hypothesis

- In this model, the size of the largest events is a random draw. The more often you draw, the more likes a larger event is.
- The time of the largest events is also a random draw, with bad luck it could be the first one.
- When you hit a traffic light threshold is random too, but your chance if reaching it correlates with the seismogenic response (which is why TLS work, sort off)



But: Initial uncertainties are HUGE

How many earthquake of a given size do we get when injecting 1000m³ in the Bedretto tunnel?

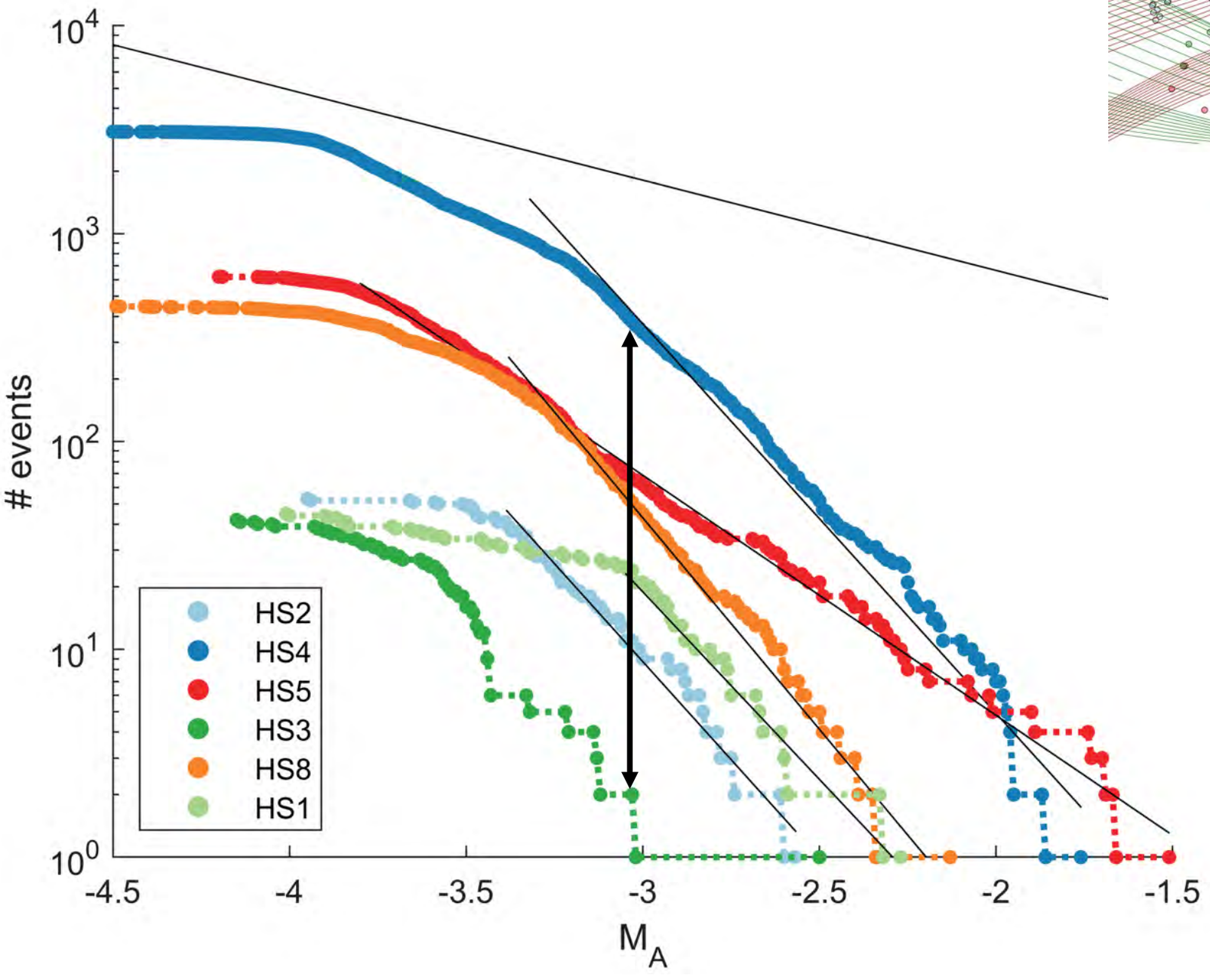


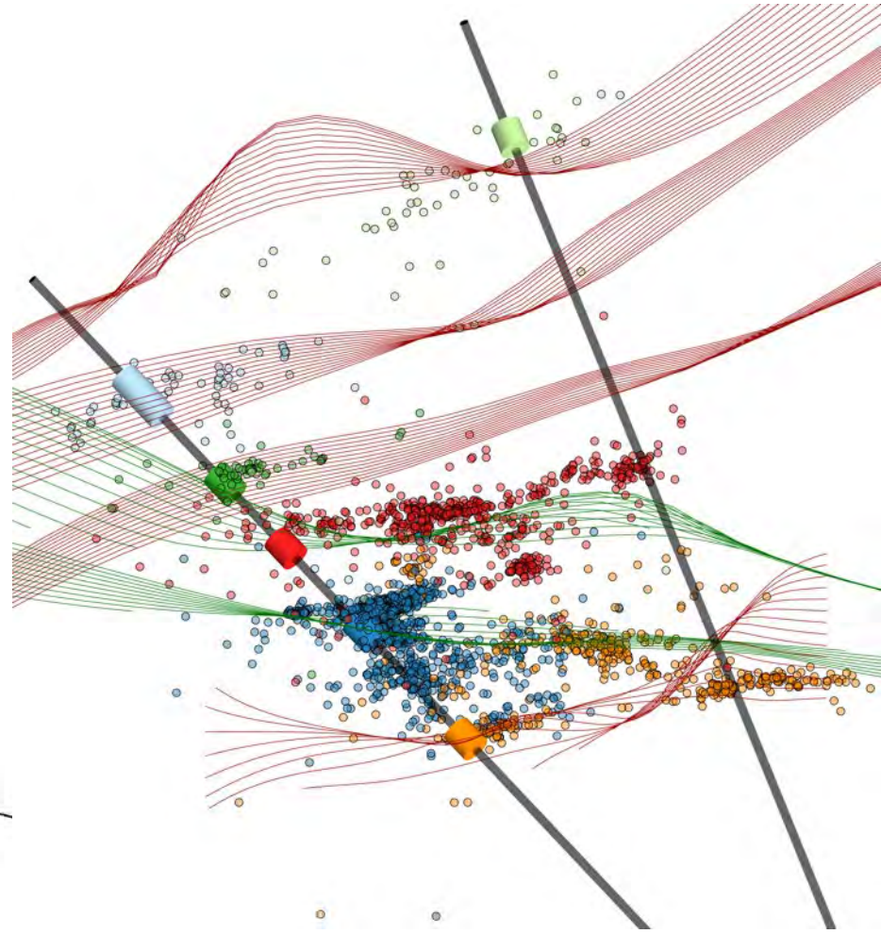
Magnitude rates

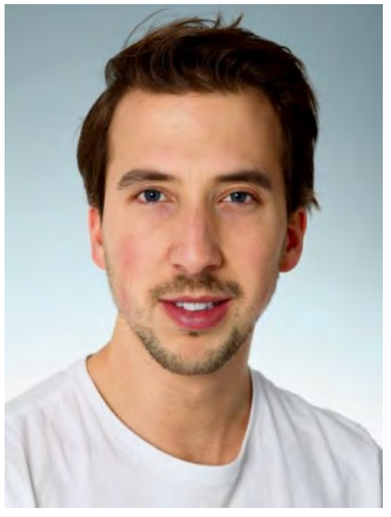
St. Gallen, 2013
Basel, 2006
Garvin, 2011
KTB, 1994a KTB, 1994b KTB, 2000
