UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

The era of high-resolution earthquake catalogs

What are we learning and where are the limits?

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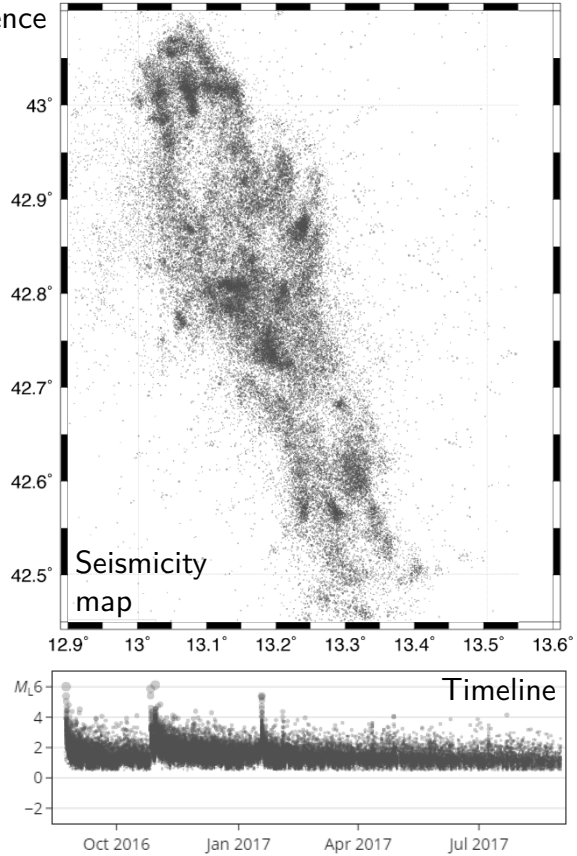
Società Italiana di Fisica - 107° Congresso Nazionale
Sezione 4 - *Geofisica e fisica dell'ambiente*
Seduta: *Geodinamica, Tettono-fisica, Sismologia*

Virtual Meeting | Thursday, Sept. 16, 2021

Horizon 2020
European Union funding
for Research & Innovation

- Earthquake catalogs reflect seismicity
  - Seismicity = a fundamental data type in earthquake science
- Higher resolution – **Why?**
  - = study seismicity in more detail

Central Italy 2016/17 sequence



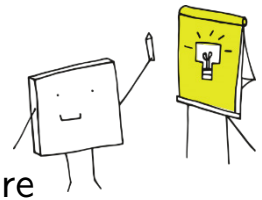
Real-time catalog (INGV monitoring room)
[Chiaraluce, pers. comm. 2020]

- Earthquake catalogs reflect seismicity
  - Seismicity = a fundamental data type in earthquake science
- Higher resolution – **Why?**
  - = study seismicity in more detail

1. include many more small earthquakes
2. locating earthquakes more precisely

→ gain more insight into the underlying processes that drive earthquake occurrence and interaction
(in small incremental steps)

→ extend classical views
with broader perspectives on physics

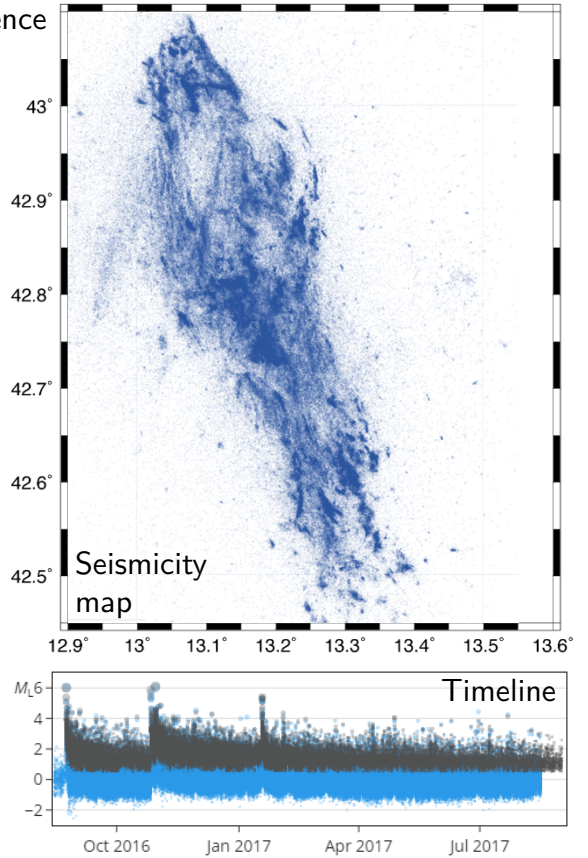


- Understanding = a better idea about the future
  - help to forecast the evolution of seismicity

→ support decision making during ongoing sequences

→ reduce seismic risk

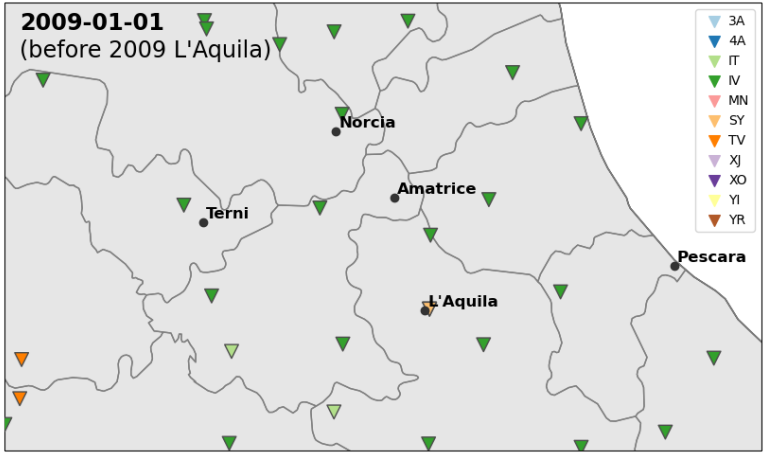
Central Italy 2016/17 sequence



High-res. catalog (offline, advanced methods)
[Tan et al. 2021]

How? **(to obtain a better resolution & quality)**

1. Denser seismic networks
   (sometimes only temporarily)



Evolution of the seismic network in central Italy

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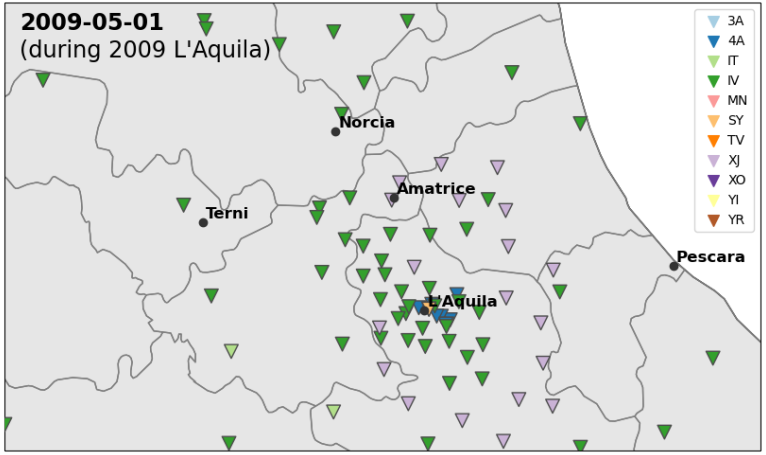

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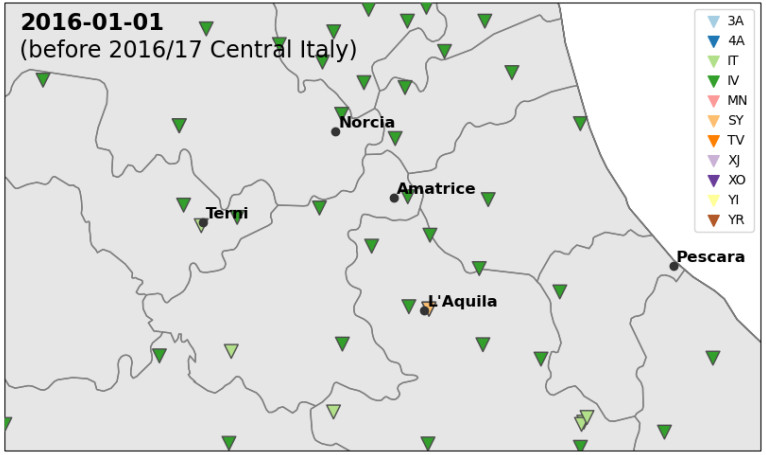

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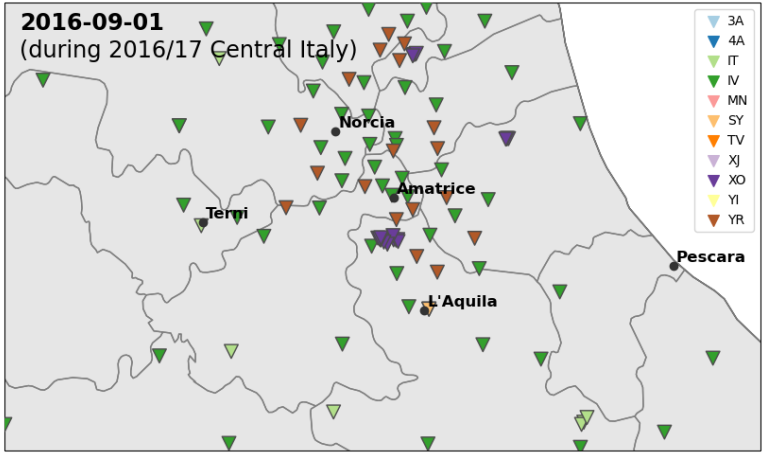

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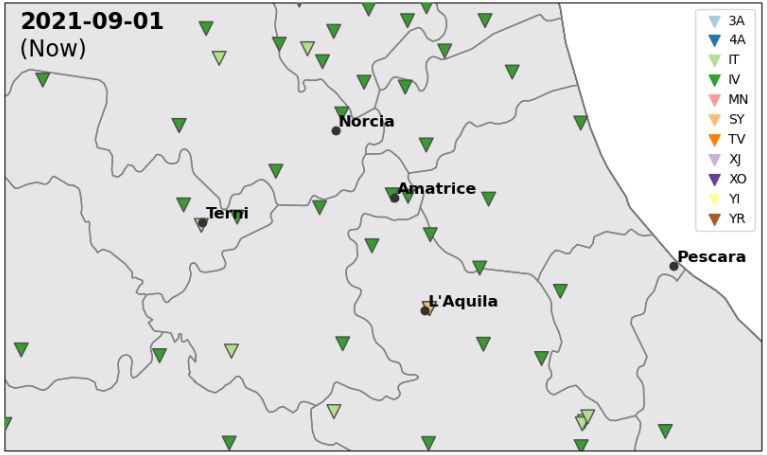

Evolution of the seismic network in central Italy

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1. Denser seismic networks
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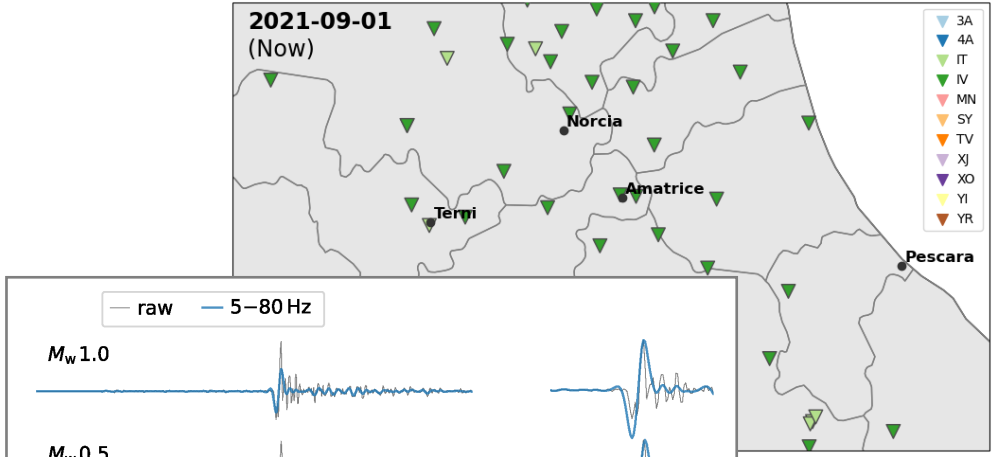
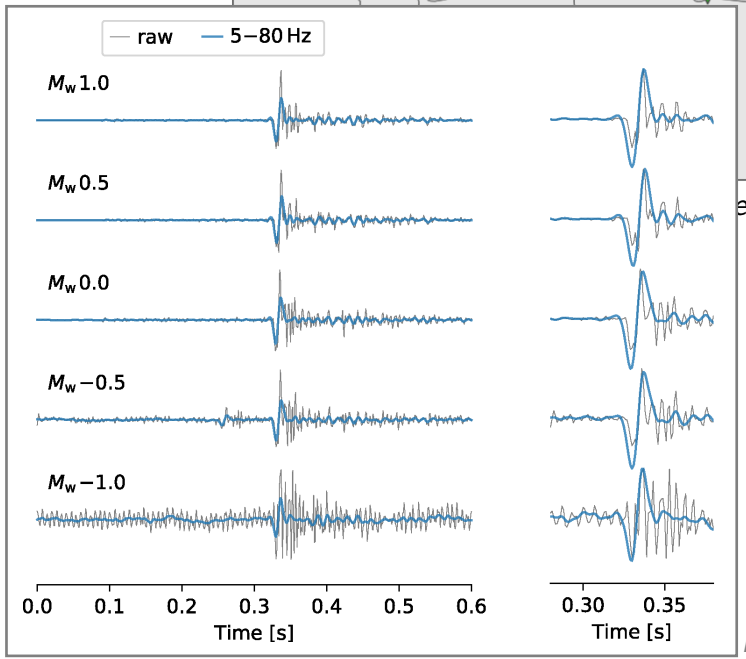
   - detection / phase-'picking'
     - waveform template matching
       (search for similar waveforms)
   - phase association
     (among different seismometers)
   - locating



entral Italy



[Herrmann et al. 2019]

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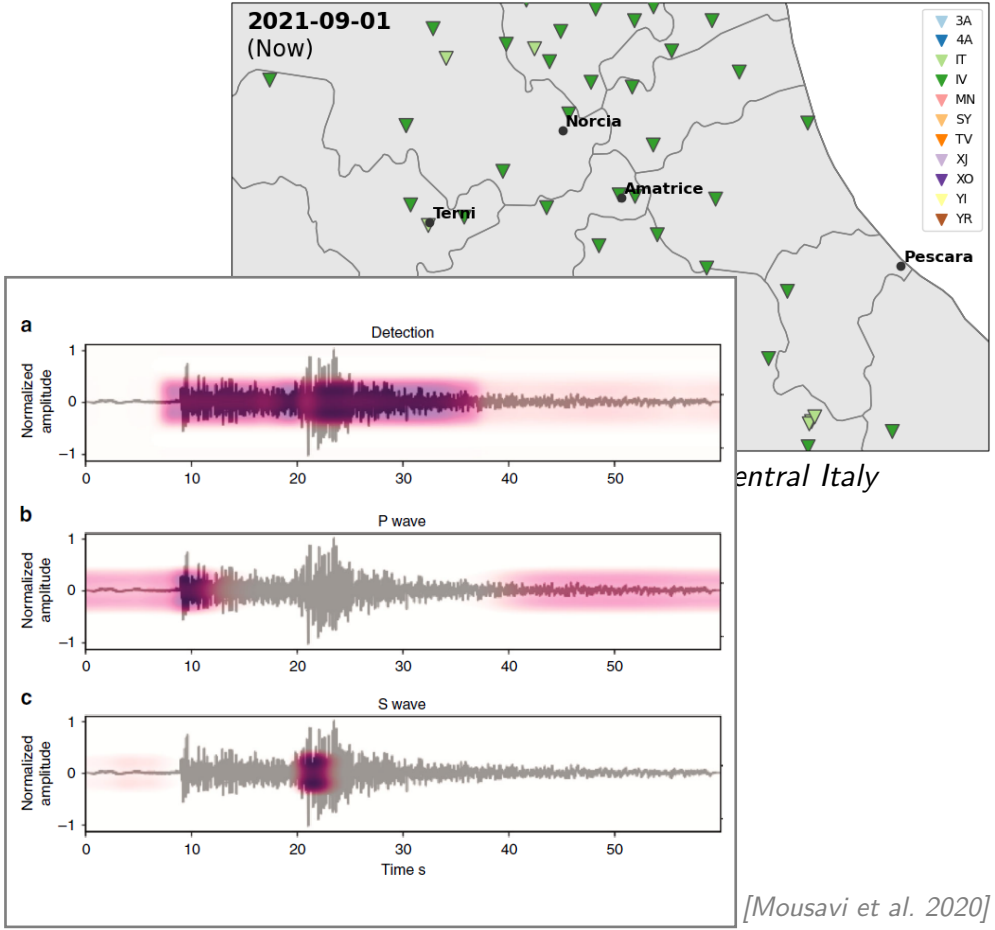

entral Italy

[Mousavi et al. 2020]

