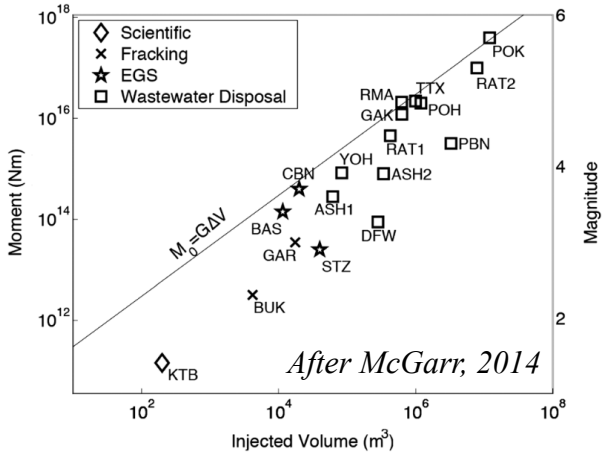
ETH zürich

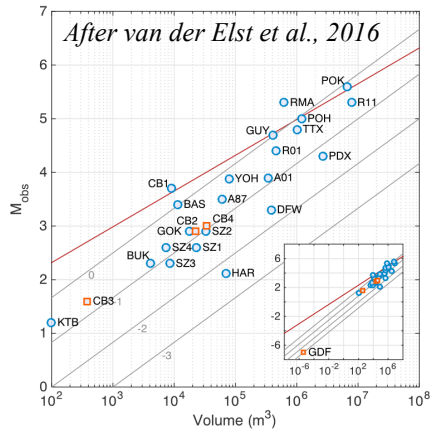
The bound growth of induced earthquakes could de-risk hydraulic fracturing

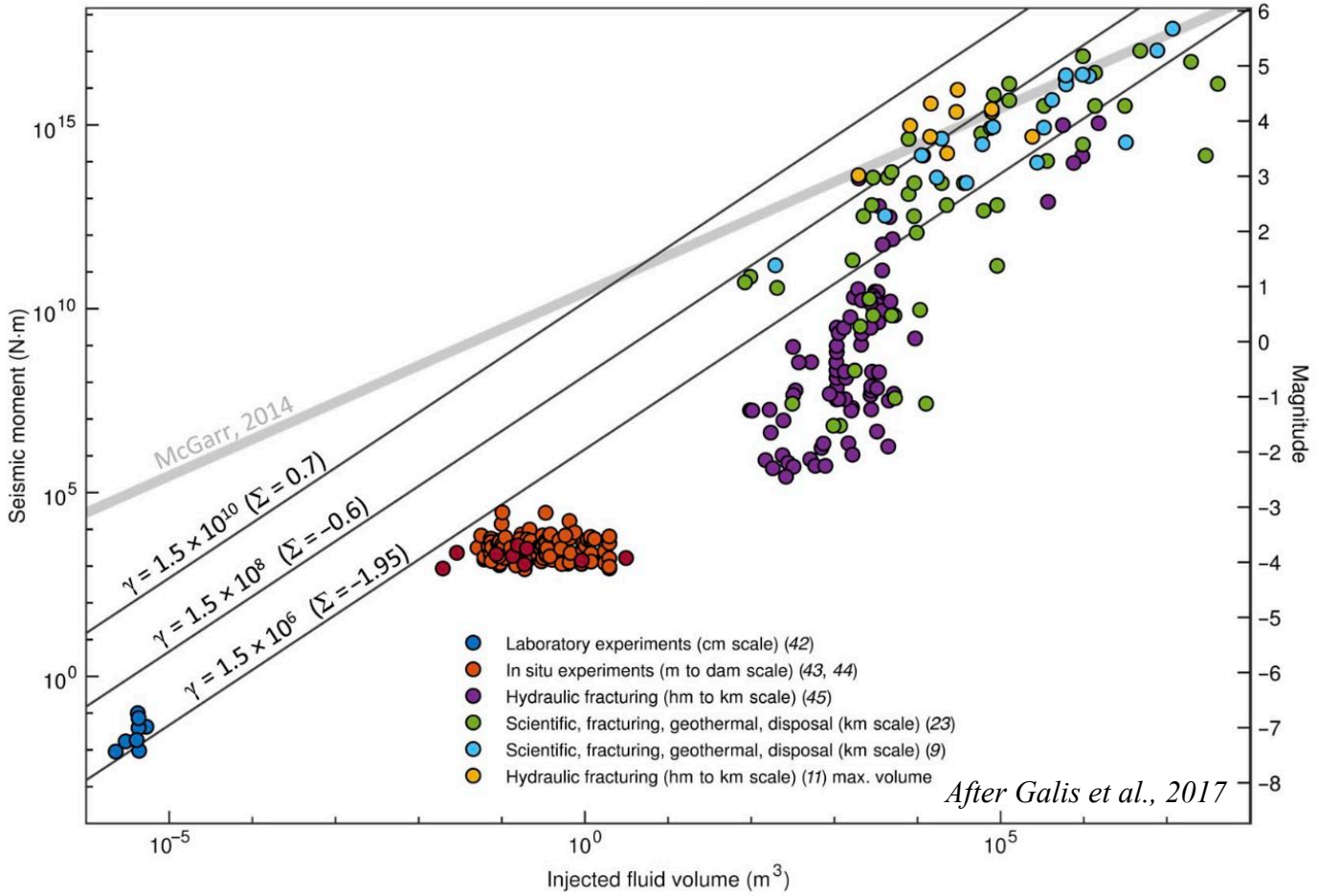
Ryan Schultz, Federica Lanza, Ben Dyer, Dimitrios Karvounis, Remi Fiori, Peidong Shi, Vanille Ritz, Linus Villiger, Peter Meier, & Stefan Wiemer