Paradox Valley, 1994 Paradox Valley, '96-'00
Newberry, 2012 Newberry, 2014a Newberry, 2014b
Soultz, 1993a Soultz, 1993b Soultz, 2000 Soultz, 2004
Cooper Basin, 2003
Paralana, 2011
Ogachi, 1991 Ogachi, 1993
Rosemanowes 2A Rosemanowes,2B
Grimsel, 2017 HS1 Grimsel, 2017 HS2 Grimsel, 2017 HS3 Grimsel, 2017 HS4 Grimsel, 2017 HS5 Grimsel, 2017 HS8
Aspö, 2015

Weights: 1/13 per group / location

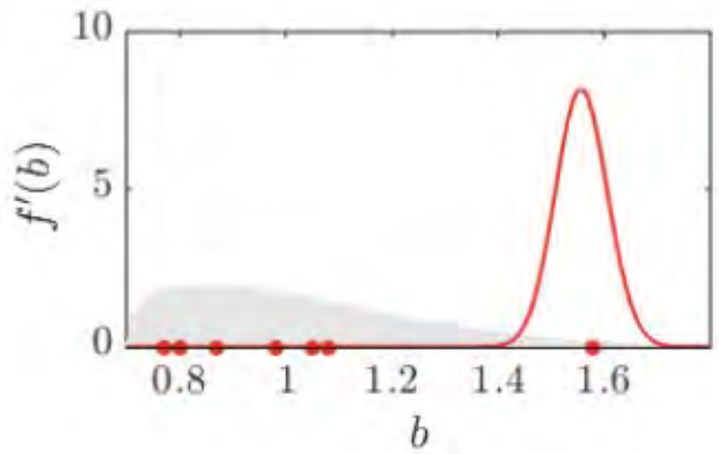
But is it so unknown?
Grimsel, identical conditions, factor 100

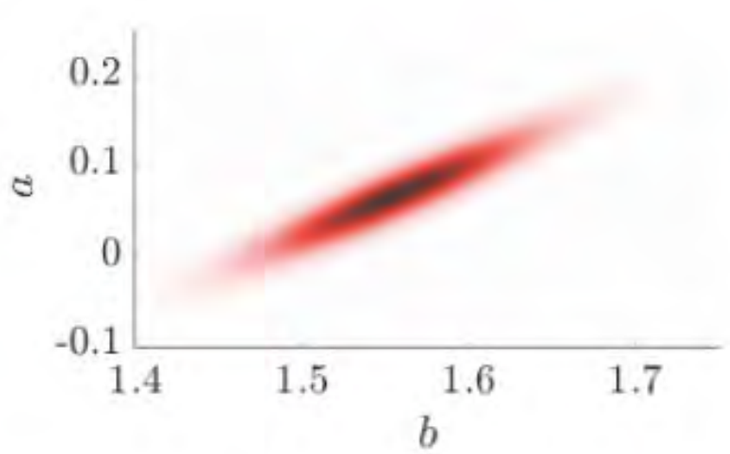


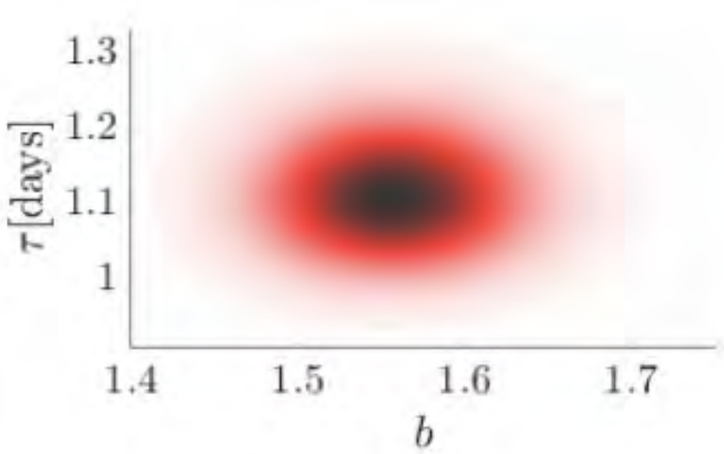


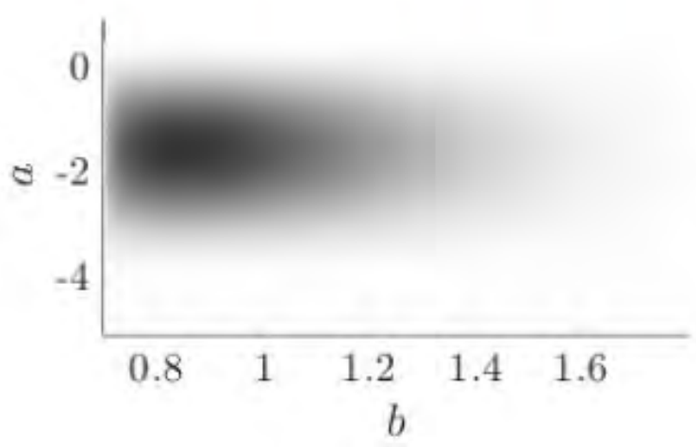


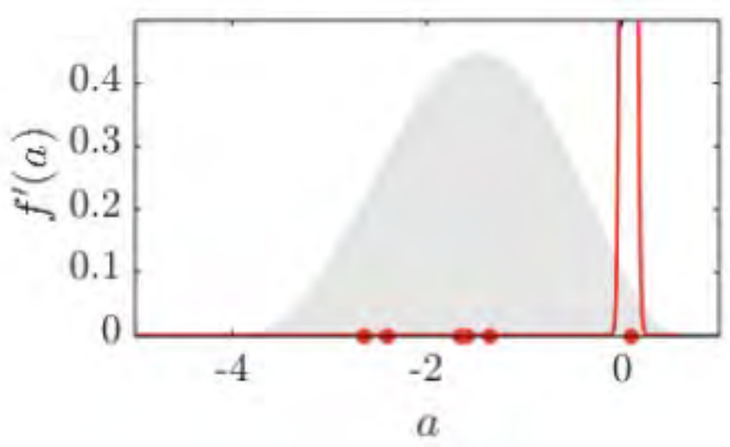
Adapt in Real-time: Hierarchical Bayesian Model Updating