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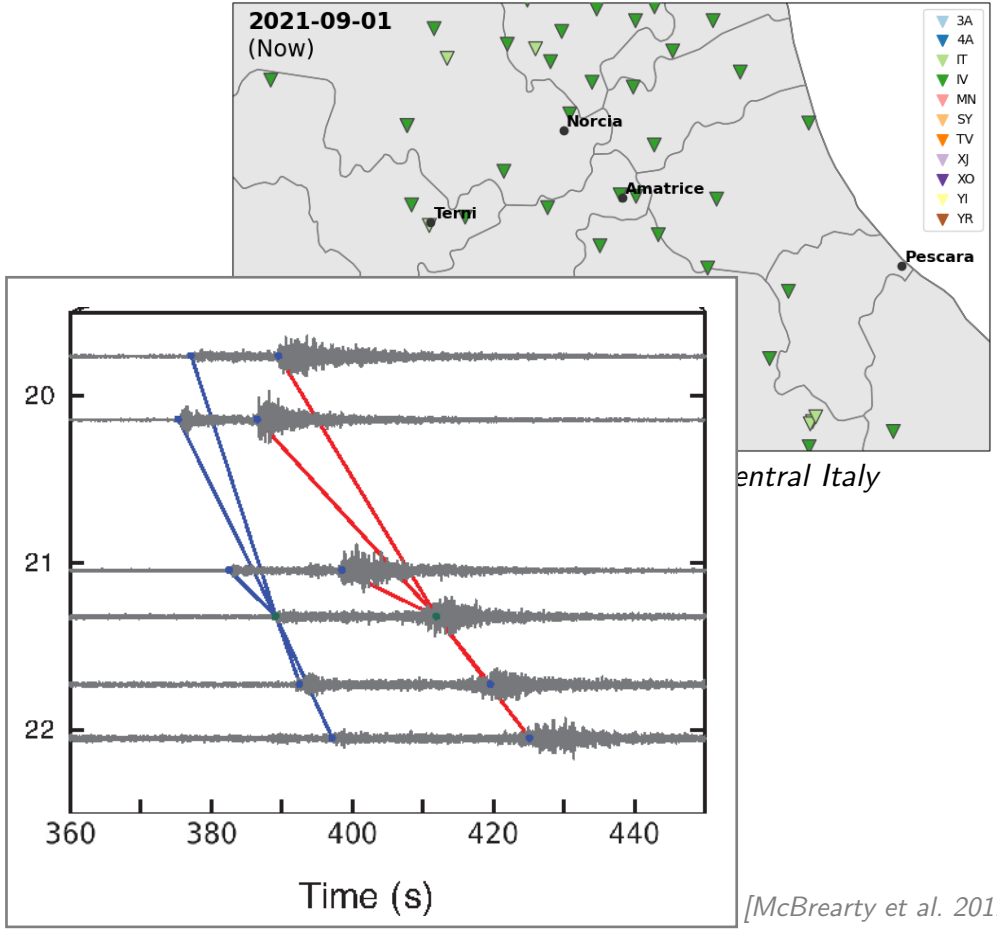

entral Italy

[McBrearty et al. 2019]

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       (particularly deep neural networks;
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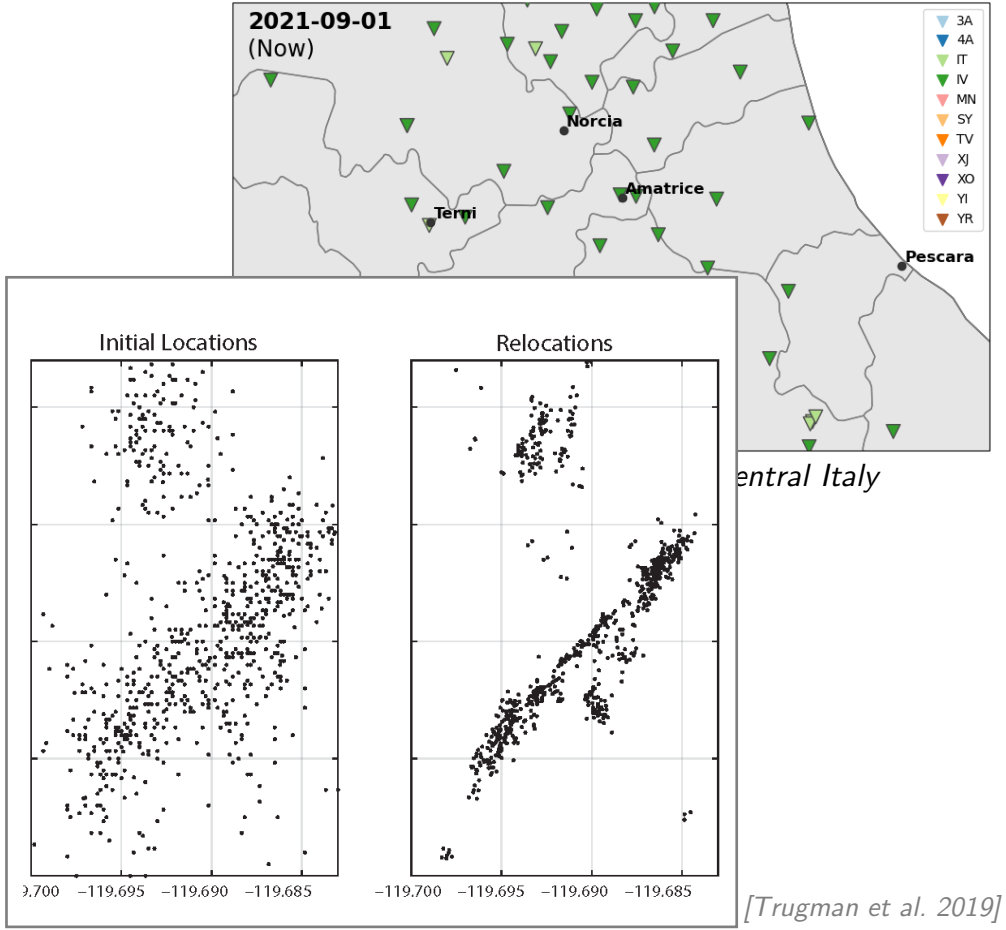
   - phase association
     (among different seismometers)
   - locating
     - relative relocation
       (jointly relocate events based on
       waveform similarity;
       avoids several error sources)

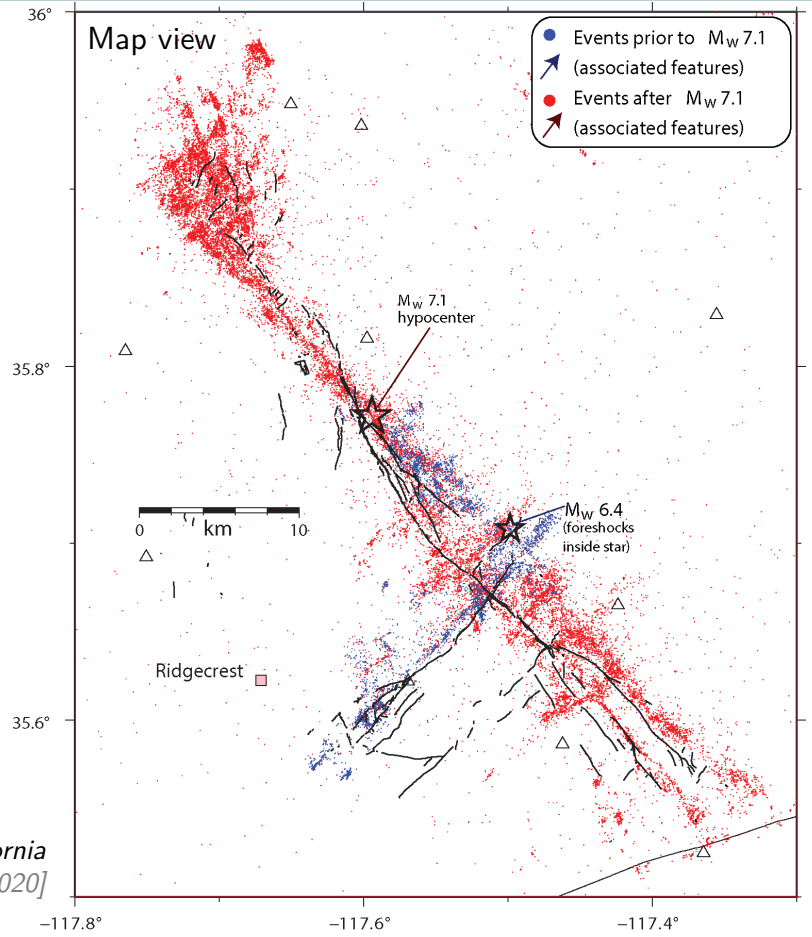


entral Italy

[Trugman et al. 2019]

Benefits of higher detail – **Fault architecture**

- Infer properties of fault architecture/geometry
  - *Ridgecrest 2019, California*
    - M_w6.4 foreshock; M_w7.1 mainshock
    - Catalog illuminates network of orthogonal faults (over the entire depth range)
      - Fault strands
      - Cross-cutting faults
      - Multi-fault branching



Ridgecrest 2019, California
Modified after [Shelly 2020]

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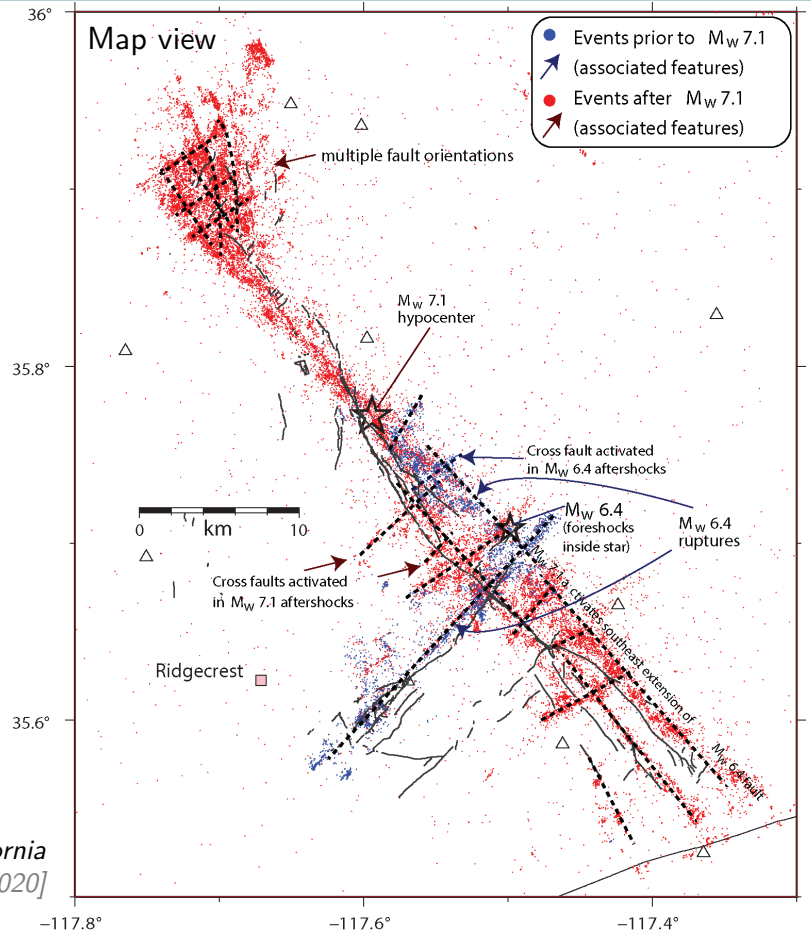
  - Complement geologic/geodetic observations

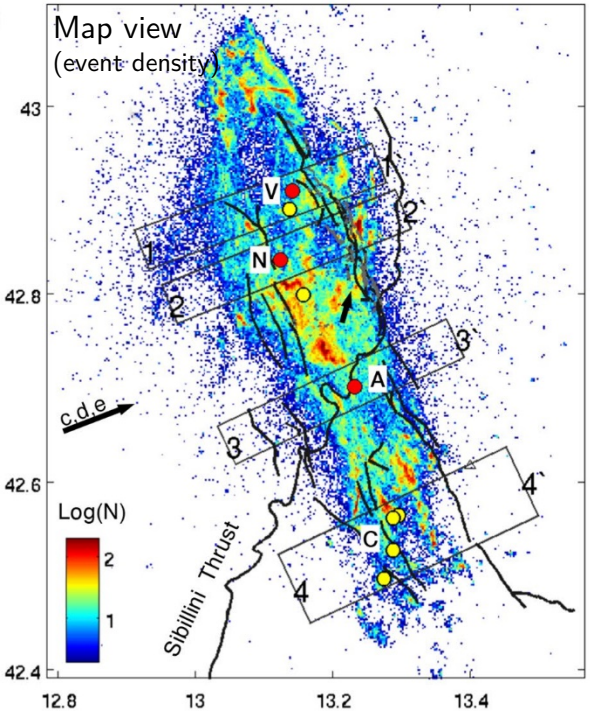
→ fault zones are more complex at depth

- better definition of tectonic environment

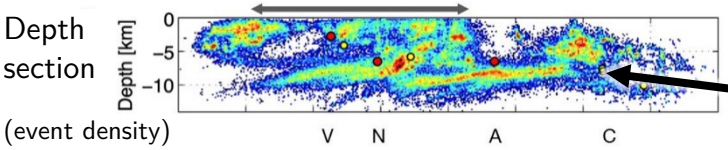


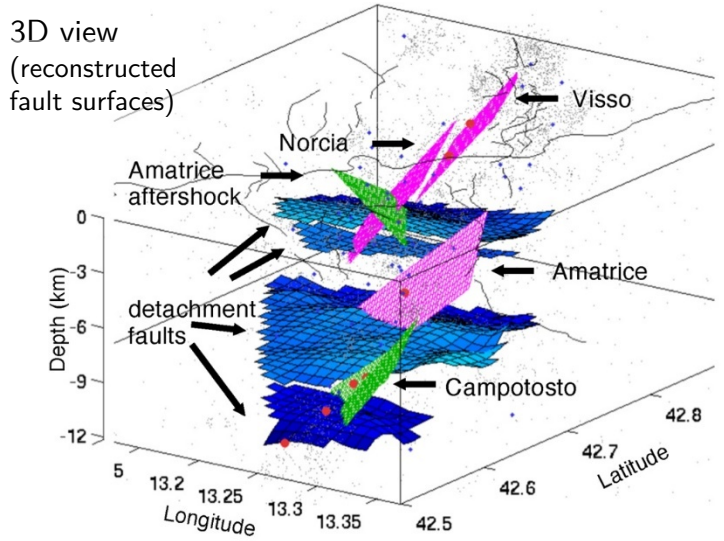
Ridgecrest 2019, California
Modified after [Shelly 2020]

Benefits of higher detail – **Complex structures**



Central Italy sequence 2016/17
[Waldhauser et al. 2021]