IS & M_{MAX}

- Multiple models of M_{MAX} vs V.
  - Evolution of moment release
  - Arrested rupture dynamics
  - Geometry of stress perturbation
  - *Tectonic fault size limitations*
- Attractive, impactful for mitigation.
- Similar response from statistics.
- Can these be falsified (or verified)?

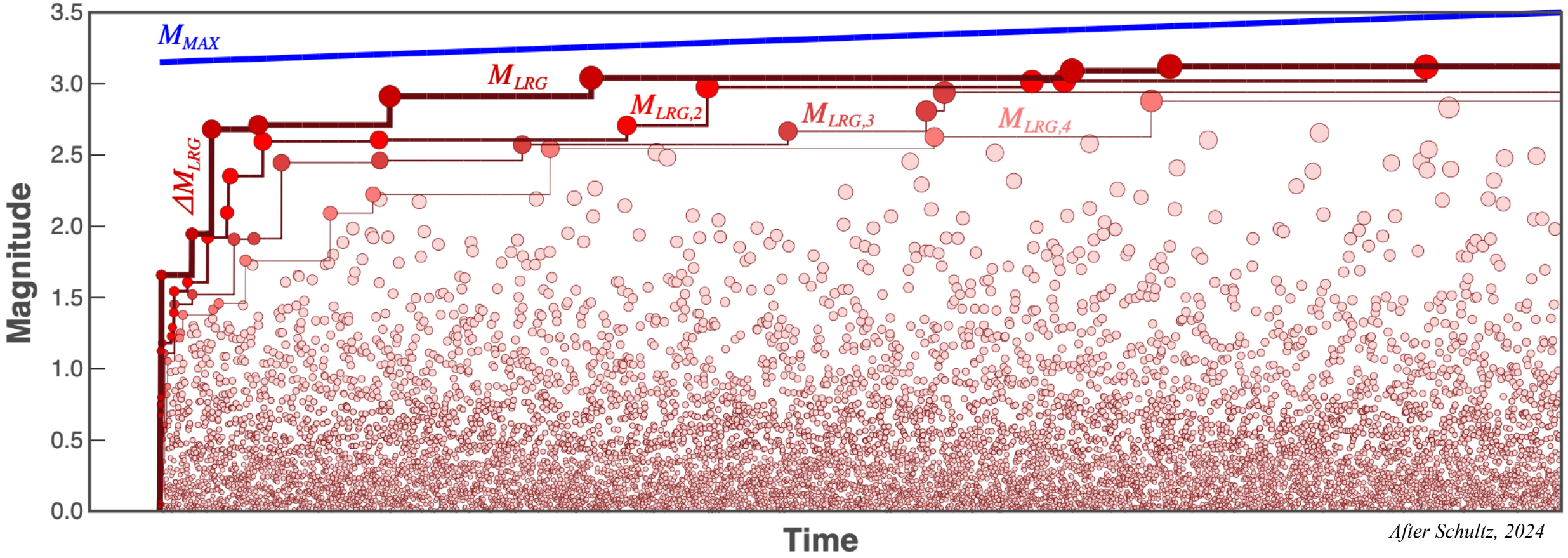






Definition of Catalogue Terms

- Draw from a (doubly truncated) GR-MFD.
- Catalogue M, ΔM, M_{LRG}, & ΔM_{LRG} (M_{MAX}).