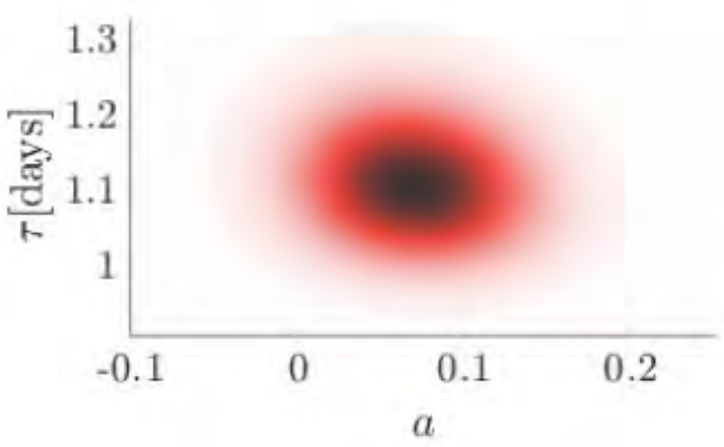












Grey: prior distributions (past experiments)
Red: posterior distributions (data updates)

Broccoardo et al., 2017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Geophysical Research Letters

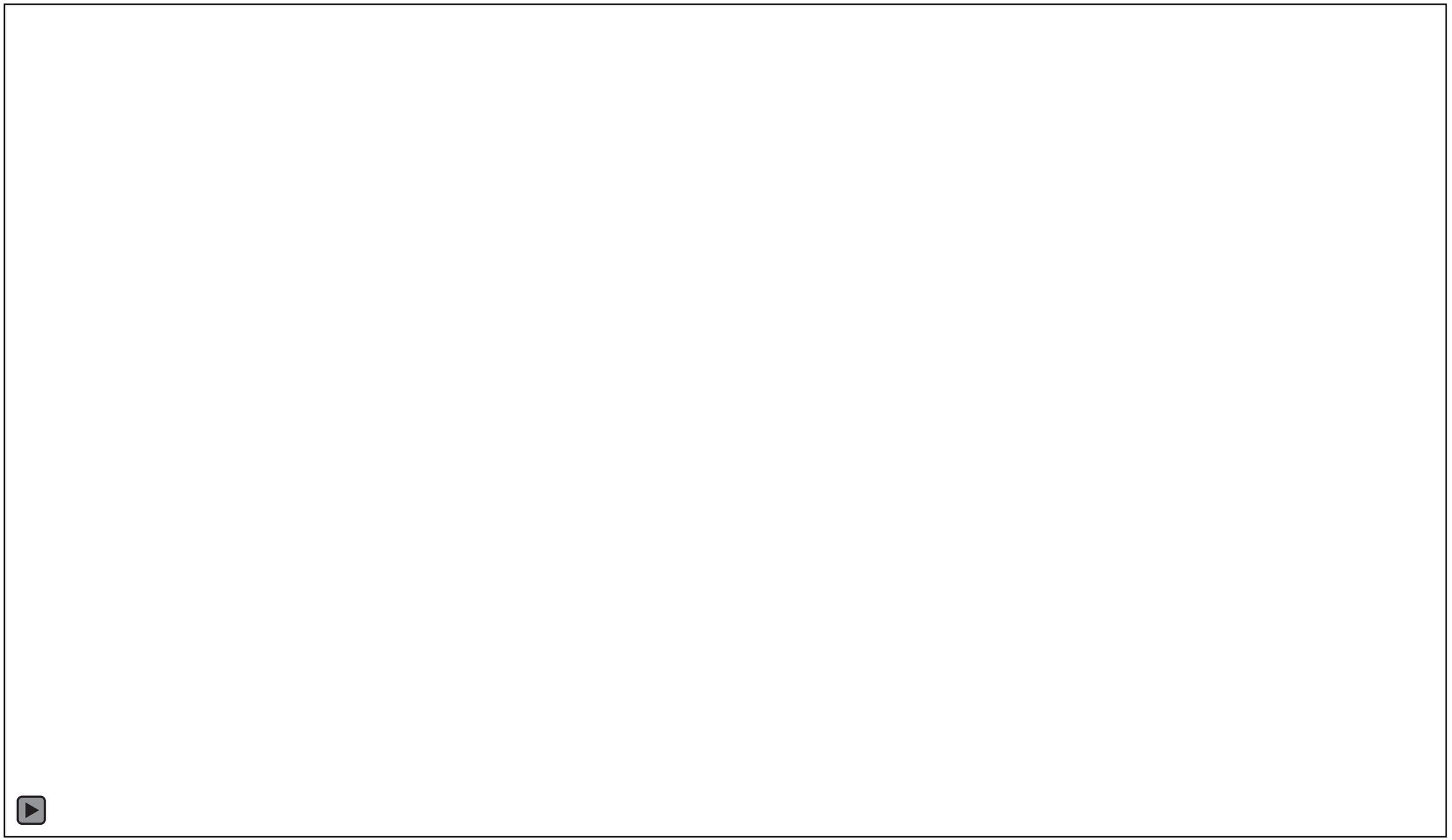
RESEARCH LETTER
10.1002/2017GL075251

Hierarchical Bayesian Modeling of Fluid-Induced Seismicity

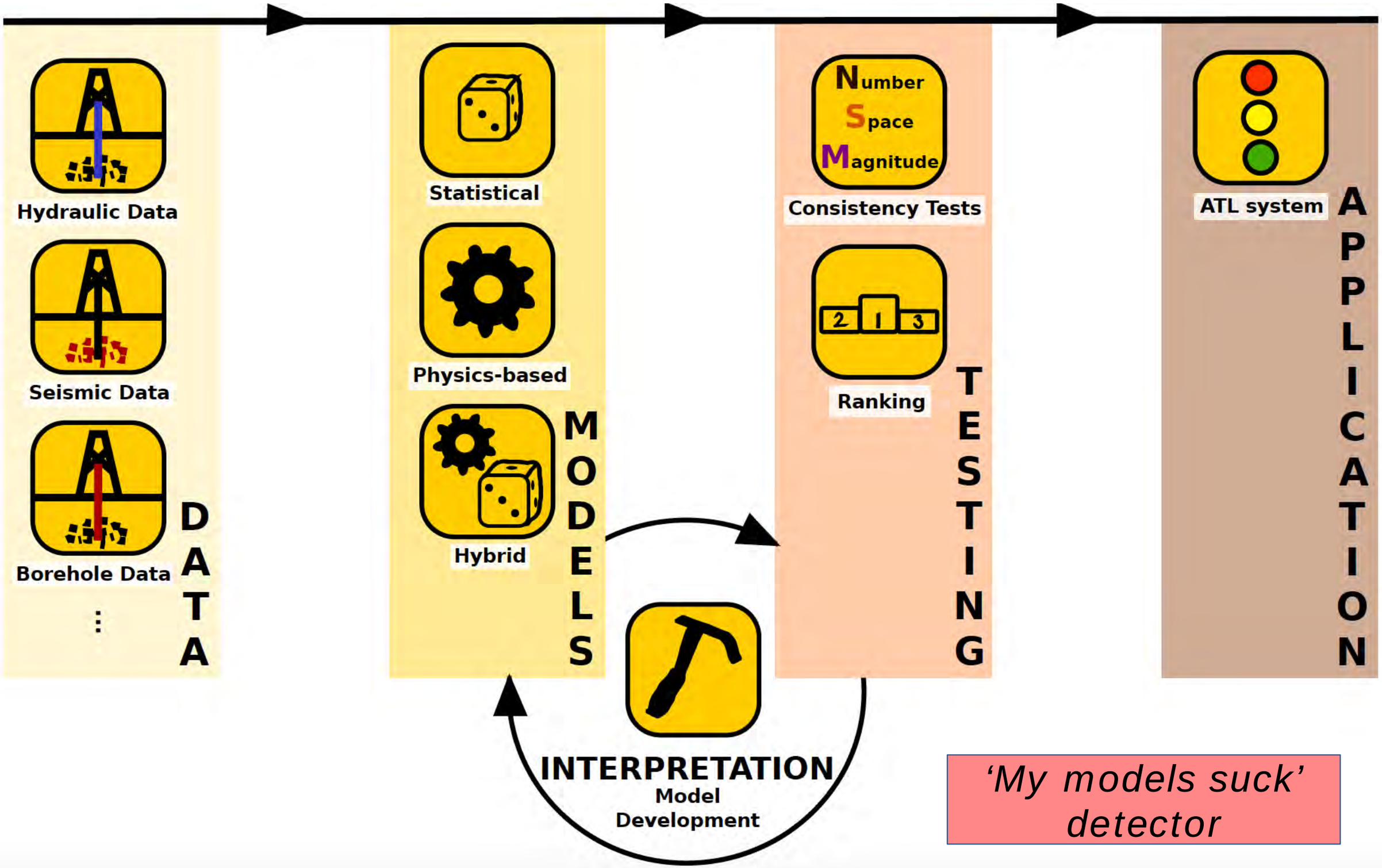
M. Broccardo[1], A. Mignan[1,2,3], S. Wiemer[1,2,3], B. Stojadinovic[1,4], and D. Giardini[1,2,3]