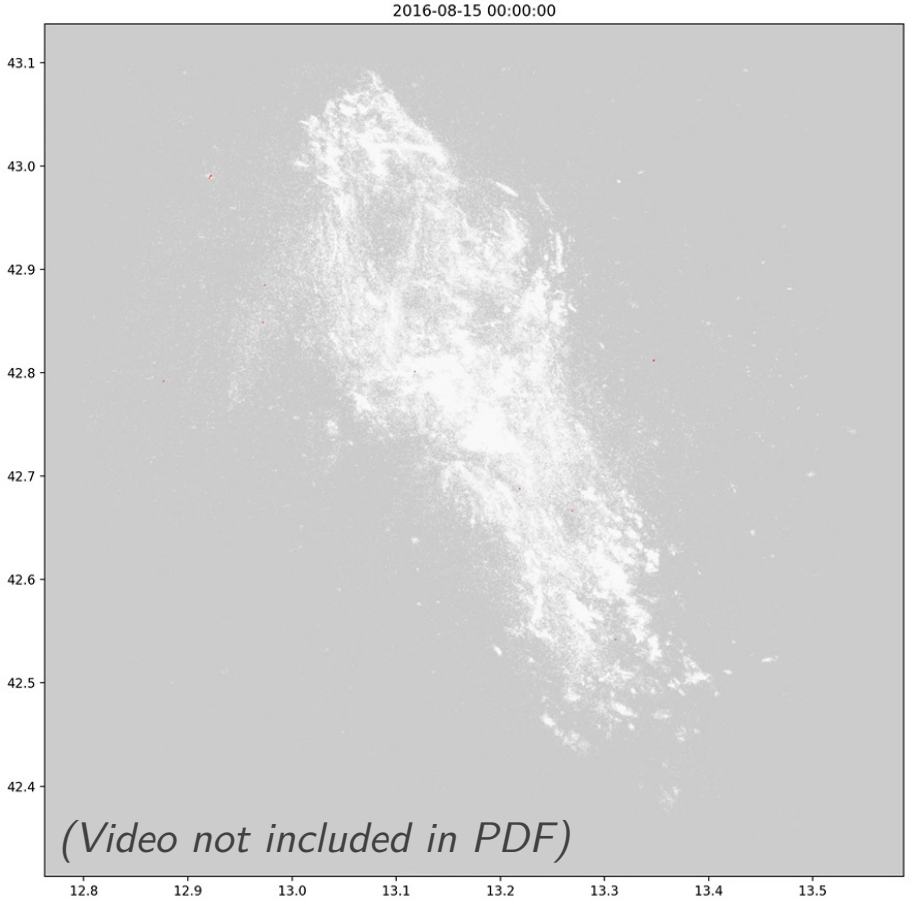




→ Fault zones can be 3D systems with complex faulting pattern that interacts (reflecting a heterogeneous stress field)

Benefits of higher detail – **Temporal evolution**

- Reveals more precisely how earthquake sequences progress
  - *Central Italy sequence 2016/17*
    - *Activity in small clusters*
      → small fault patches/segments gradually rupture
      → small-scale heterogeneity



Central Italy 2016/17
[Tan, pers. comm. 2020]

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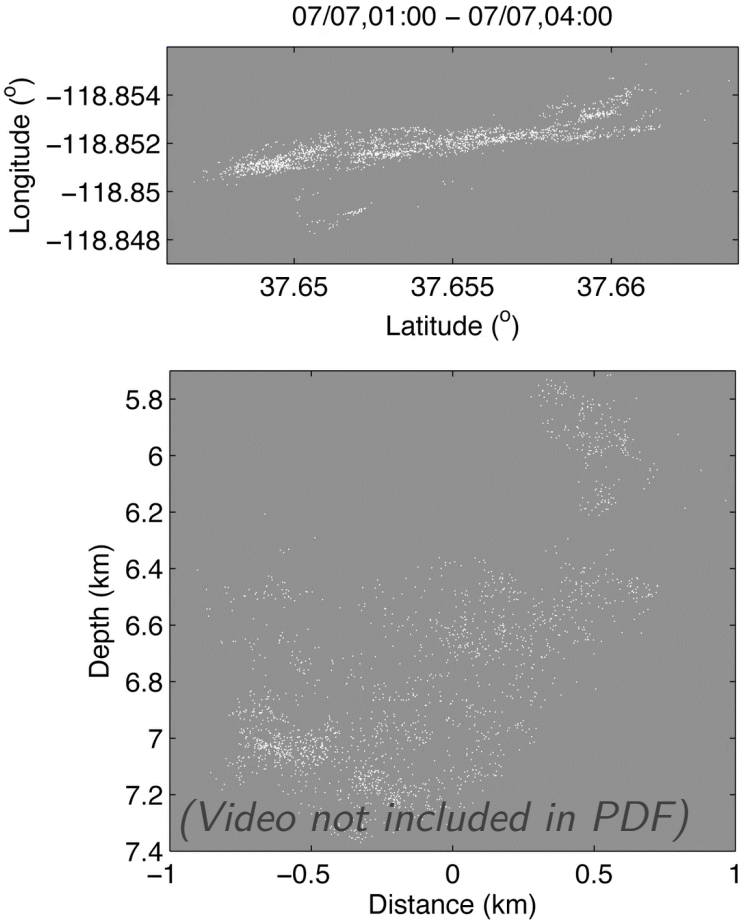
  - *Long Valley 'swarm' 2014, California*
    (no dominating mainshock; largest: 3x M3.5)
    - *Episodic seismicity migration*
      → identify fluid diffusion
      (in preexisting faults and fractures)

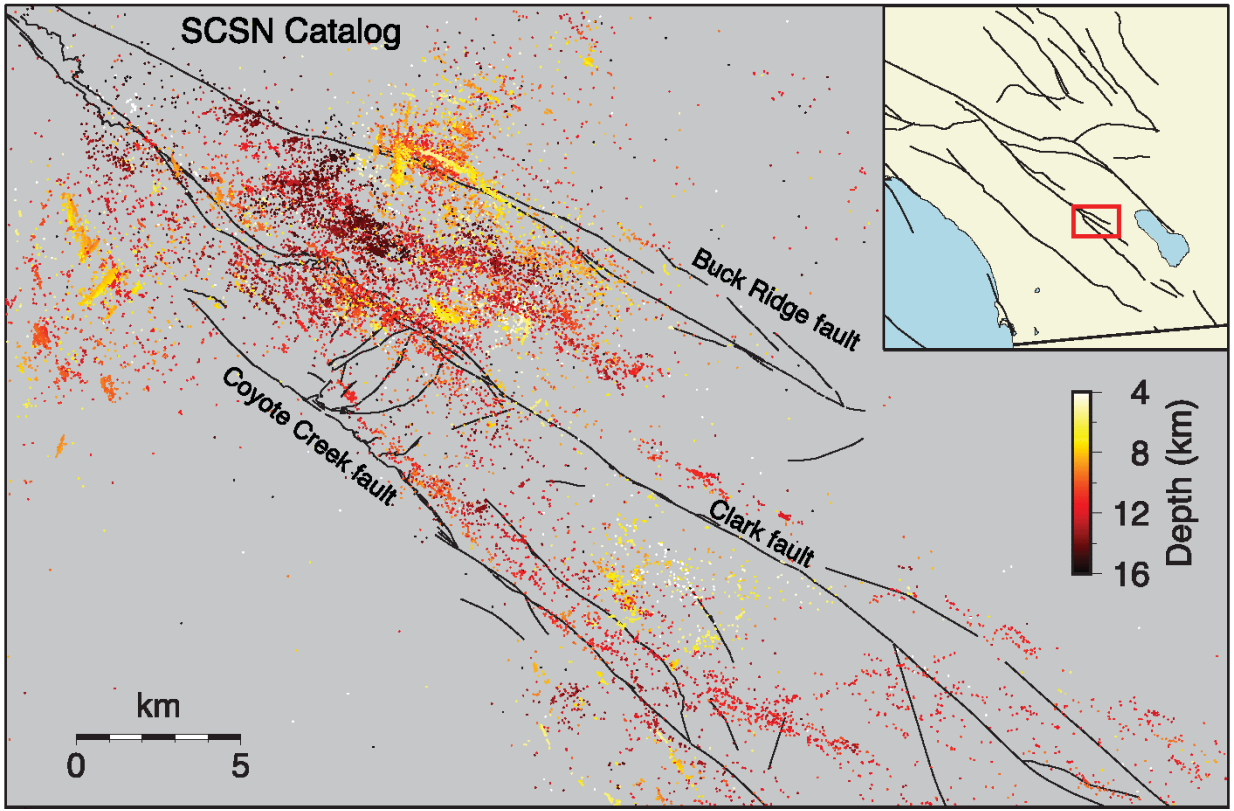
→ track behavior of a fault zone/system

Long Valley Swarm 2014, California
[Shelly 2016]



Benefits of higher detail – **Reveal less active structures**

- Even in the absence of a sequence...



San Jacinto fault zone, Southern California
(Segment of San Andreas fault)
2008–2017
[Ross et al. 2020]

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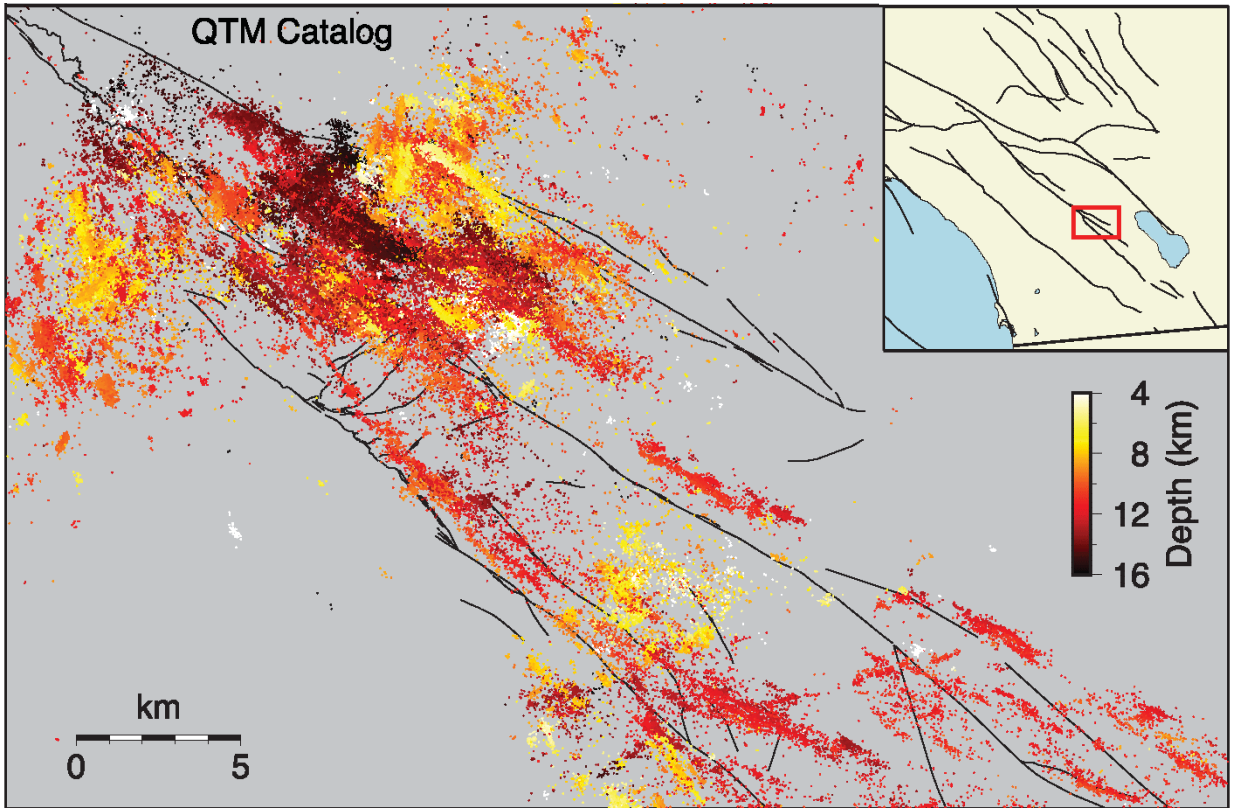

San Jacinto fault zone, Southern California
(Segment of San Andreas fault)
2008–2017
[Ross et al. 2020]

- Highlight less active or unknown tectonic structures
  → location, extent, and 3D geometry of active faults
- ...which could potentially rupture in a bigger event
  → contribute to seismic hazard assessment

Benefits of higher detail – **Reveal long-term behavior #1**

- Induced seismicity in a (failed) geothermal system (Basel, Switzerland)
  (hydraulic stimulation in Dec. 2006; unacceptably high seismicity – M_w3.2)

Induced seismicity in Basel 2006-2019
[Herrmann et al. 2019]

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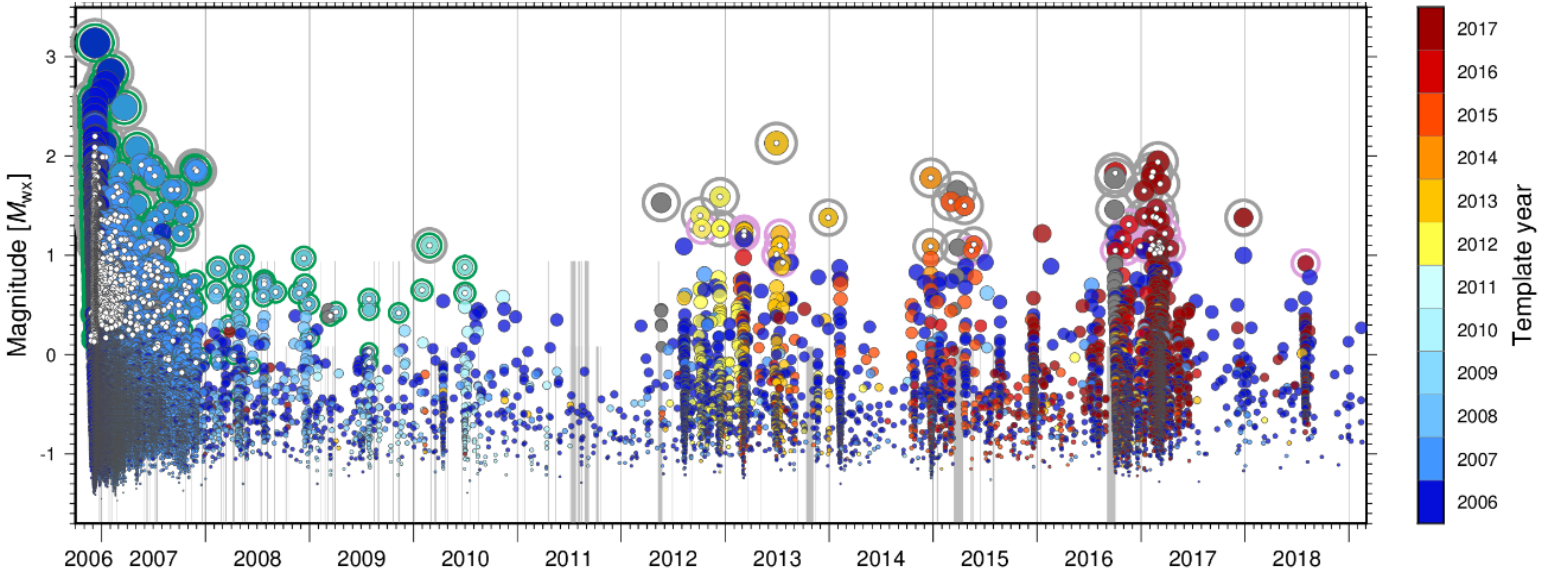


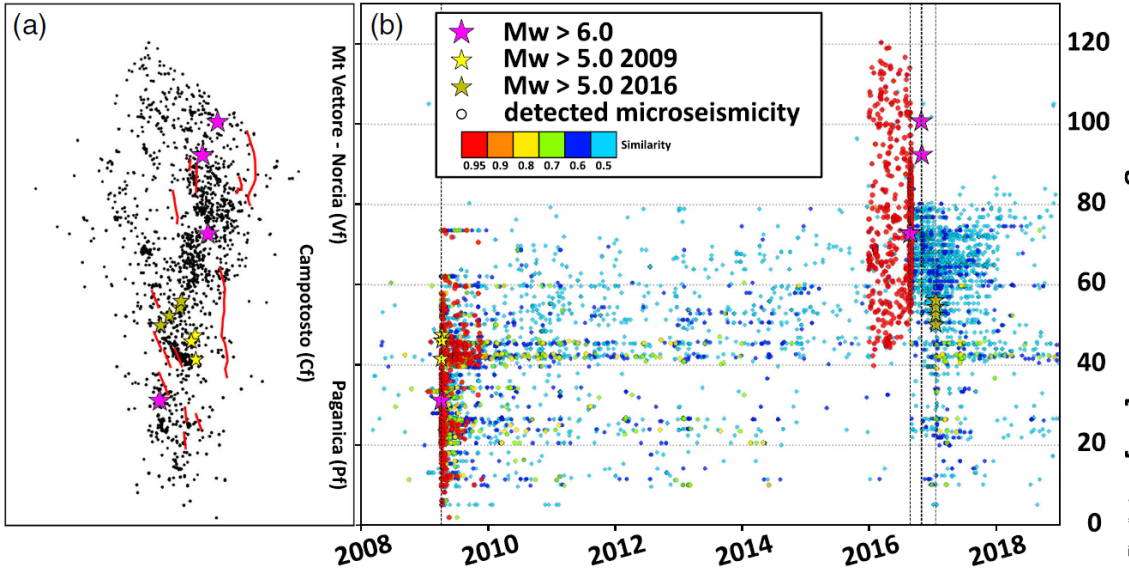
Induced seismicity in Basel 2006-2019
[Herrmann et al. 2019]