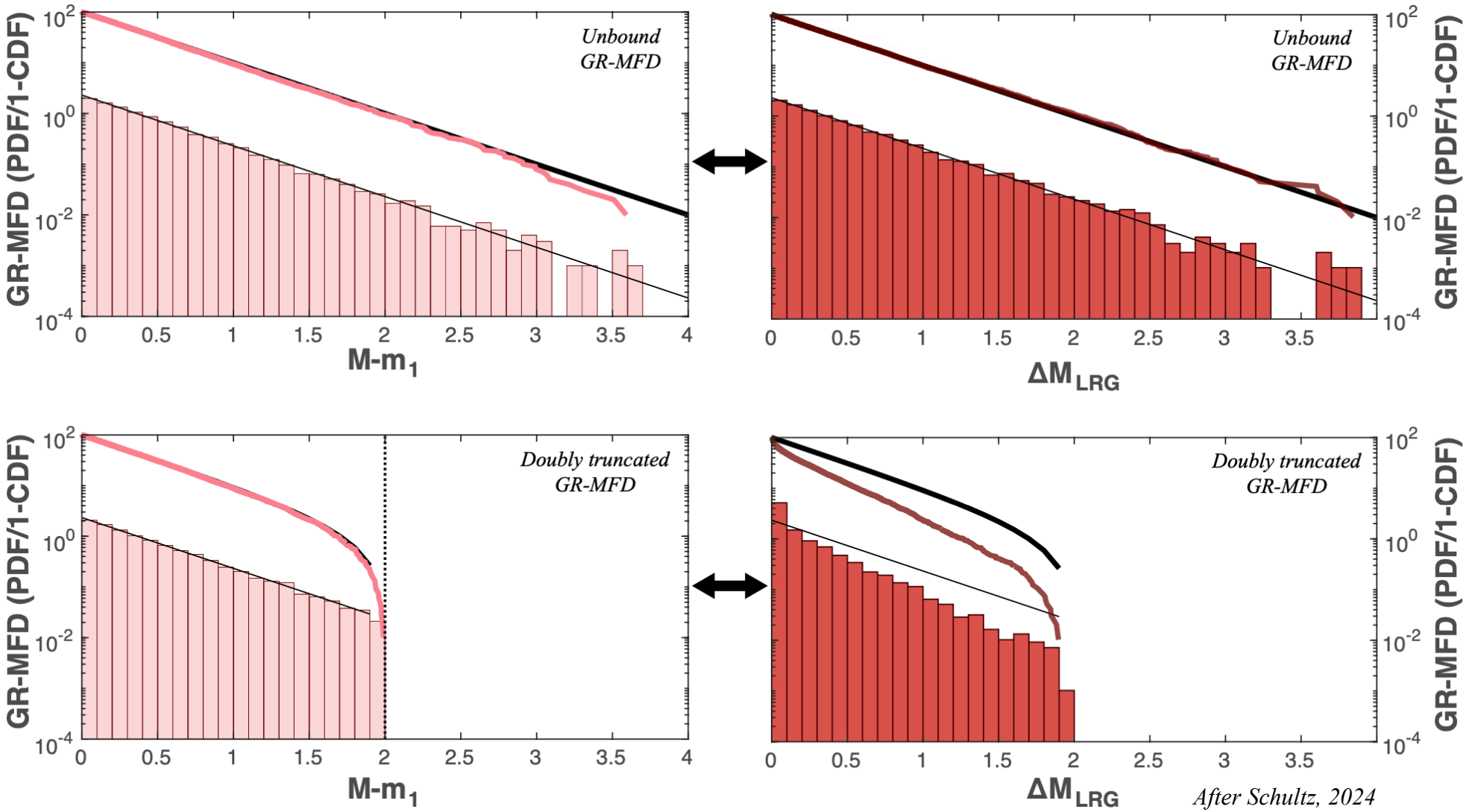


After Schultz, 2024