Key Points:

Time evolution of parameters



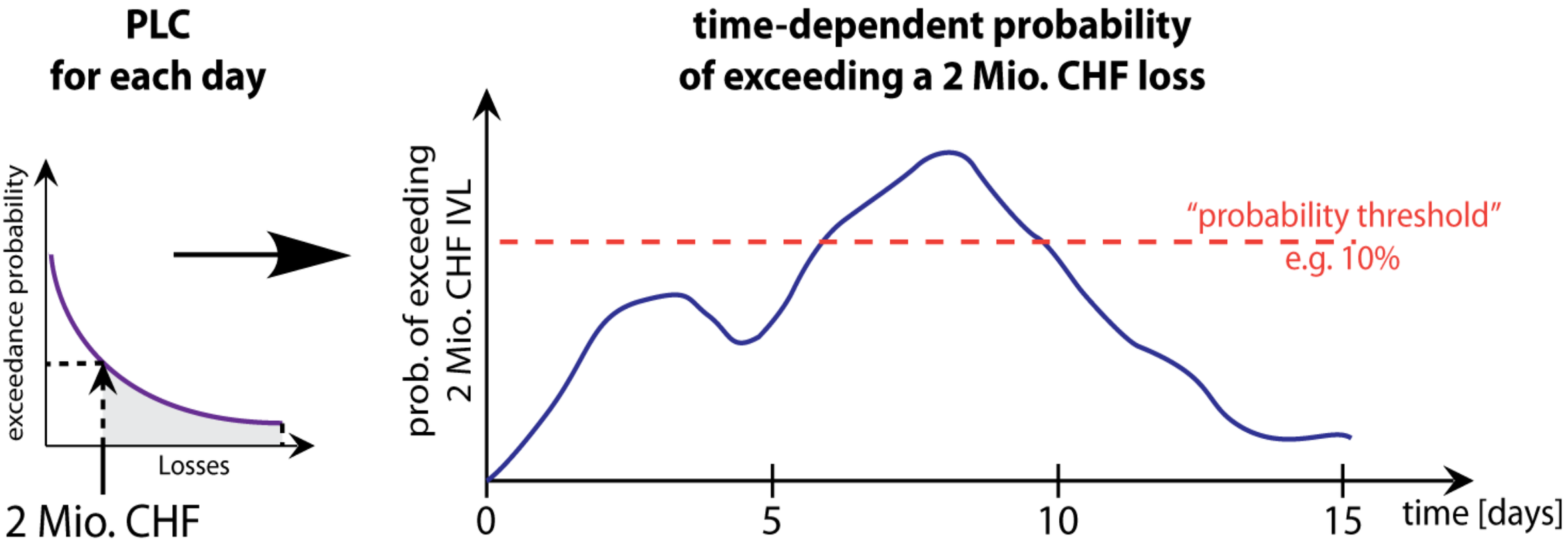
Consistency & Performance Check



'My models suck' detector

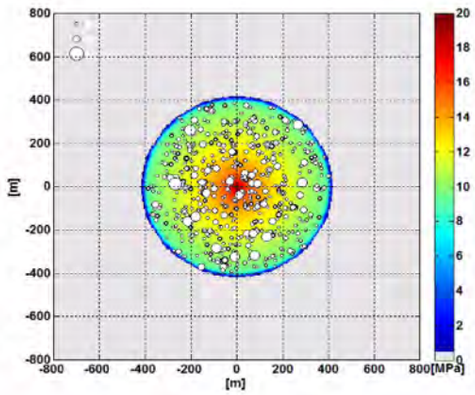
Kiraly et al., 2017

Monitoring risk with time

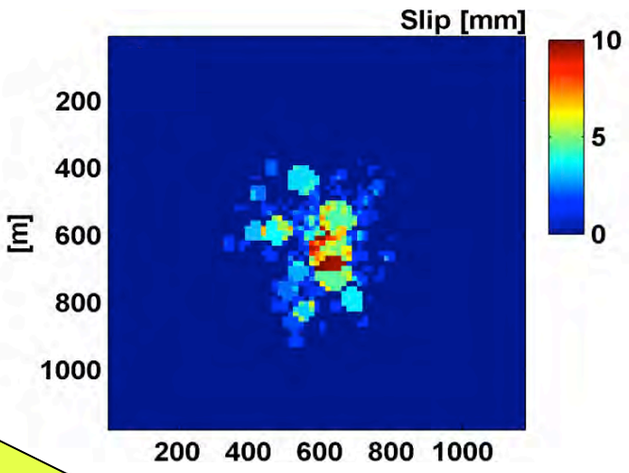


ATLS can be based on more realistic THMC models

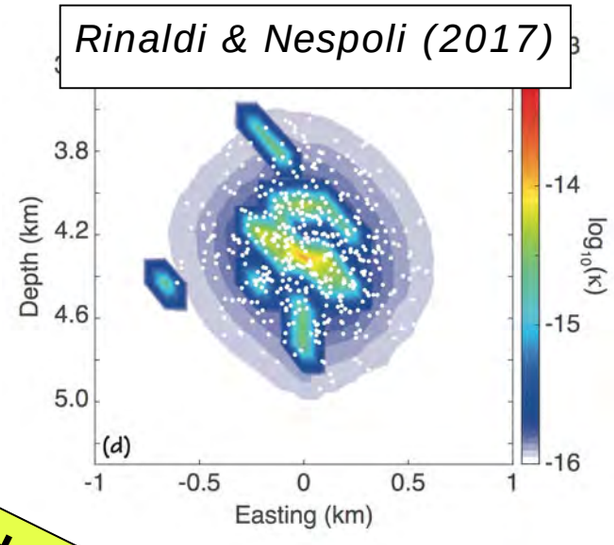
Gishig & Wiemer (2013)
Goertz-Allmann & Wiemer (2013)