- Reveals continuously active system (once fluid is in the underground)

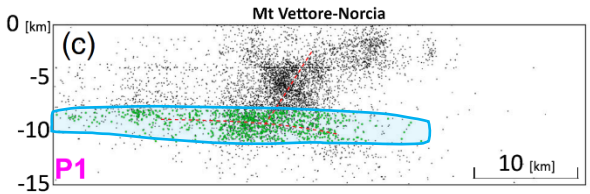
  → need for long-term high-res monitoring to track its behavior

Benefits of higher detail – **Reveal long-term activity #2**

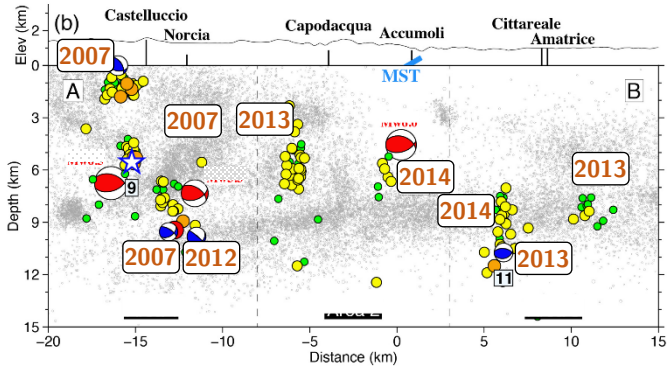
- Seismicity between sequences (during apparent quiescence)



Seismicity in central Apennines 2008-2019
(only in subhorizontal layer at ~10km depth)
[Vicic et al. 2020]



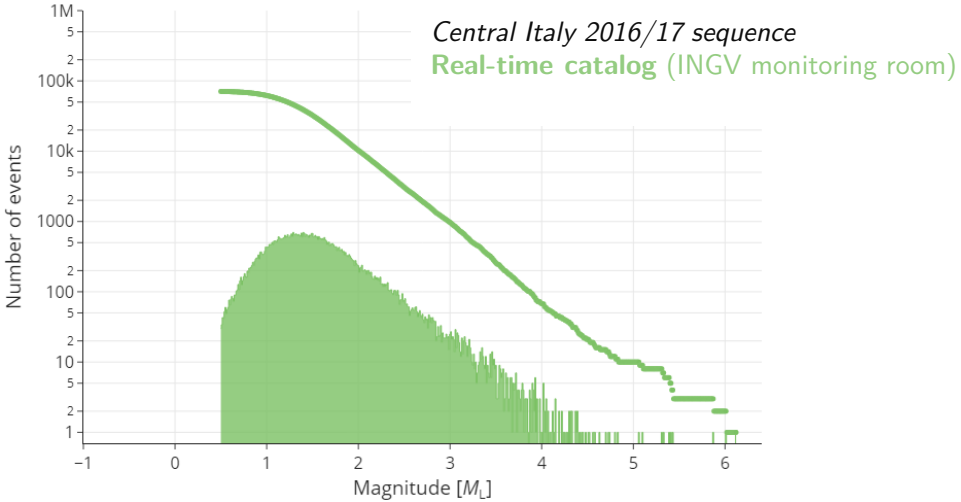
Minor sequences before central Italy sequence 2016
[Moschella et al. 2021]



- Reveals background activity
  → obtain a more complete picture of regional seismicity
- Insights into foreshock sequences
  (What happens before large earthquakes; how do they initiate?
  Do foreshocks indicate something?)

Benefits of higher detail – **Smaller magnitudes**

- MFD (Magnitude–Frequency Distribution)
  (major ingredient for forecasting & hazard models)



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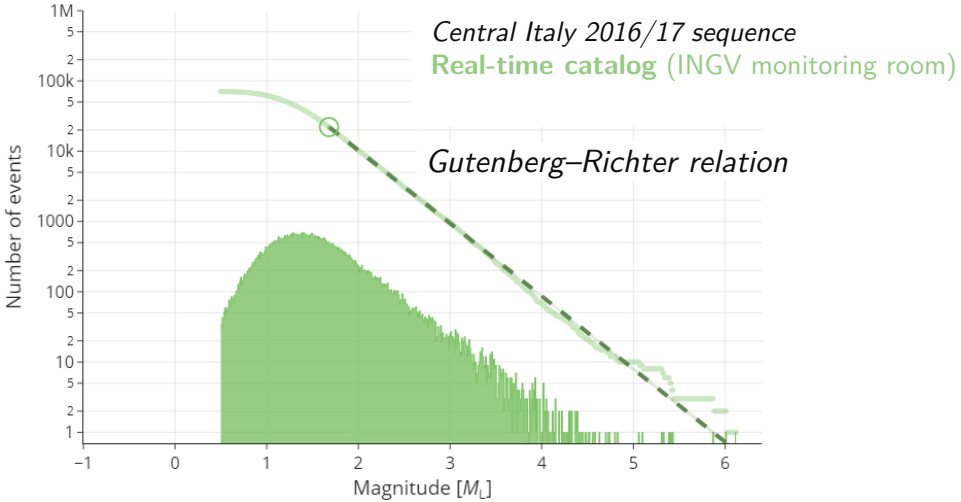

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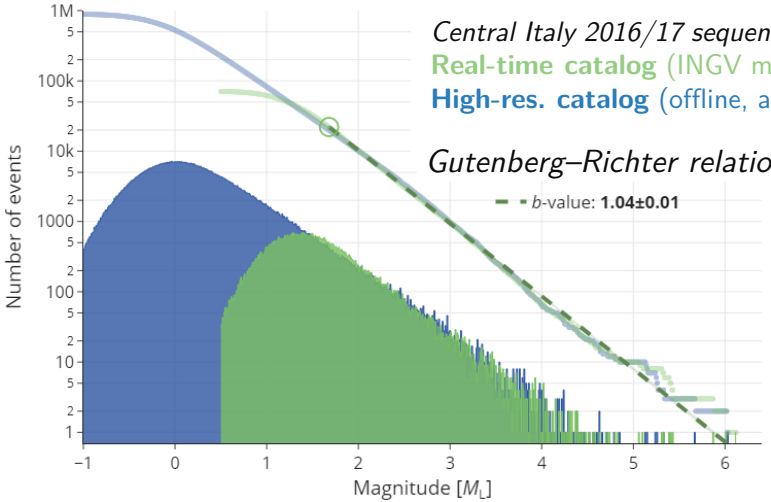
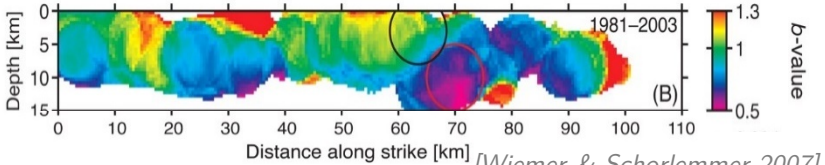
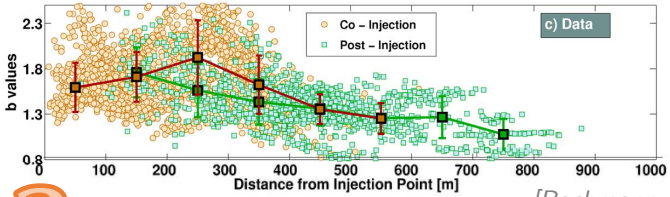


- Varies on fault – locked/creeping fault patches



[Wiemer & Schorlemmer 2007]

- During injection – relation to pore-pressure perturbations



[Bachmann et al. 2012]

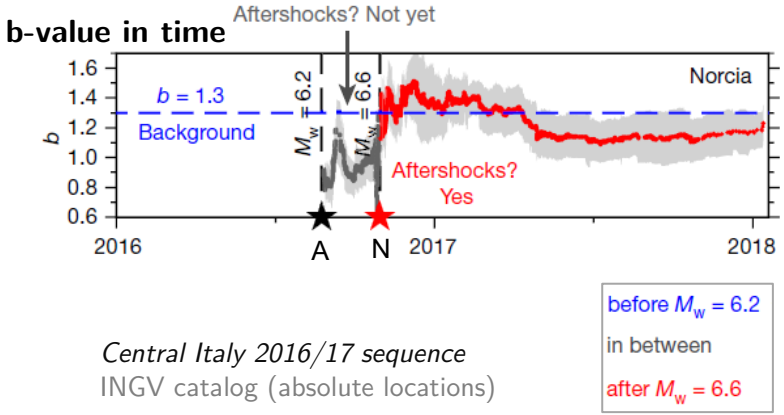
- Extend toward low magnitudes
  - provide better conditions for statistical seismology
    e.g., better explore (the variability of) the MFD (in space and time) ? *potentially…*
- *b*-value – indicator for stress state and related properties

→ study its variation; may contain information on earthquake occurrence → could improve their predictability

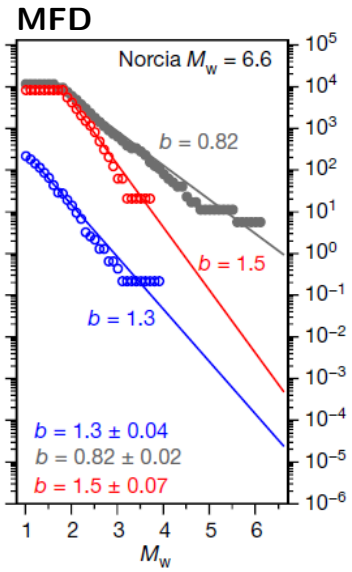
- Proposal: *b*-value variation indicates …

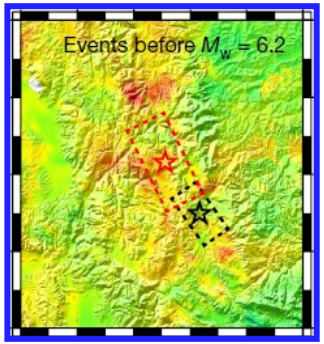
  … *"whether an ongoing sequence represents a decaying aftershock sequence or foreshocks to an upcoming large event" [Gulia & Wiemer 2019]*

  (the *b*-value generally increases after the mainshock *[Gulia et al. 2018]*)



Central Italy 2016/17 sequence
INGV catalog (absolute locations)





Amatrice
M_w 6.2, 24/08/2016
Fault projection
Epicentre

Norcia
M_w 6.6, 30/10/2016
Fault projection
Epicentre

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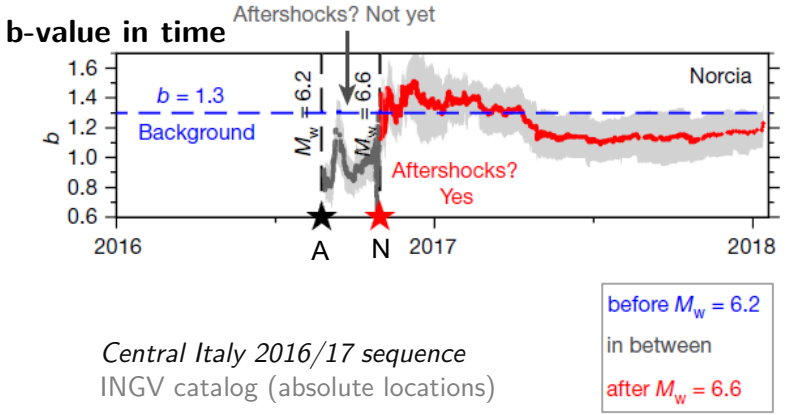

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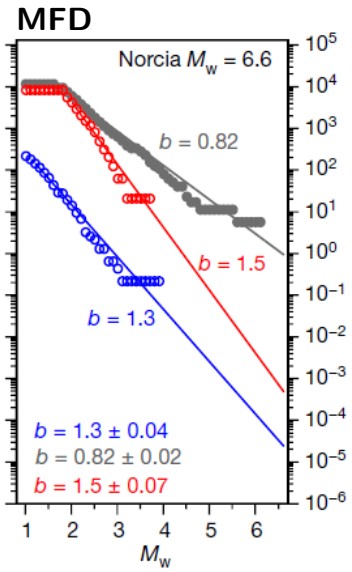
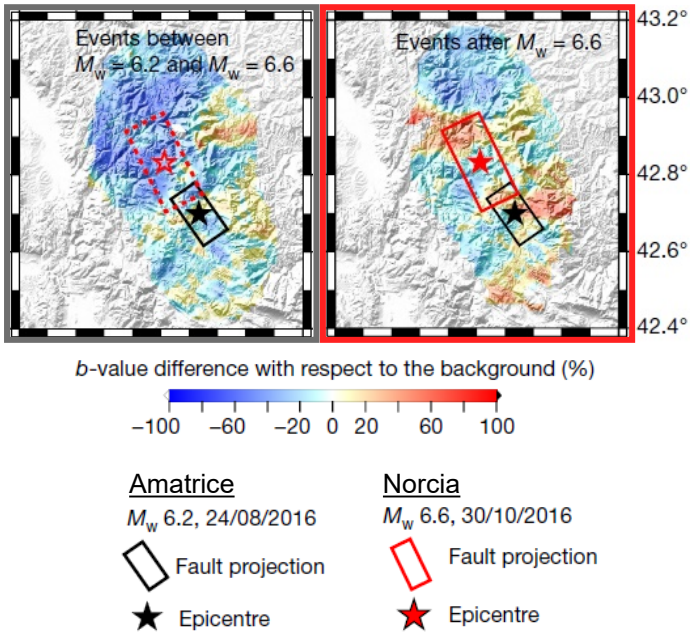
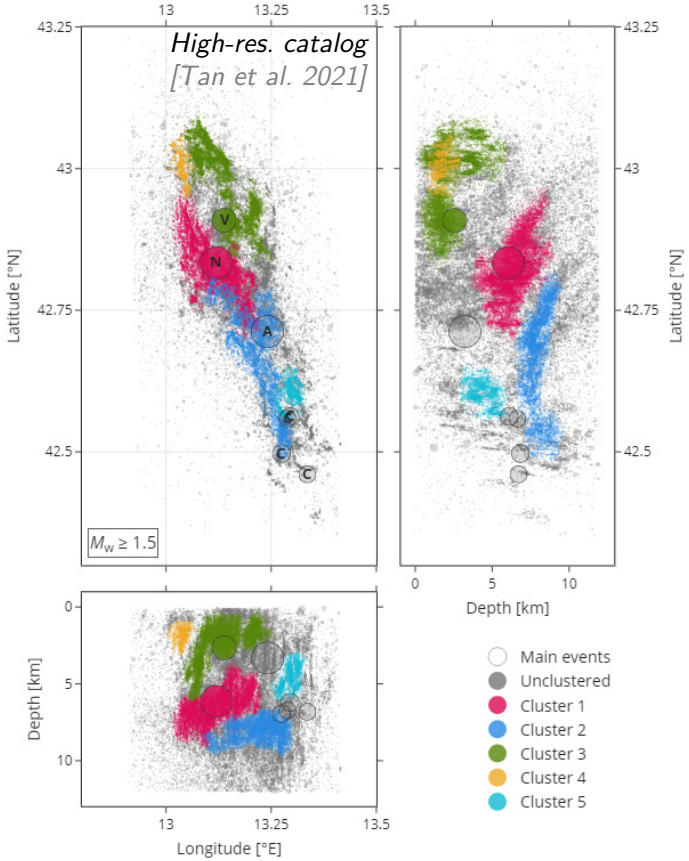


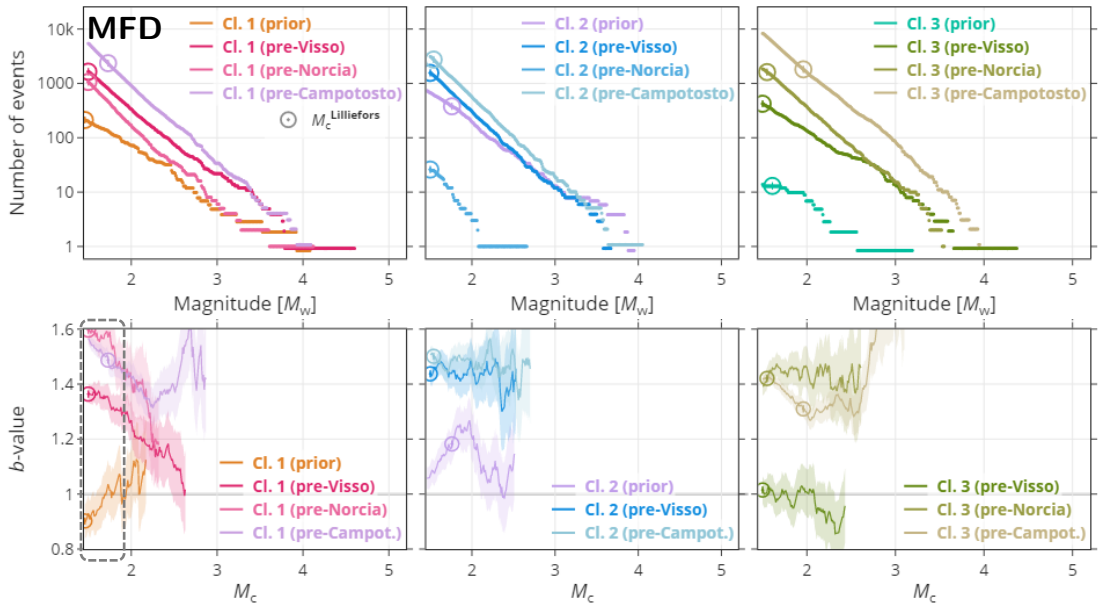


b-value of **what**?