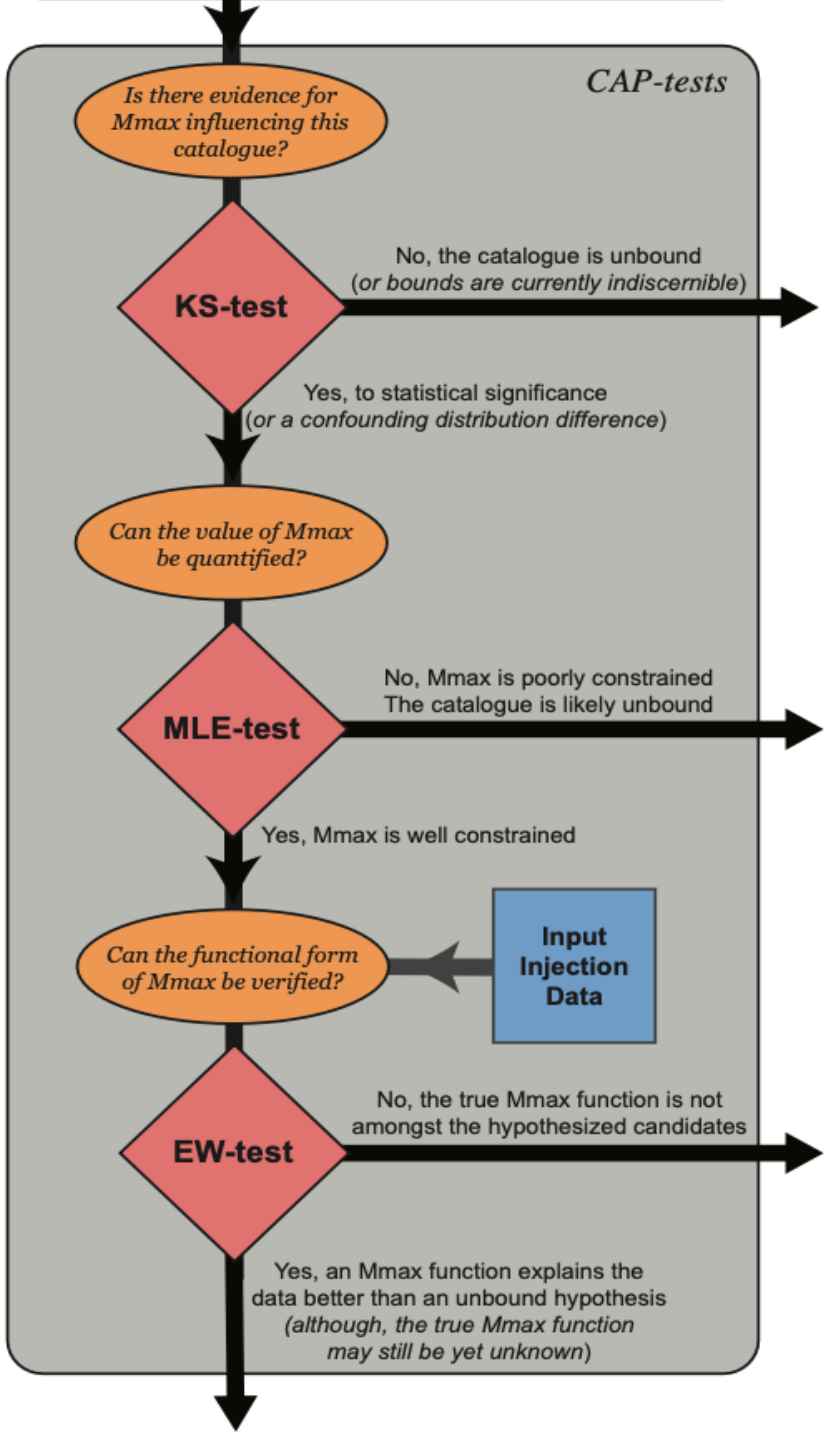
Key Insight!