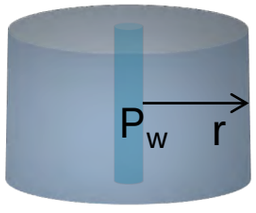
Gishig et al. (2014)



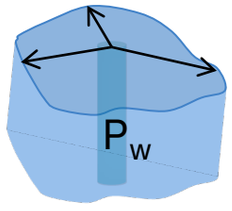
Rinaldi & Nespoli (2017)



Model Complexity

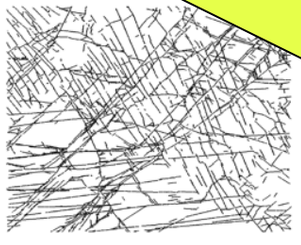


1D with
COMSOL &
Seed model



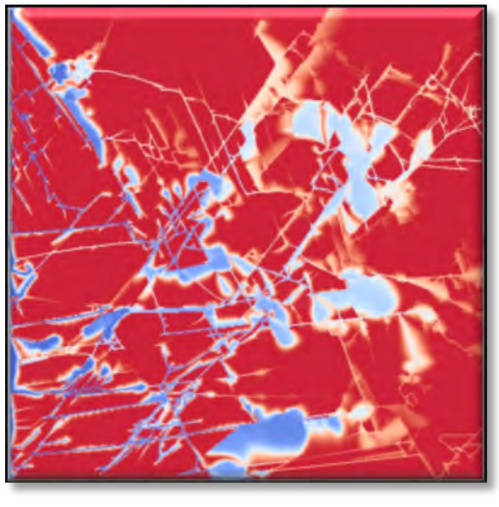
2D with
SUTRA &
Seed model

TOUGH2-Seed
Full 3D model
With k change



HFR-Sim: 3D Discrete
Fracture Modeling &
Seed model

Karvounis & Wiemer (2018)



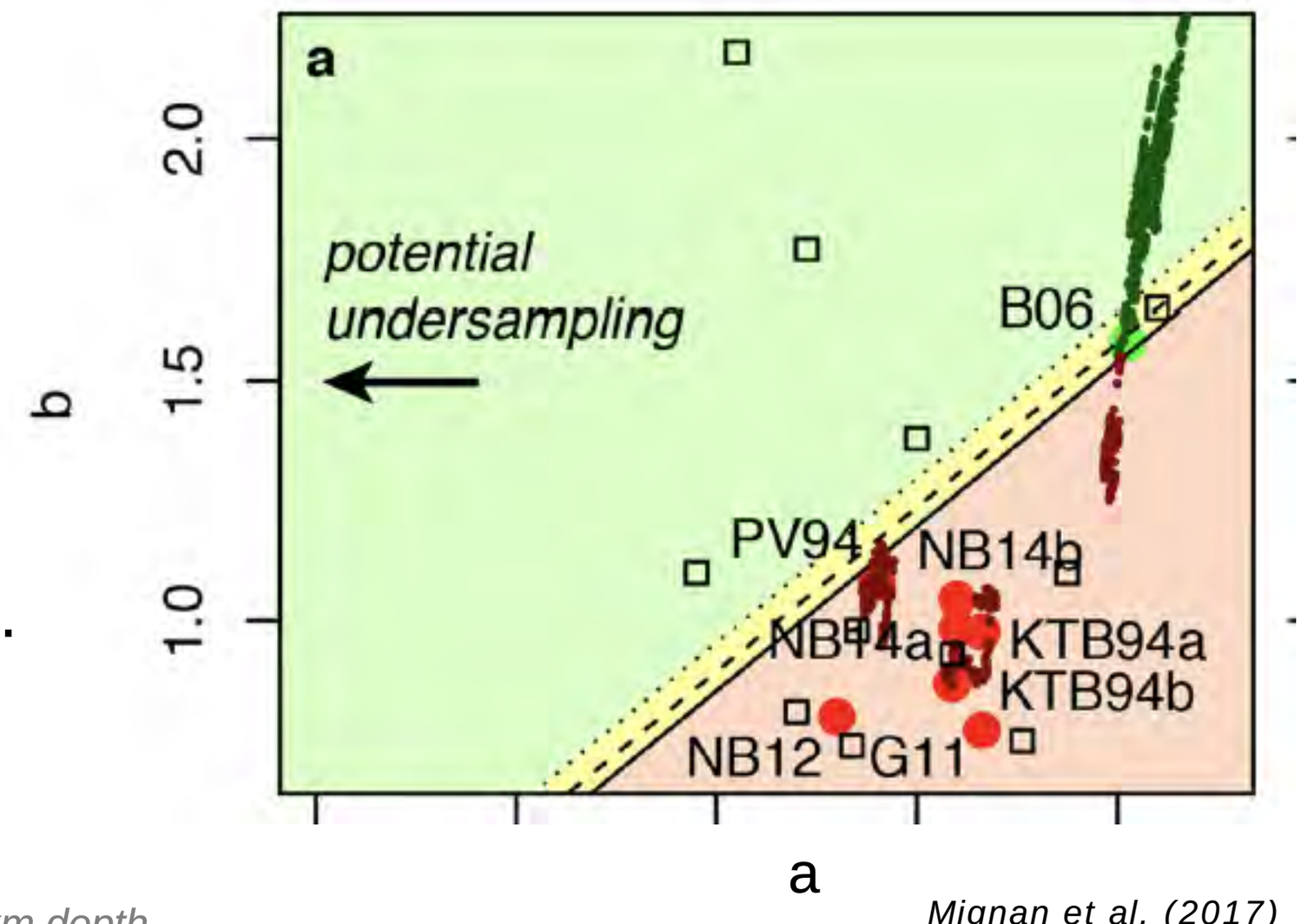
ATLS based on a safety norm

- ✓ **Risk-based safety norm:**
  - ➢ **Pr(fatality/year) = *Y* = 10^{-6}**

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

→ Even before a traffic light: Do not try to do n massive stimulation at KTB

→ Basel was green at first, then turned red.