- Central Italy 2016/17 sequence re-analyzed

[M. Herrmann, E. Piegari, W. Marzocchi; in preparation]





→ What is the appropriate spatiotemporal scale to resolve the *b*-value?

- need to appreciate the complexity of a sequence
- requires high-res. catalogs

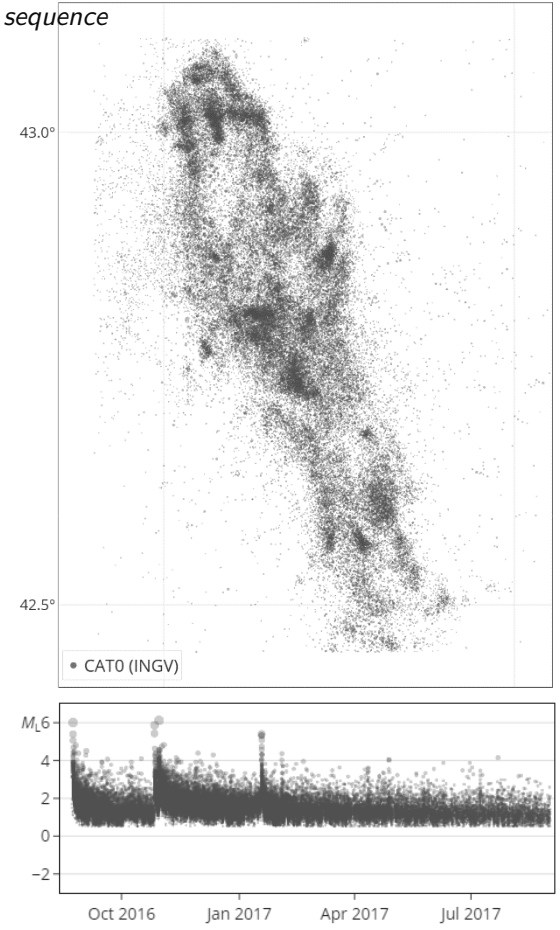
BUT…

(there is always a ‘but’)

- Delayed availability
  (offline data processing, quality control, ...)
  - resolution/quality evolves over time
  - future: immediate availability
    (online mobile stations, real-time processing)

Central Italy 2016/17 sequence

#0. Real-time [INGV]



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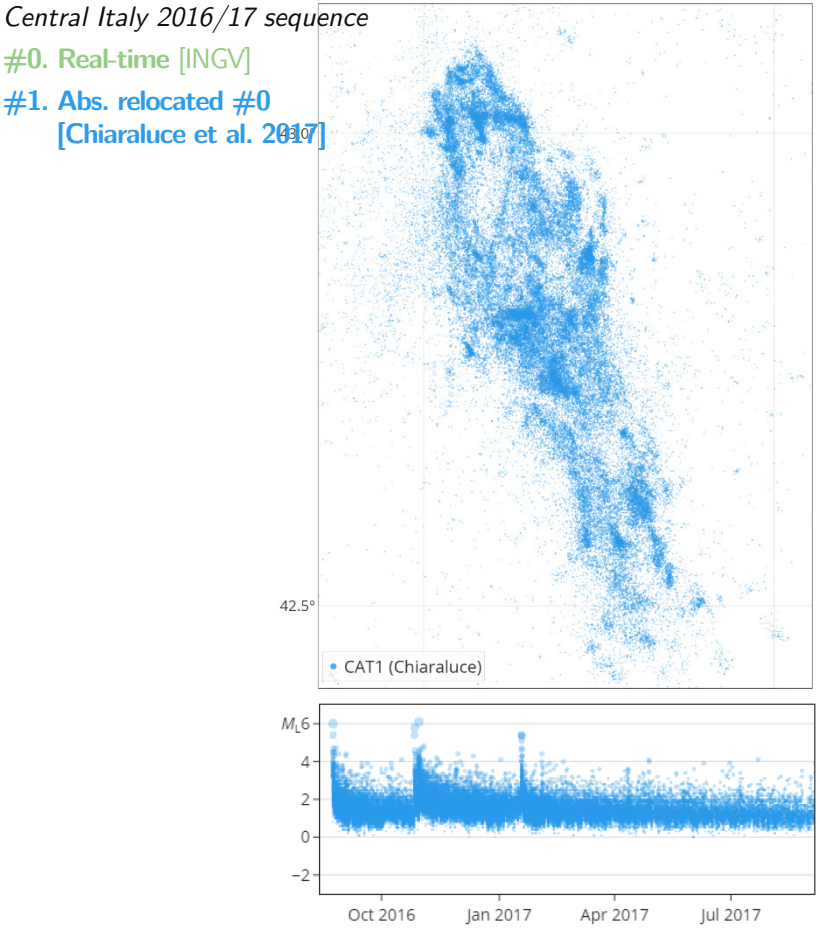

Current Limits of high-res catalogs

- Delayed availability
  (offline data processing, quality control, ...)
  - resolution/quality evolves over time
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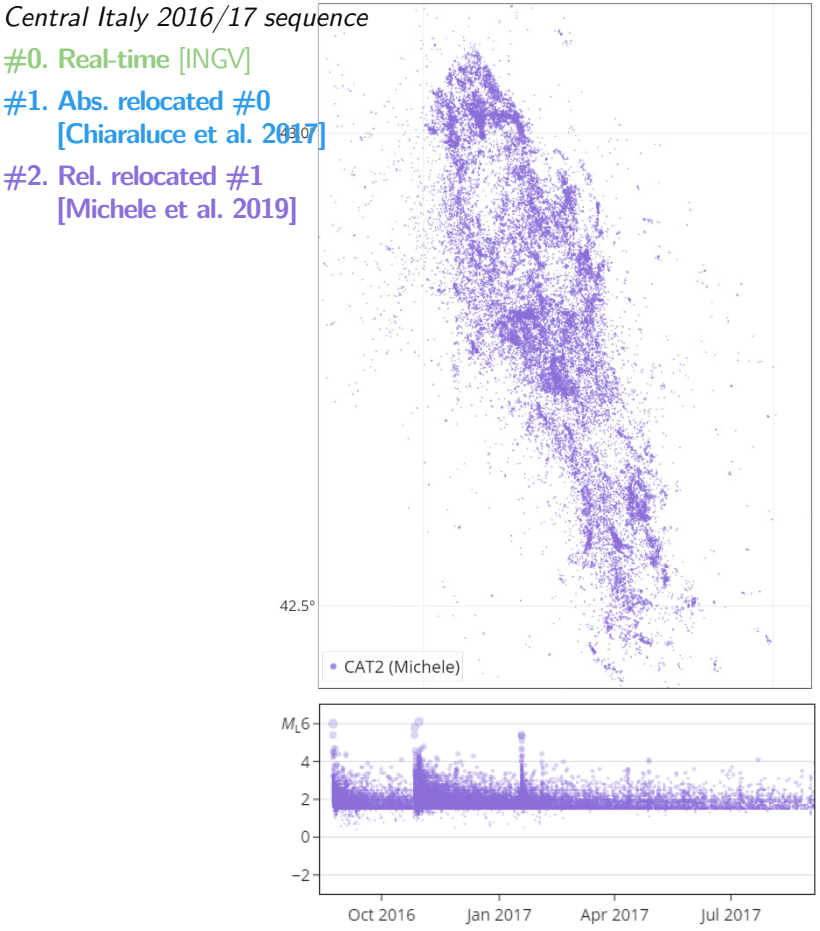

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Central Italy 2016/17 sequence

#0. Real-time [INGV]

#1. Abs. relocated #0
[Chiaraluce et al. 2017]

#2. Rel. relocated #1
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#3. #1 +offline data + auto-pick
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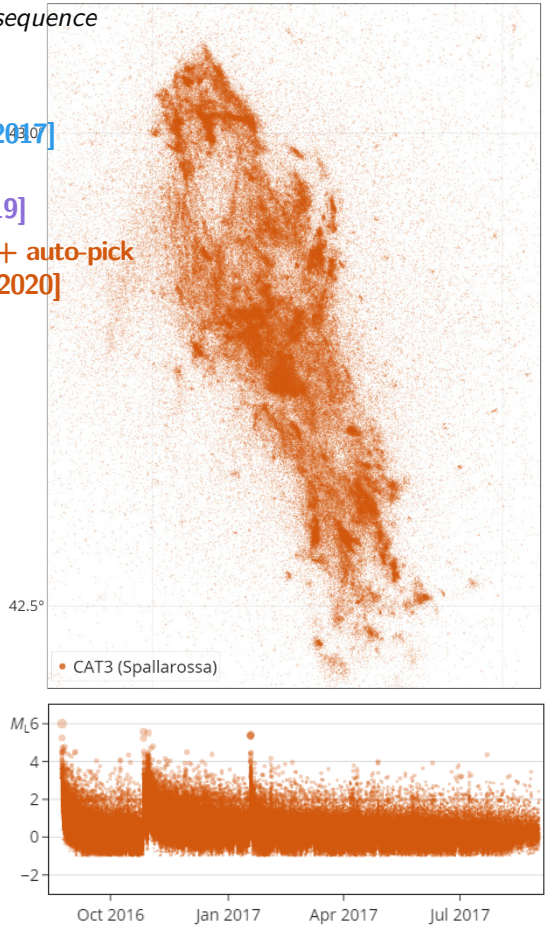

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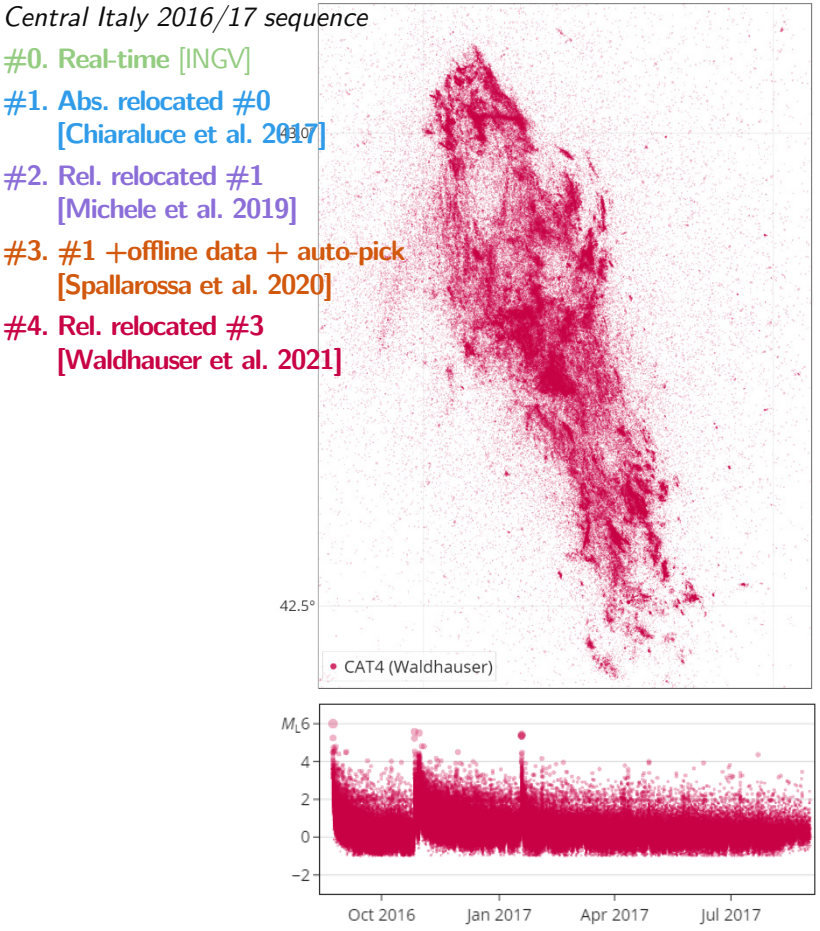

Current Limits of high-res catalogs

- Delayed availability
  (offline data processing, quality control, ...)
  - resolution/quality evolves over time
  - future: immediate availability
    (online mobile stations, real-time processing)
- No consistent quality
  - Spatially: depends on regional seismic network
  - Temporally: seismic network densified
    after a large event & *during* a sequence
- Magnitude estimation

→ better conditions for statistical seismology..
... only if MFD is consistent
(i.e., small magnitudes consistent with large ones)