- Catalogue.
- **Large event diffs.**
- ***GR-MFD PDF***
- **GR-MFD CDF**

- **Same when unbounded (b+).**
- **Different when doubly truncated.**

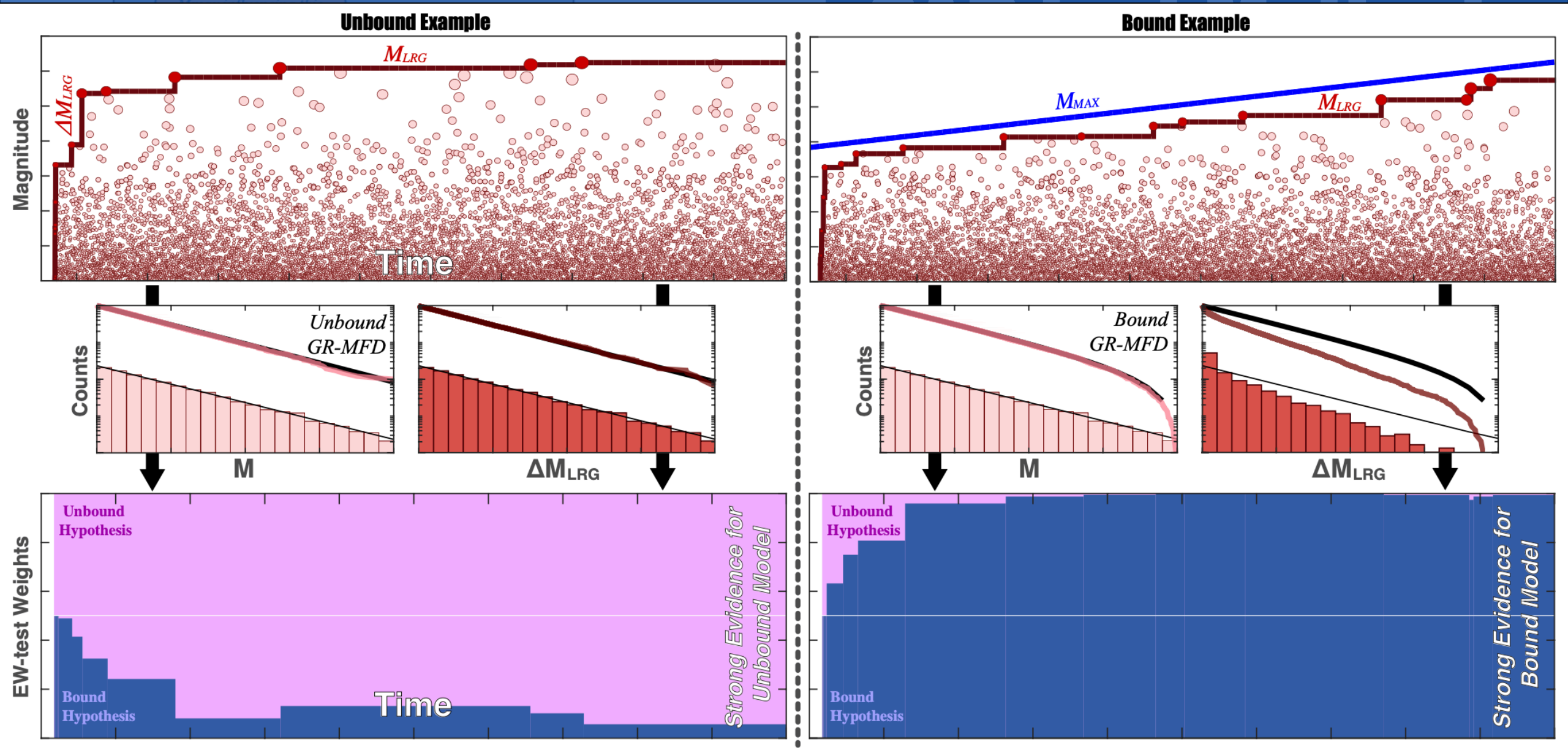


After Schultz, 2024



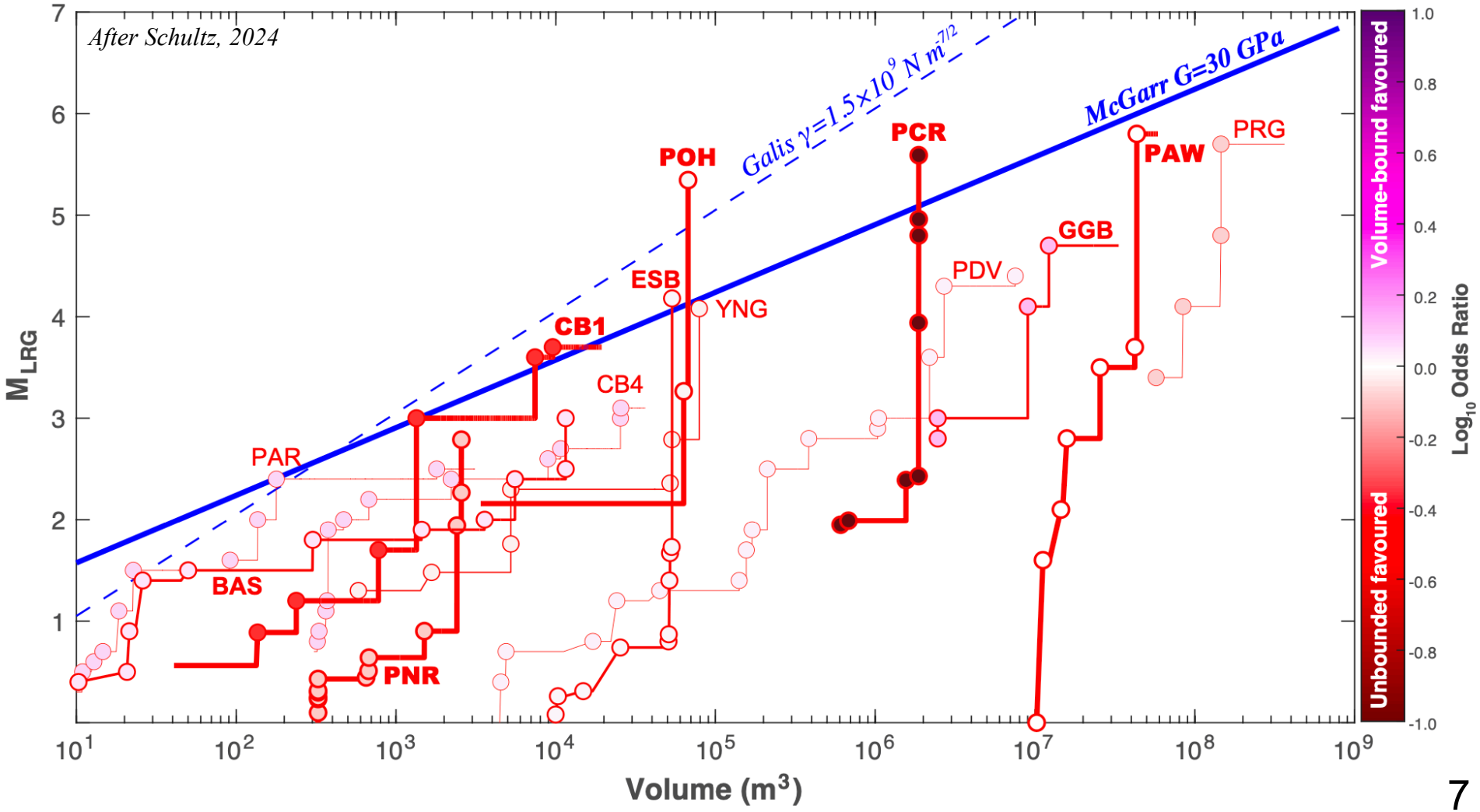
CAP-test Methods

- **Simple tests :**
  - **Visually examine GR-MFD.**
  - **Quantify expected-observed.**
- **CAP-tests**
  - **Hypothesis test for M_{MAX}.**
  - **MLE for M_{MAX}.**
  - **EW-test, select best M_{MAX} model.**
- ***Orders-of-magnitude more sensitive to M_{MAX} than traditional approaches.***
- ***Start testing on real data!***


Unbound Example
Bound Example
Magnitude
M_{LRG}
ΔM_{LRG}
Time
M_{MAX}
Counts
Unbound
GR-MFD
Bound
GR-MFD
M
ΔM_{LRG}
EW-test Weights
Unbound
Hypothesis
Bound
Hypothesis
Strong Evidence for
Unbound Model
Strong Evidence for
Bound Model