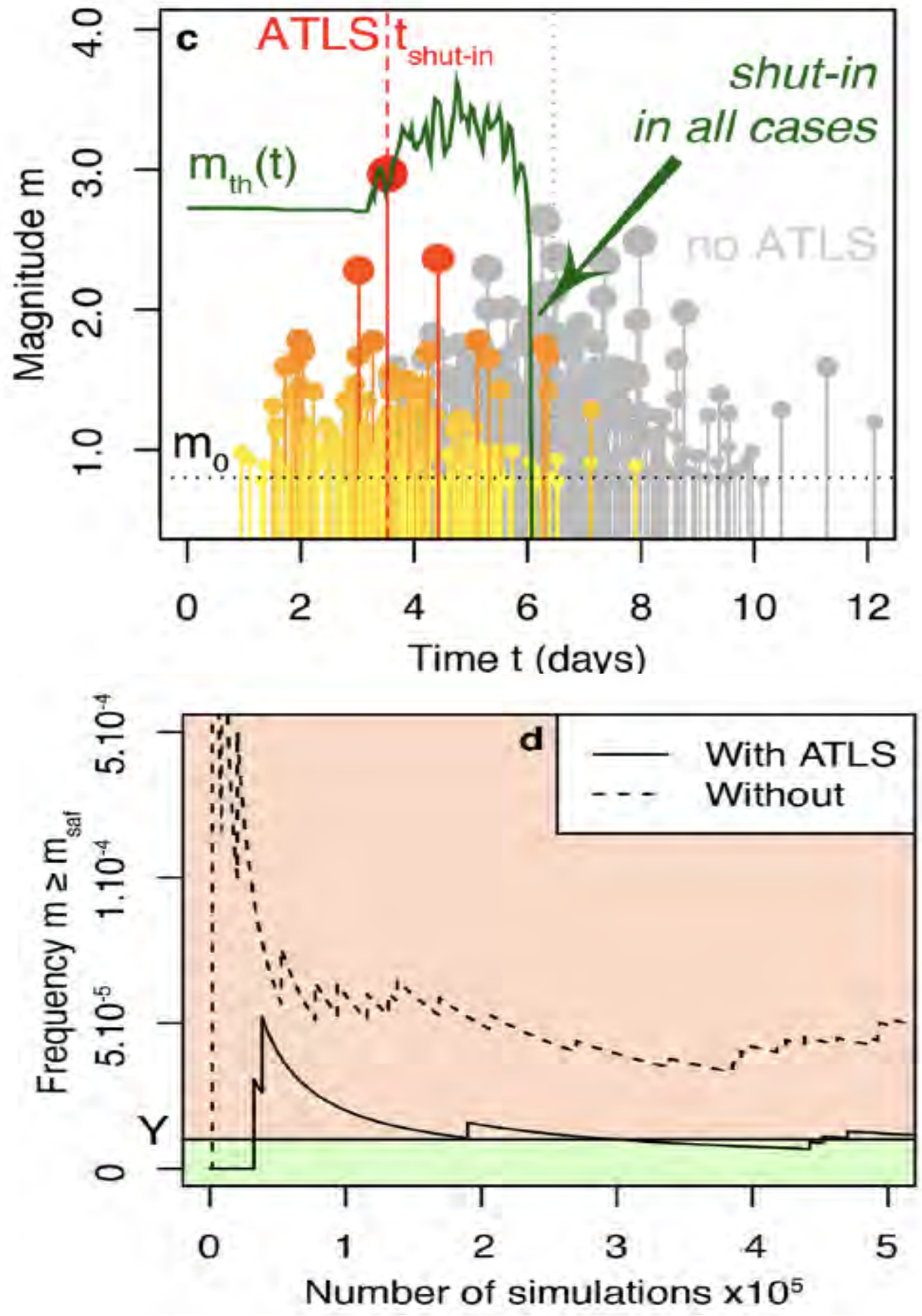


Volume injected = 10,000m³, borehole at 4km depth, distance = 0km from EGS plant)

Mignan et al. (2017)

In an ideal world, and based on simulations, ATLS outperform TLS

- It turns **red** earlier than the TLS (on average) if the underground conditions are unfavorable).
- It will stay **green** more consistently if conditions are favorable
- It will have fewer ‘false alerts’ and ‘missed alerts’.
- The defined safety norm is met in a quantitative way.
- Plus some extra benefits …



Real-time application

- Detecting smaller events and operating an ATLS in real-time costs money.
- The system is more complex, thus potentially less robust.
- Models to extrapolate, are, well, models, they may not represent the reality.
- Do the rates of small events represent the rate of large ones? Are we too sensitive to b-values?
- Therefore: Always use also a TLS.
- And: Demonstrate ATLS performance in real-world conditions → Iceland