Central Italy 2016/17 sequence

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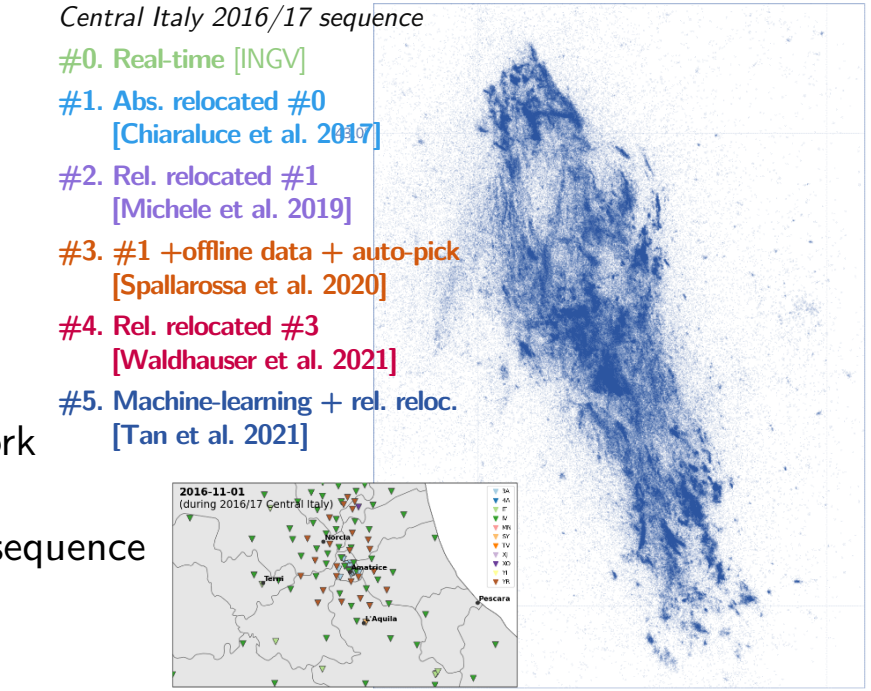
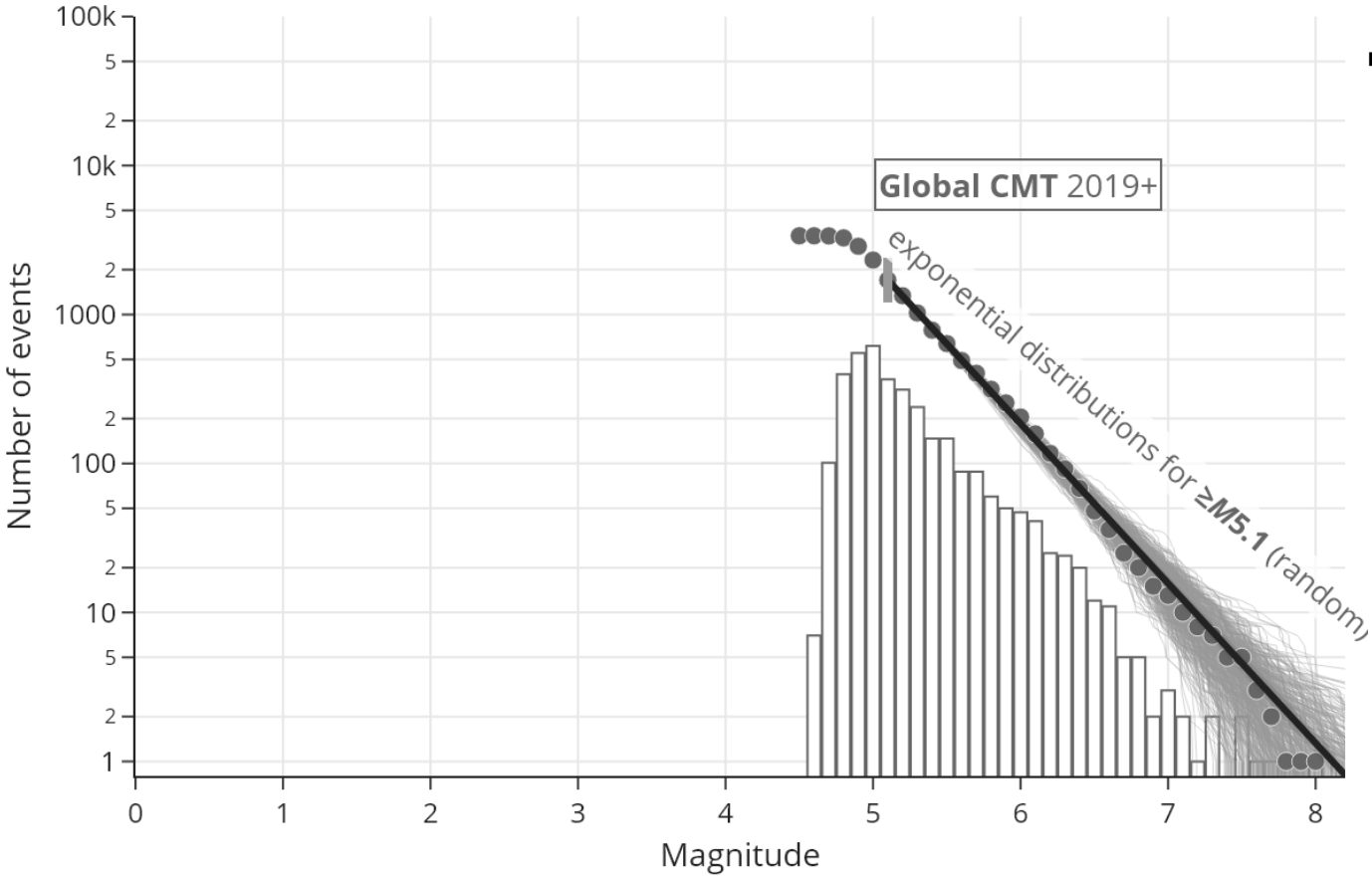
#4. Rel. relocated #3
[Waldhauser et al. 2021]

#5. Machine-learning + rel. reloc.
[Tan et al. 2021]



MFD (in)consistency



- Gutenberg–Richter law:

$$N(M) = 10^{a}10^{-bM}$$

is an

exponential distribution

$$f(M) = \beta e^{-\beta M}$$

with $\beta = b \ln 10$

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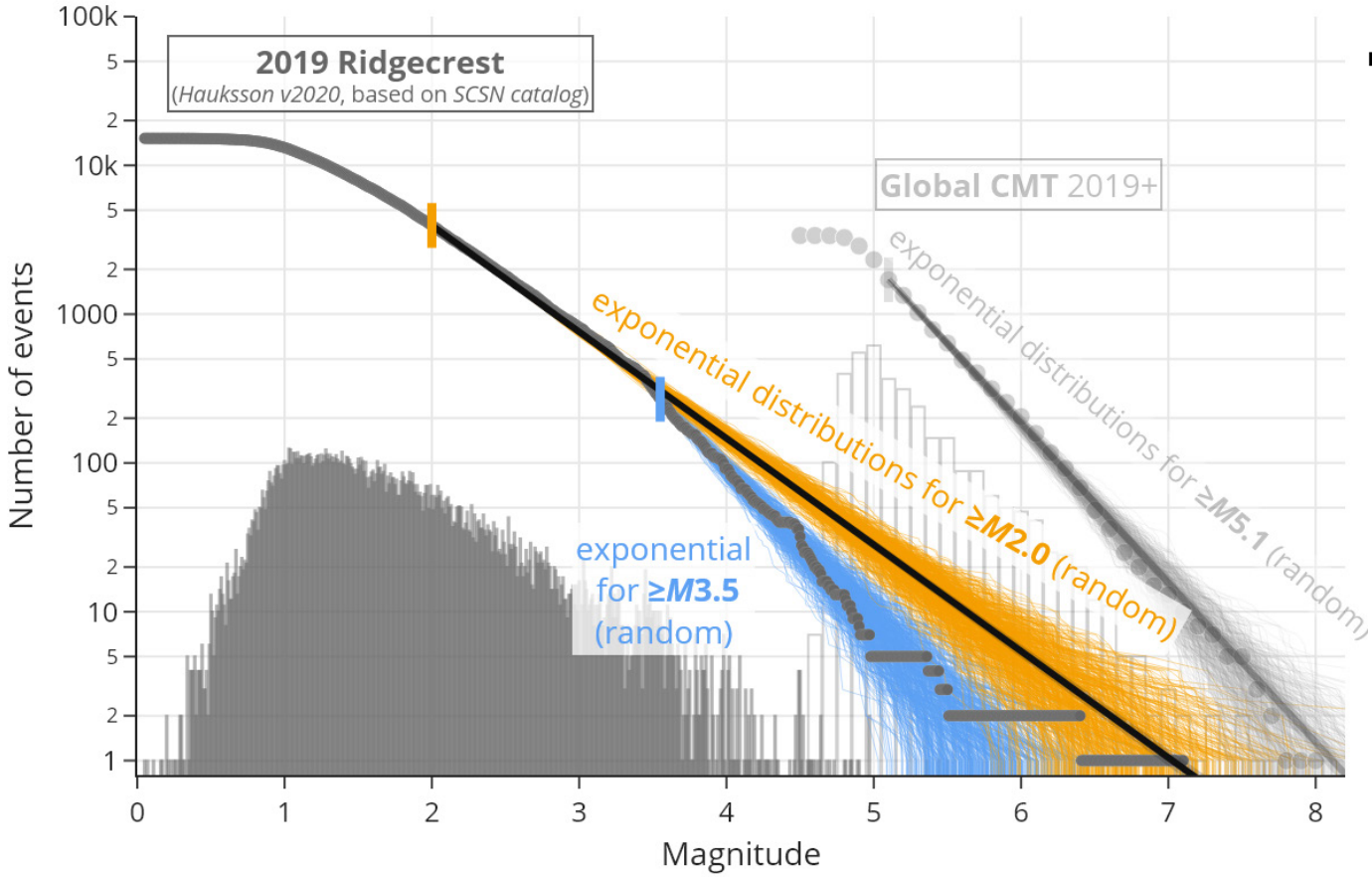

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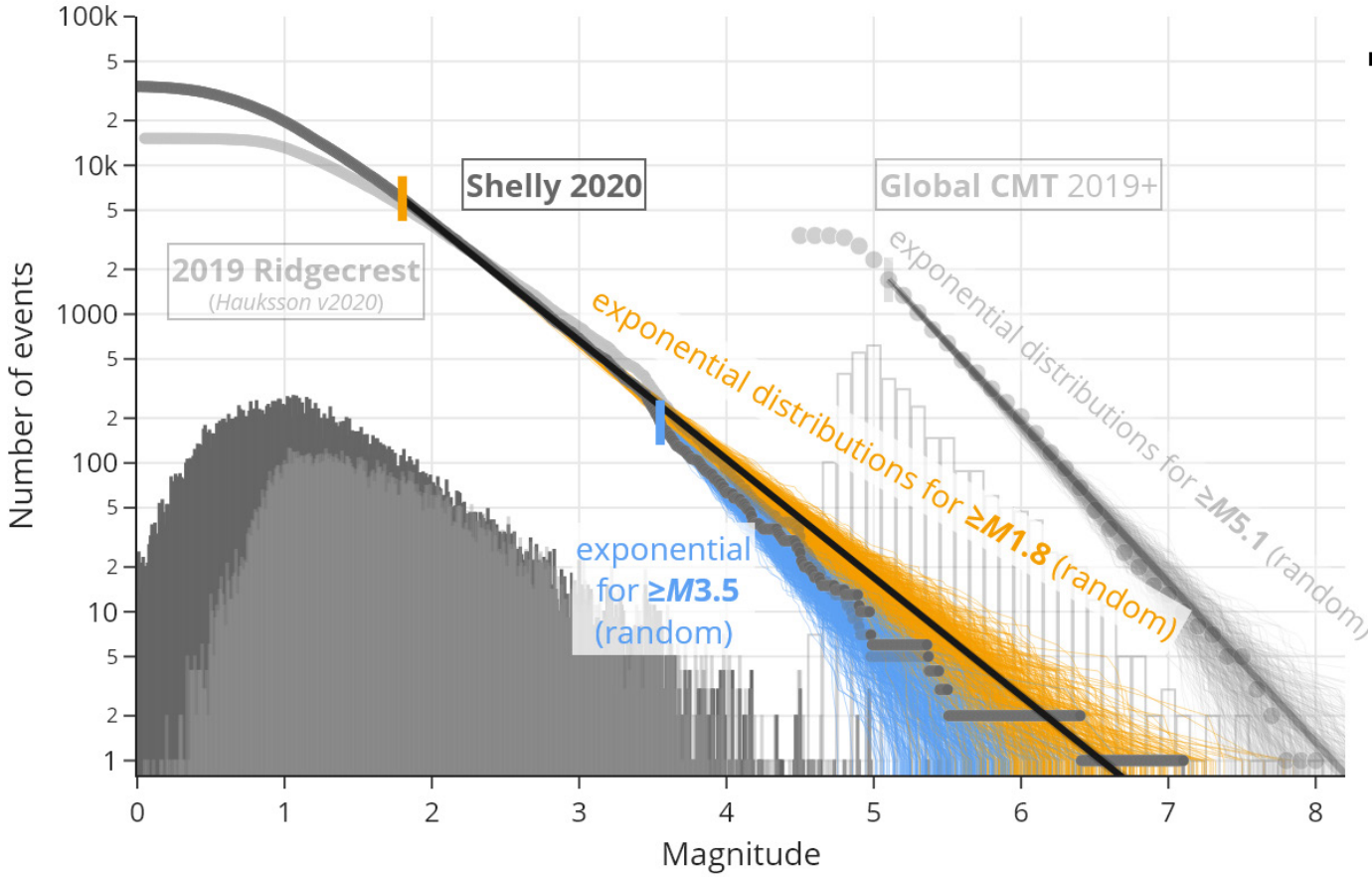

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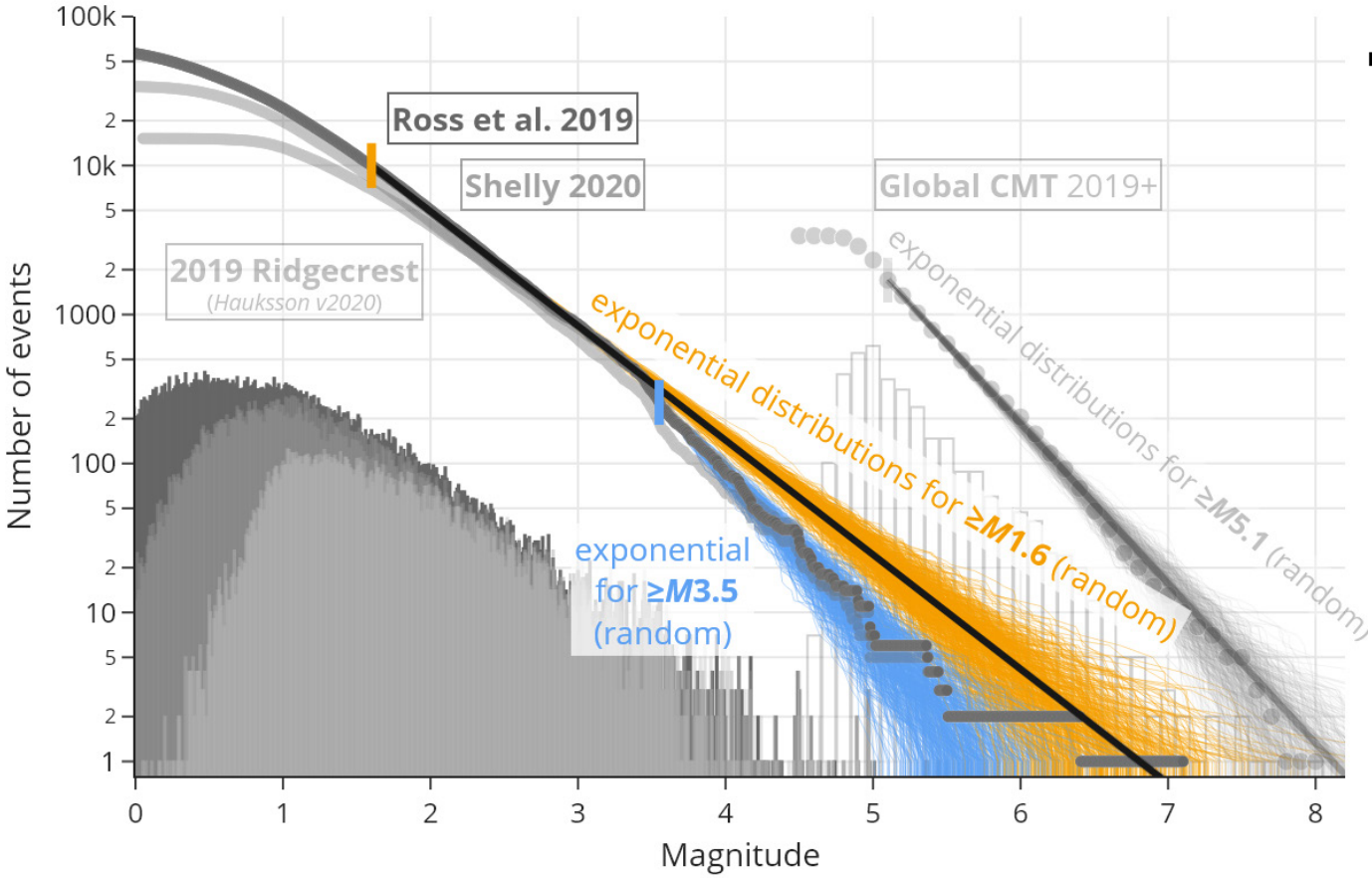