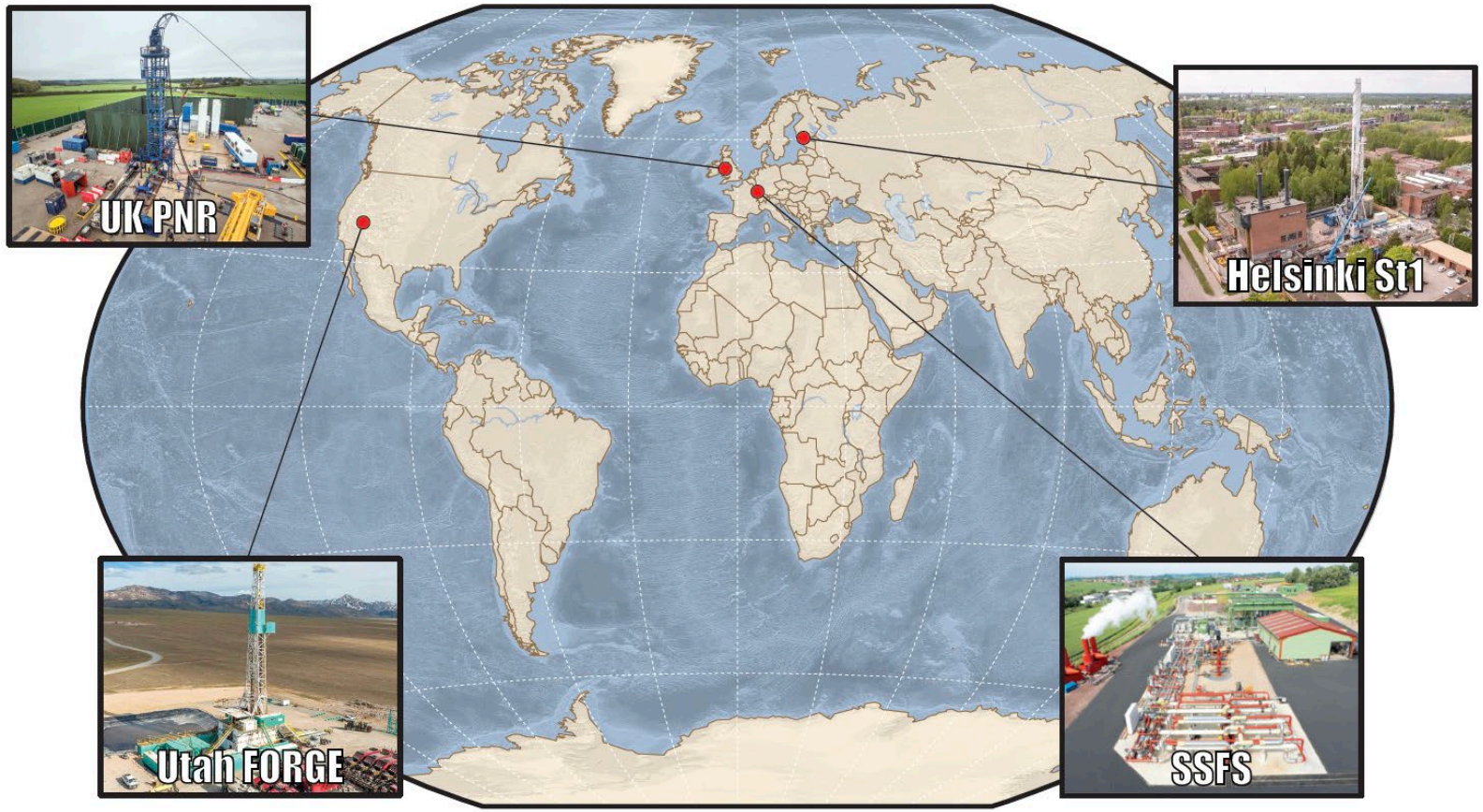
Refuted $M_{MAX}(V)$ for Large Cases

- **CAP-tests applied to all cases near the McGarr limit.**
- ***No M_{MAX} evidence, from any tests.***
- ***3 Cases of unbound.***
- ***Continue looking...***