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GEOTHERMICA

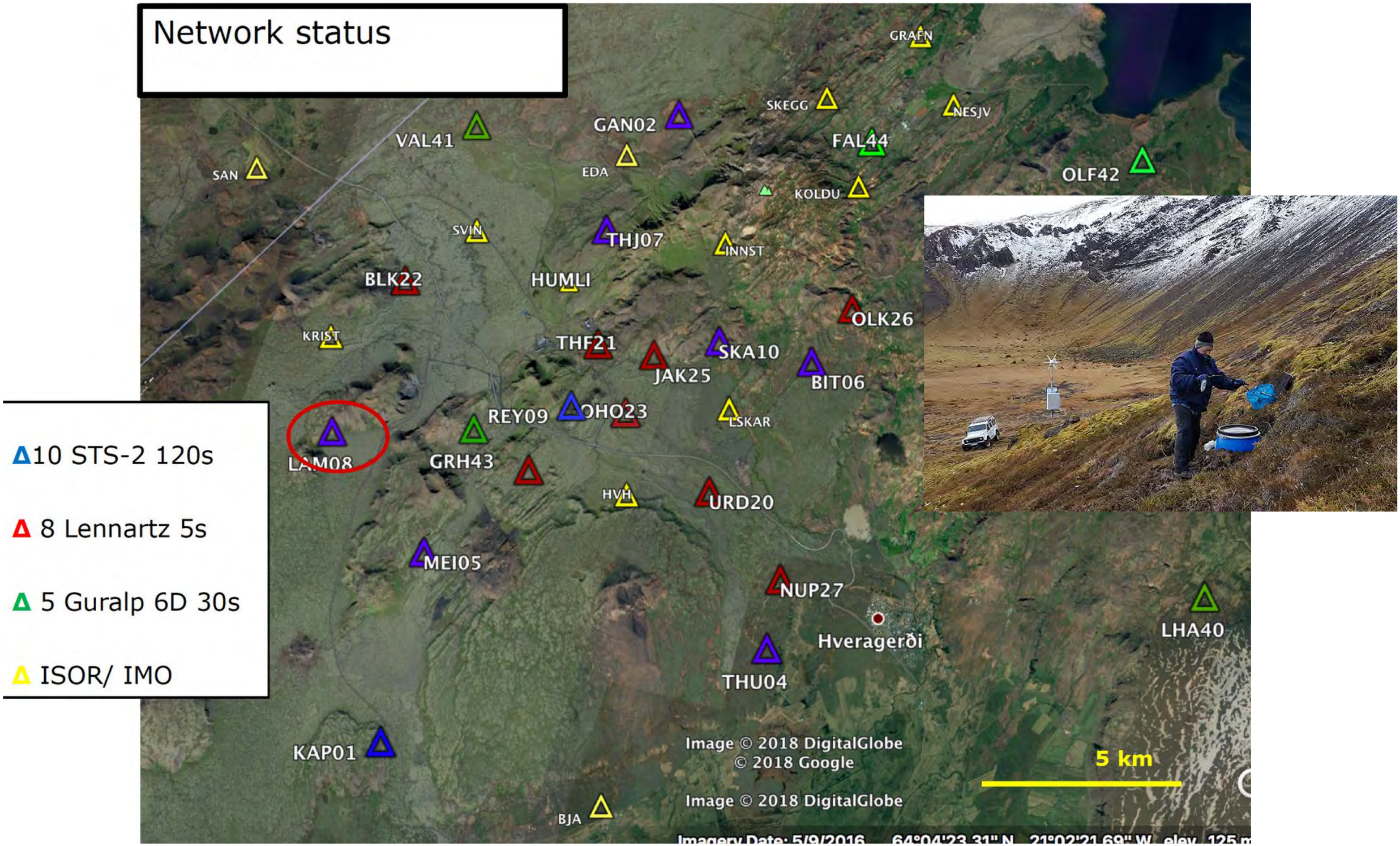
Project Partner
DIAS
Prof. Chris Bean

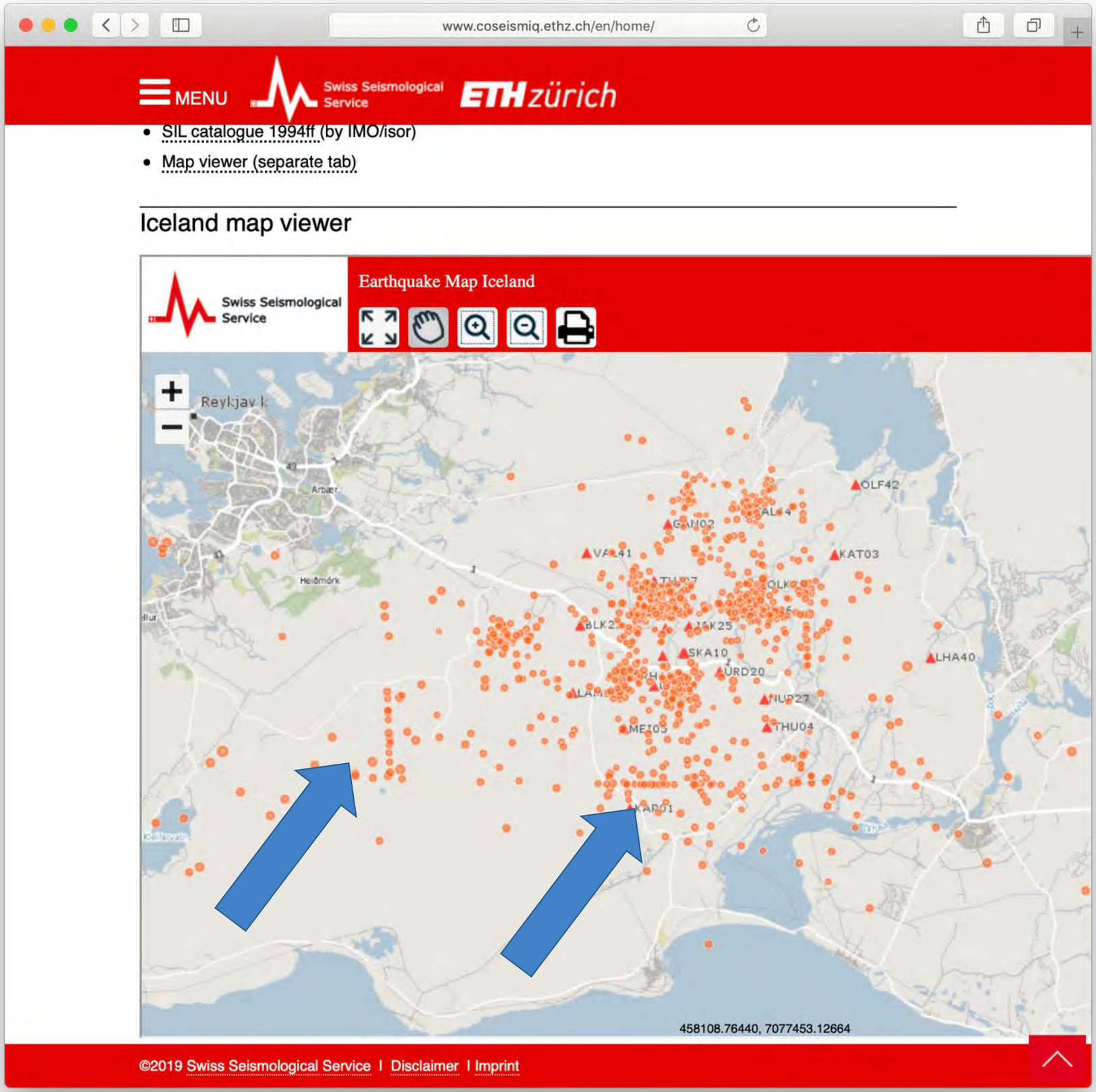
Project Partner
GES
Dr. Peter Meier

Project Partner
ISOR
Dr. Kristján Ágústsson

Cooperation Partner (*)
GFZ
Prof. Torsten Dahm

COSEISMIQ network in Iceland





Lineament detector

Thank you!

This was it !

- A few closing remarks ...

Thank you!!

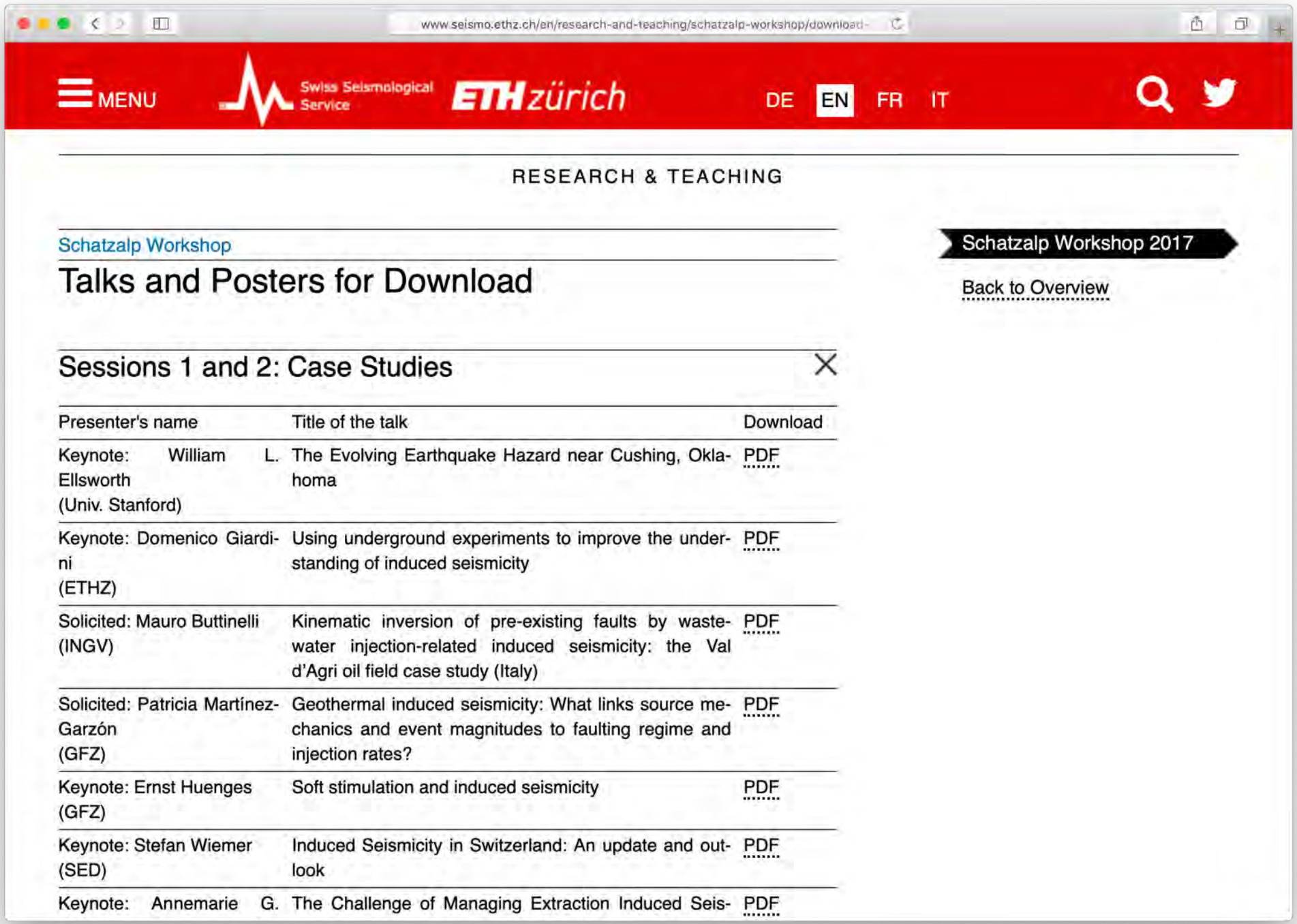
Many people worked hard to make this workshop happen:

- Barbara & Toni from the LOC
- Many people from SED
- Our sponsors BFE, SCCER & ETH
- The people of the hotel
- All speakers for being on time and well prepared.
- All of you for coming, for taking part in the discussions.

What did we learn?

- I once thought we would be able to draft main conclusions, or a roadmap ..
- But I have grown wiser (and given up).

Our Legacy: Talk & Posters online (if you want)



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Schatzalp Workshop

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Schatzalp Workshop 2017

Back to Overview

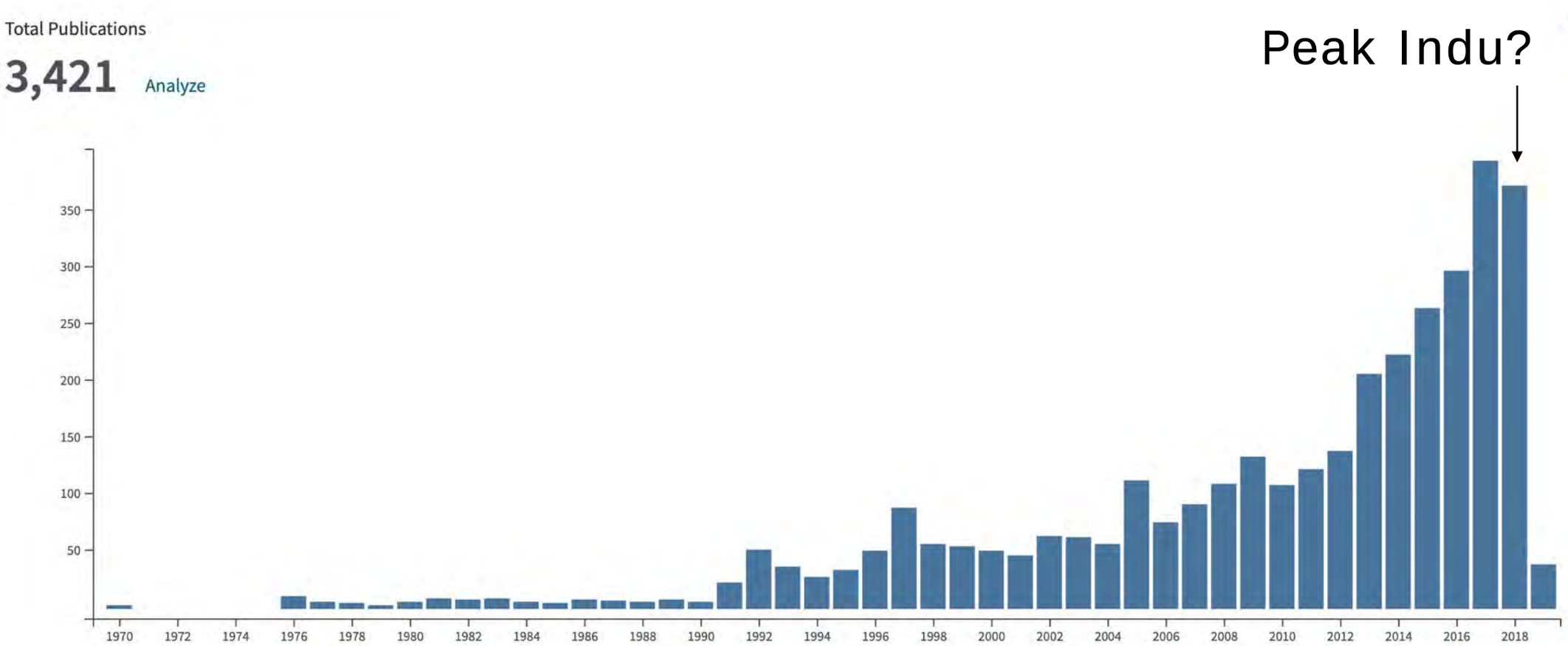
Sessions 1 and 2: Case Studies

Presenter's name	Title of the talk	Download
Keynote: William L. Ellsworth (Univ. Stanford)	The Evolving Earthquake Hazard near Cushing, Oklahoma	PDF
Keynote: Domenico Giardini (ETHZ)	Using underground experiments to improve the understanding of induced seismicity	PDF
Solicited: Mauro Buttinelli (INGV)	Kinematic inversion of pre-existing faults by wastewater injection-related induced seismicity: the Val d'Agri oil field case study (Italy)	PDF
Solicited: Patricia Martínez-Garzón (GFZ)	Geothermal induced seismicity: What links source mechanics and event magnitudes to faulting regime and injection rates?	PDF
Keynote: Ernst Huenges (GFZ)	Soft stimulation and induced seismicity	PDF
Keynote: Stefan Wiemer (SED)	Induced Seismicity in Switzerland: An update and outlook	PDF
Keynote: Annemarie G.	The Challenge of Managing Extraction Induced Seis-	PDF

Dr. Indu (and thank you for saving me from reading 300 papers!)

Total Publications

3,421 Analyze



Sum of Times Cited per Year

h-index

95

Average citations per item

17.33

Sum of Times Cited

59,269

Without self citations

43,259

Citing articles

30,587 Analyze

Without self citations

28,197 Analyze

Do we want Schatzalp 2021?

- It is fun, yes, and useful.
- But is it is expensive, and a lot of work too.
- And there are so many workshops already ….
- And three is a nice number.
- And maybe others have new, better ideas for workshops.
- So give us your feedback, your ideas, your arguments, your funding ideas, and then we shall see what we will do.

Have a safe journey home