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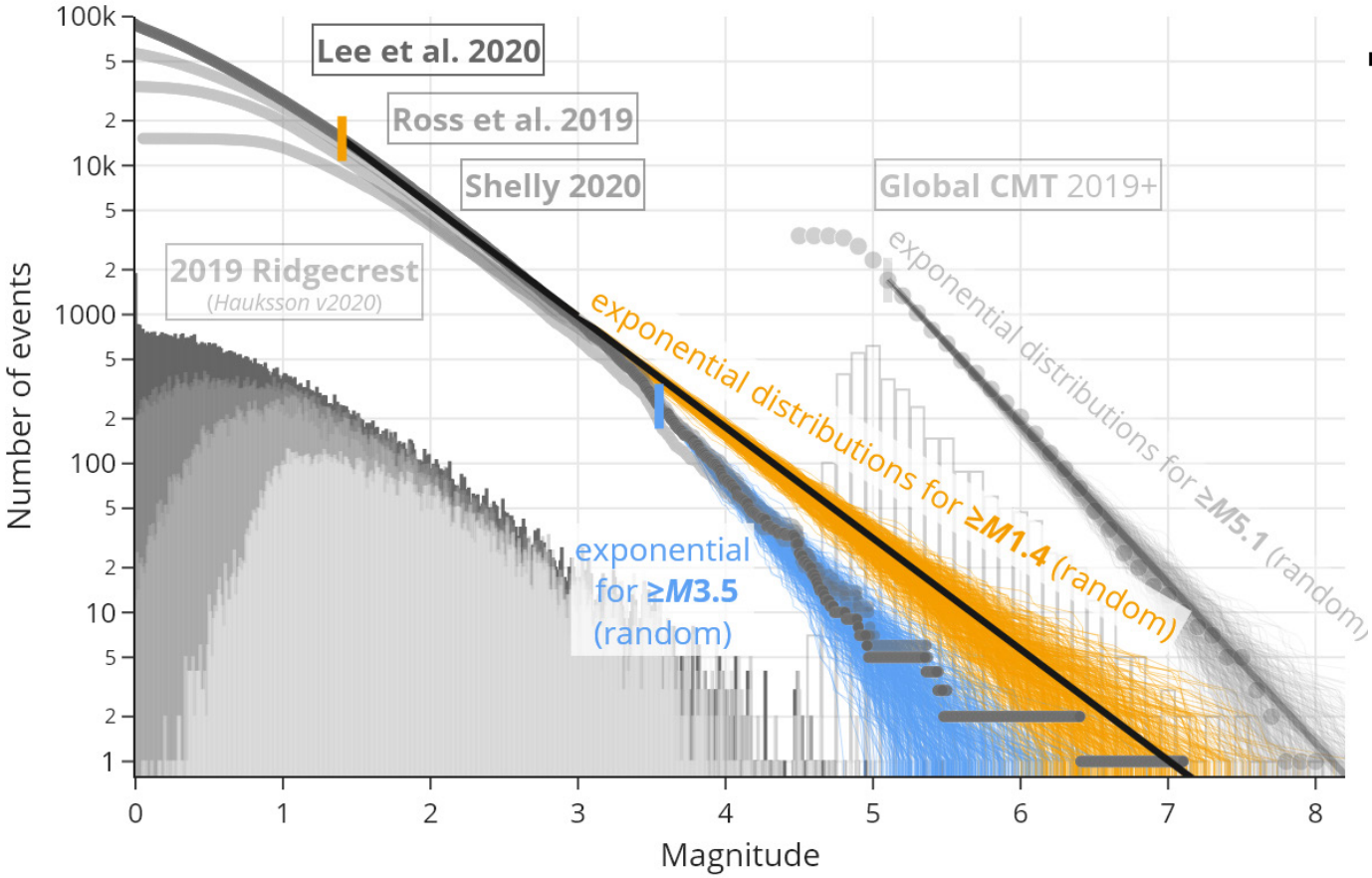

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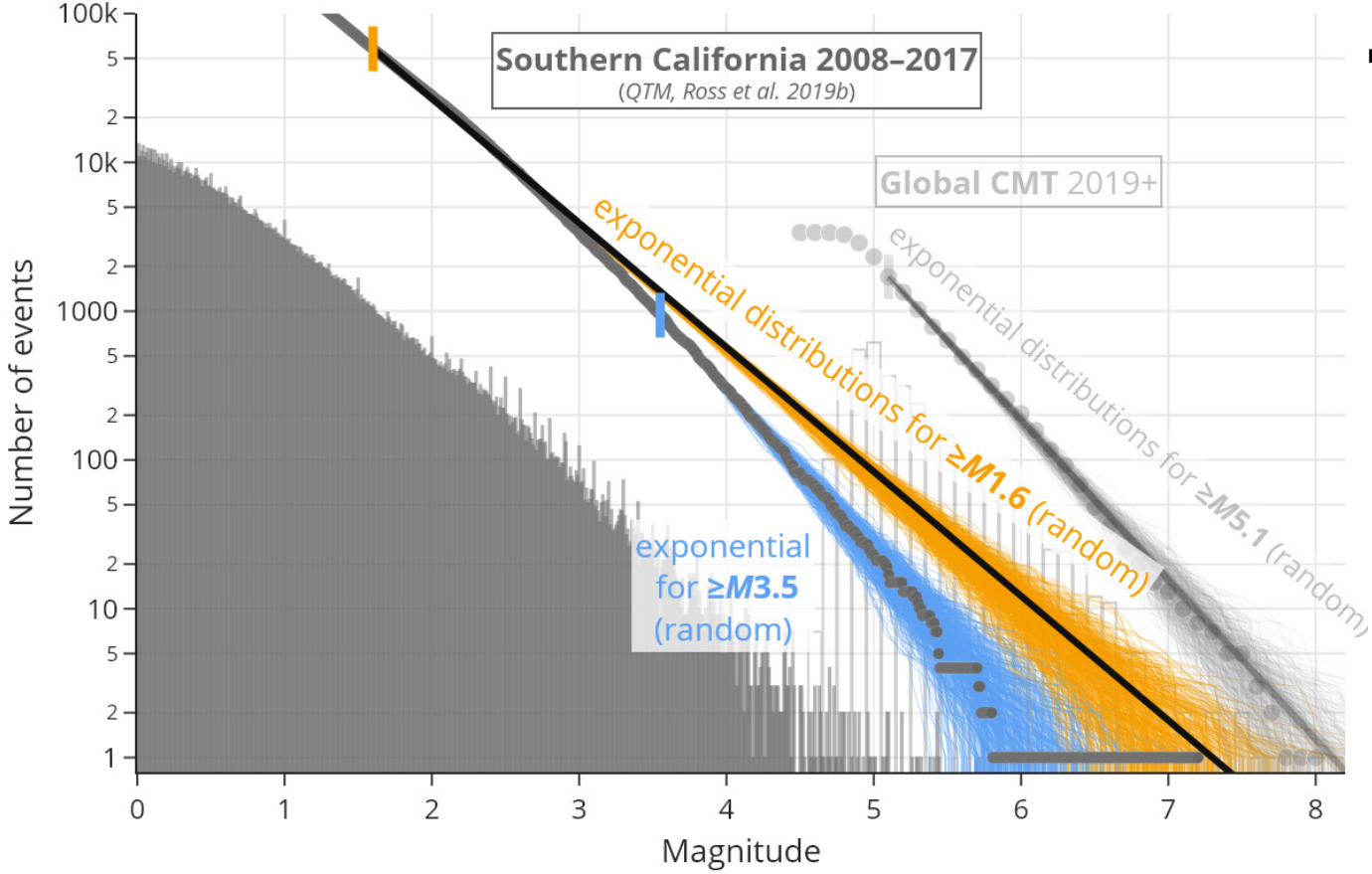

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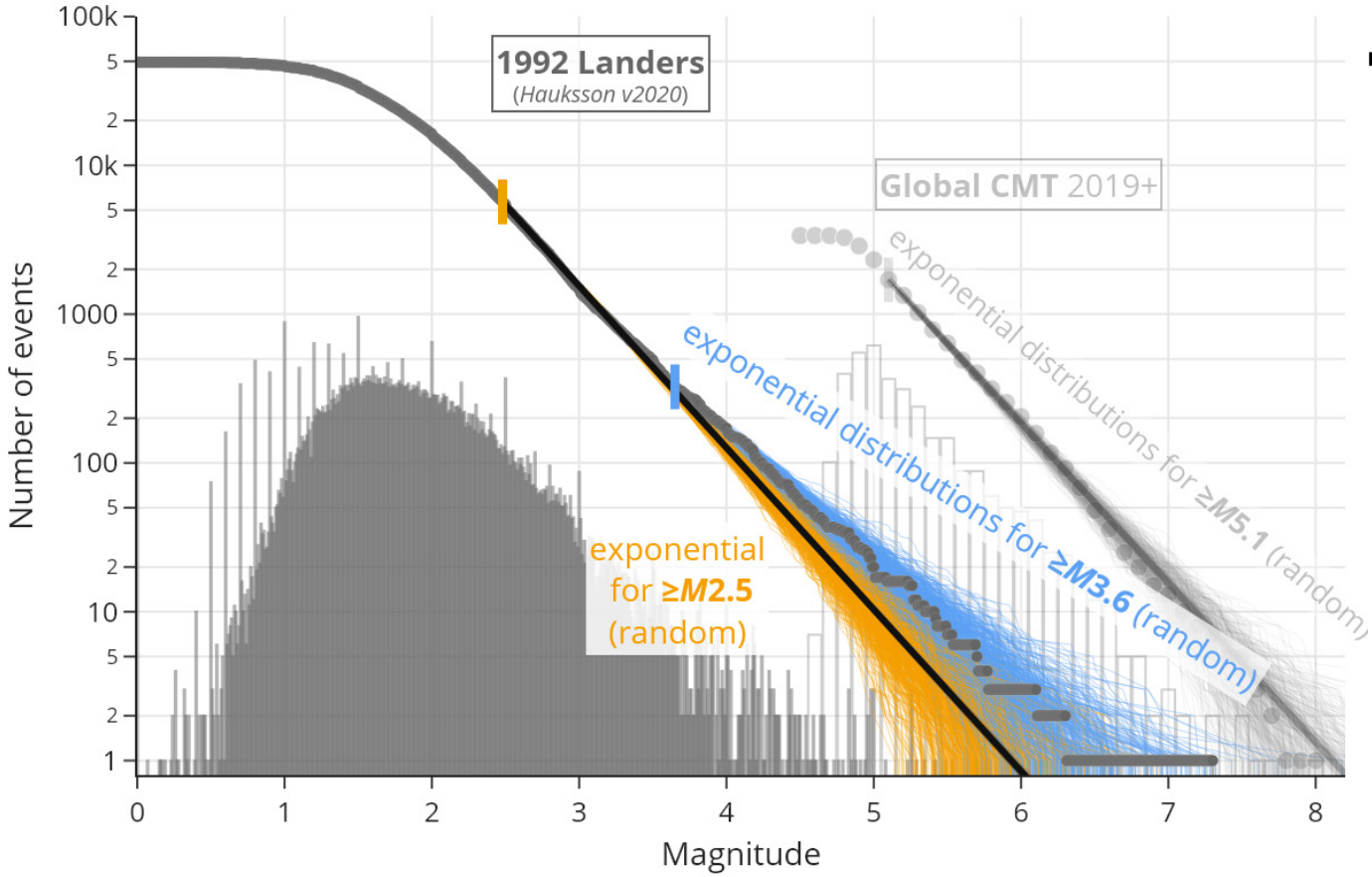

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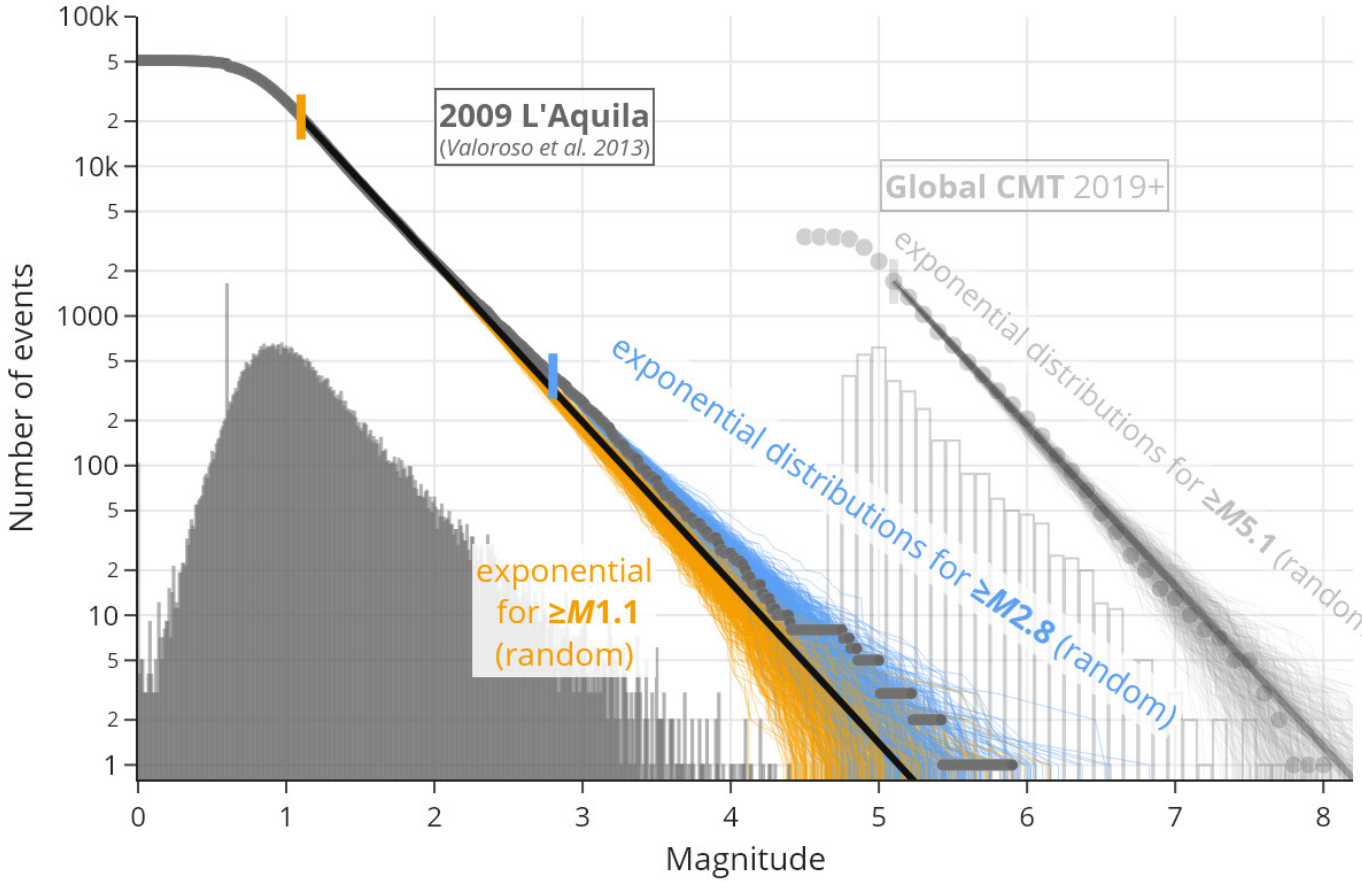

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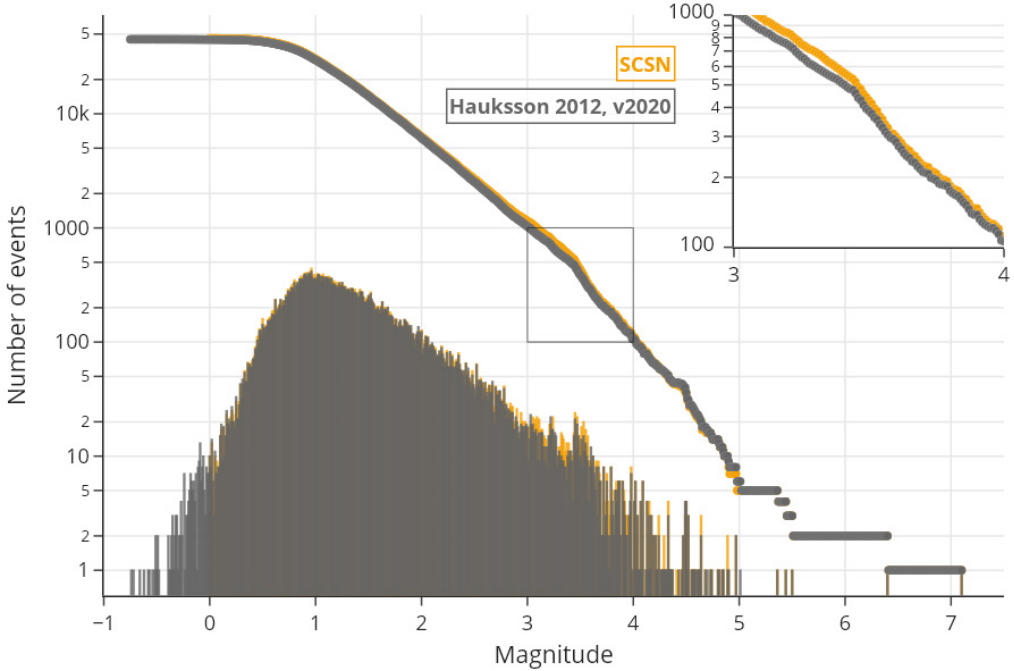
→ The MFD of high-res catalogs is usually **not consistent**

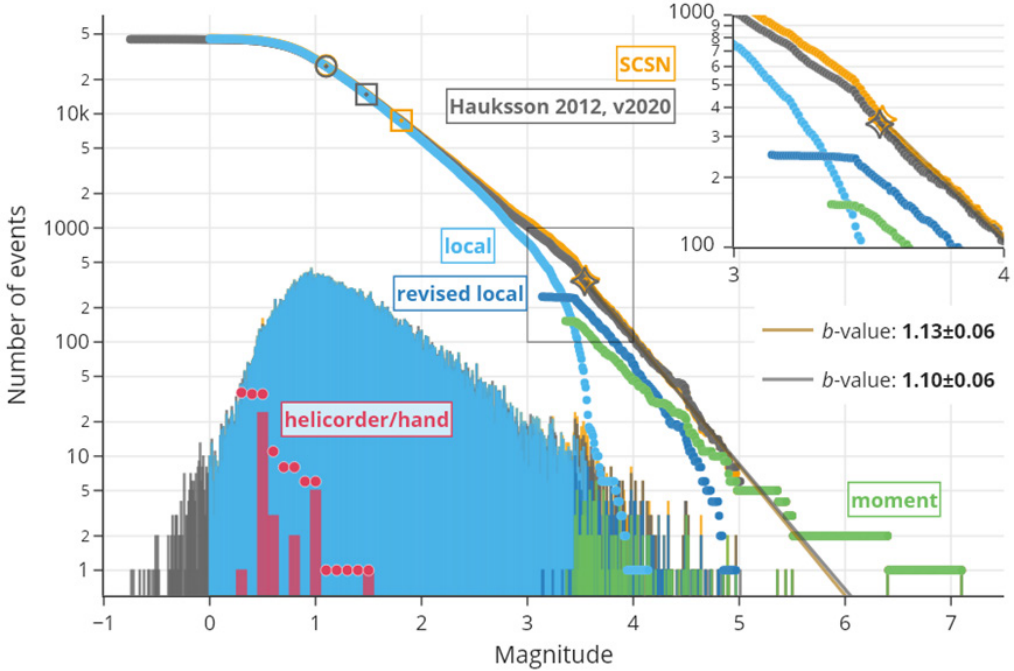
3 kinds of MFD inconsistencies



1. discontinuities
due to
merging different magnitude types

[Herrmann & Marzocchi 2020]

3 kinds of MFD inconsistencies



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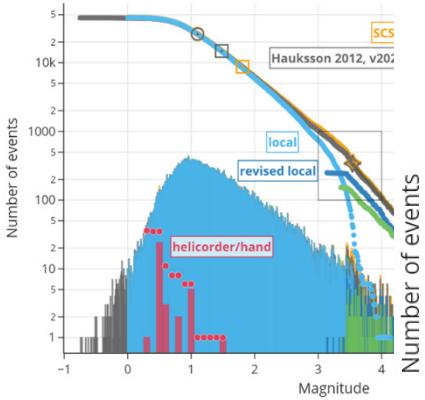

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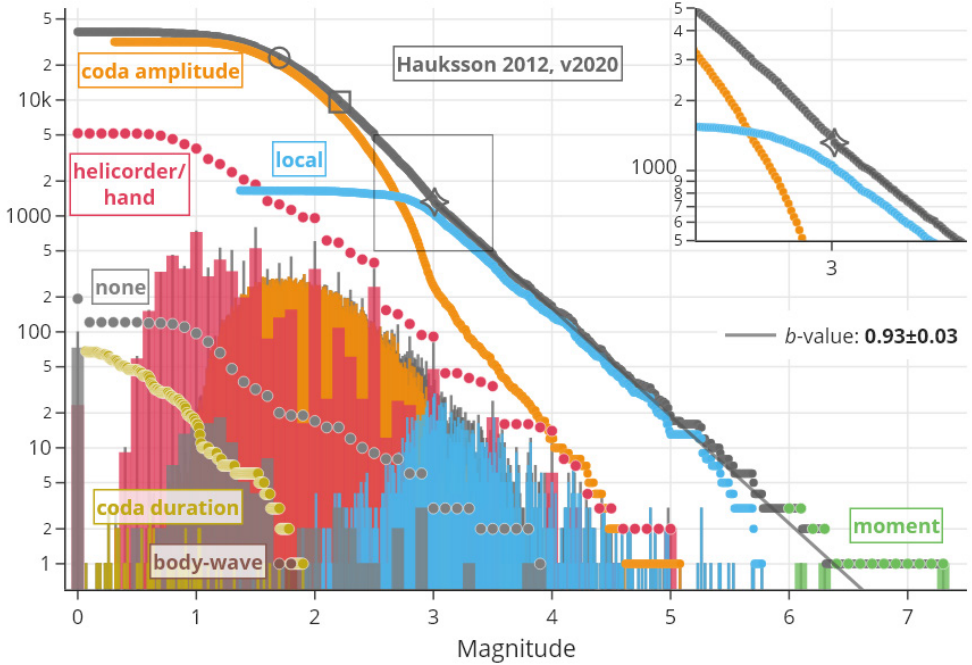

2. over-representation
due to
data recording /
processing issues

[Herrmann & Marzocchi 2020]

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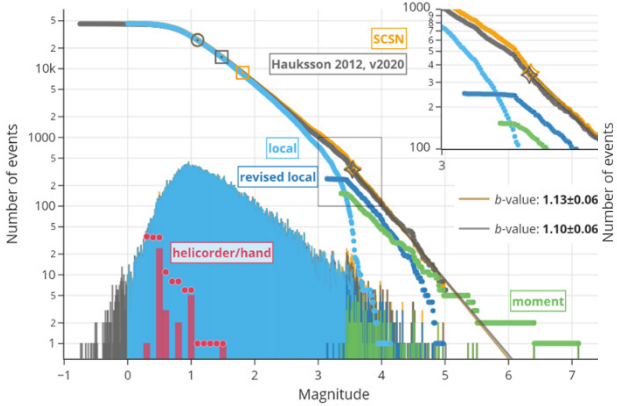

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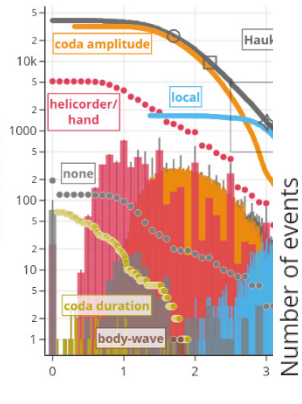

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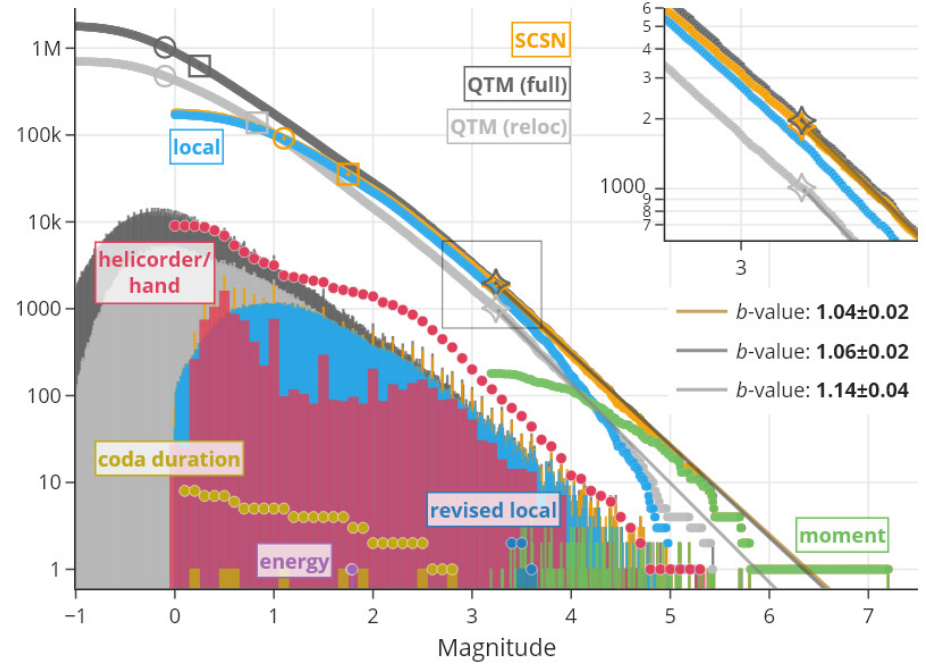

3. under-representation
due to
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& scaling break(s)

[Herrmann & Marzocchi 2020]

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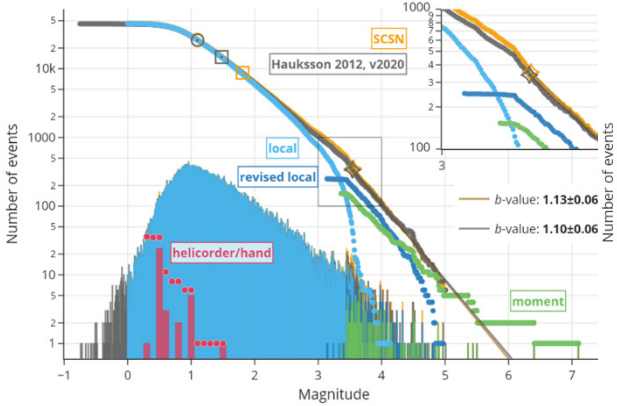

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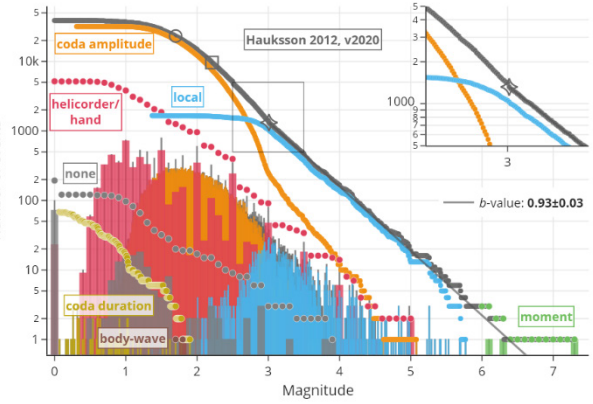

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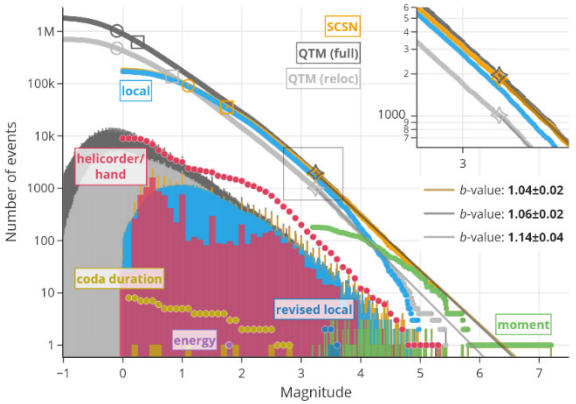

3. under-representation
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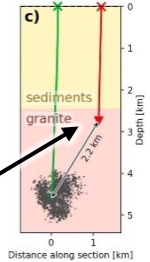
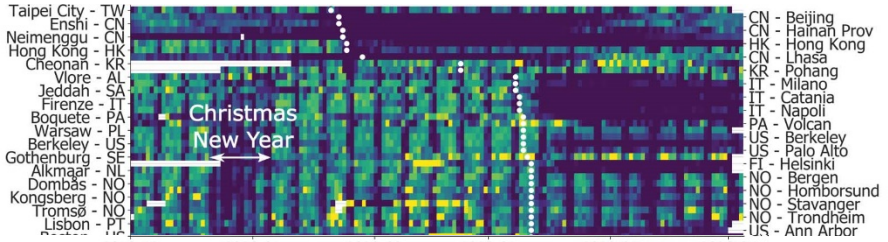
- MFD has to be analyzed carefully (doesn't agree with Gutenberg–Richter)
  (e.g., with a completeness magnitude that recognizes departures from an exponential distribution)

→ need a consistent magnitude scale (moment magnitude M_w)

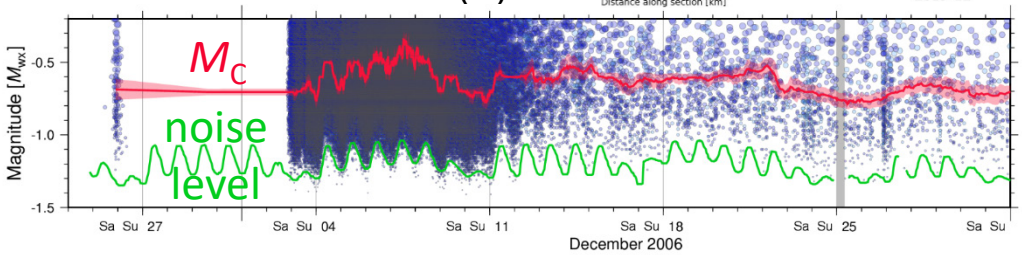
[Herrmann & Marzocchi 2020]

- Noise level
  - COVID-19 pandemic lockdowns: noise significantly anthropogenic
  - → borehole seismometers (?)





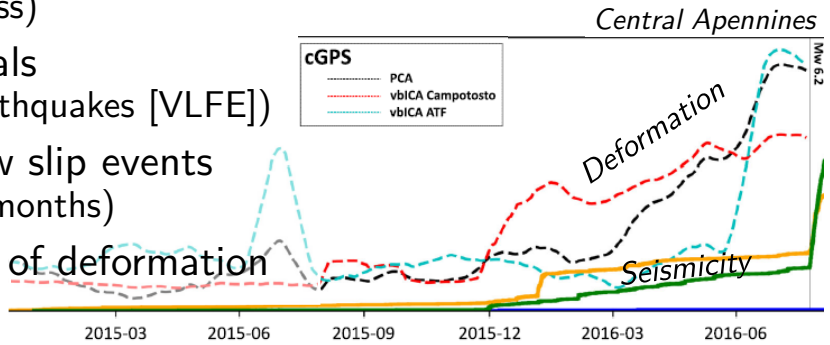
[Lecocq et al. 2020]



[Herrmann et al. 2019]

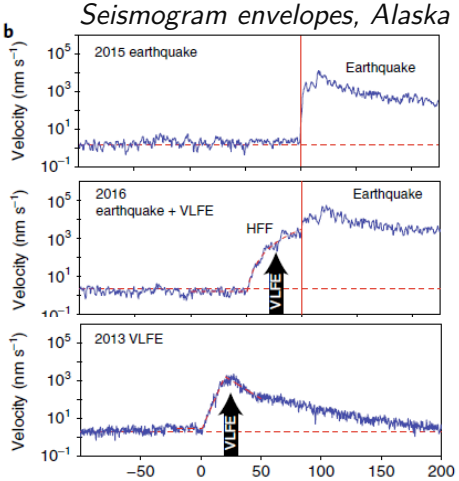
- What information do they not provide / is missing?
  (to study the earthquake process)
  - "Special" waveform signals
    (e.g., very low frequency earthquakes [VLFE])
  - Aseismic processes / slow slip events
    (release energy over weeks–months)

→ geodetic measurements of deformation
(strainmeter, GNSS, …)



[Vicic et al. 2020]

Seismogram envelopes, Alaska

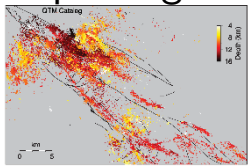


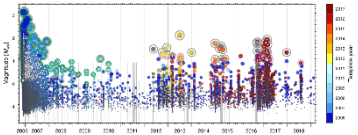
[Tape et al. 2018]

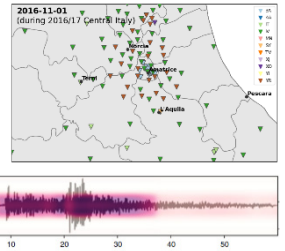
Conclusions

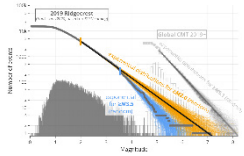
Summary

- Seismic monitoring is continuously improving
  (nowadays 'high resolution')
- Better representation of seismicity
- Range of new insights
  (reveal faults, their complexity & behavior, background activity, …)
- But:
  - Catalogs have their limits (inconsistent magnitudes, noise level)
  - & are not the only information source
    (details in ground motion records, geodetic measurements, …)









Outlook

- Multidisciplinary view – combine with other observations (geophysical, geochemical, geological, …)
  (e.g., near-fault observatories)
- Implement advanced knowledge in forecast models
  (and test & measure their significance)

Thanks for listening!