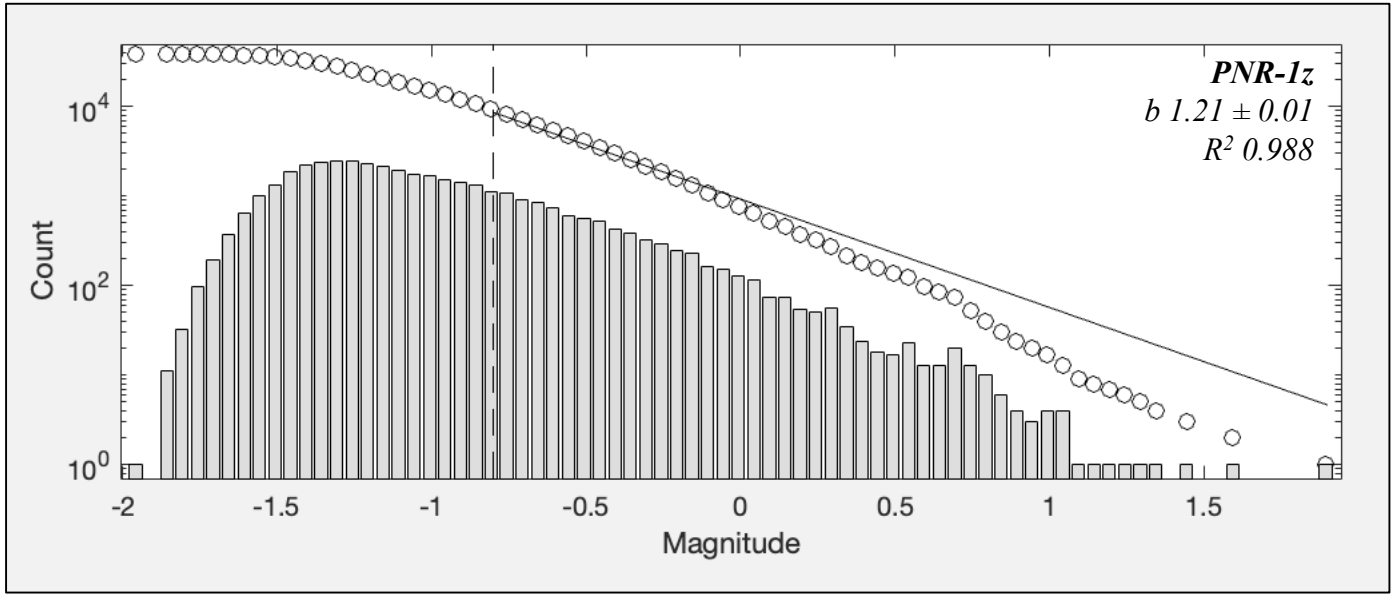
EGS & HF Cases

- Apply CAP-tests to real data.
- Consider cases which are well documented, both for large catalogues and hydraulic information.
  - *FORGE, Helsinki St1, SSFS*
  - *PNR-2, PRN-1z*



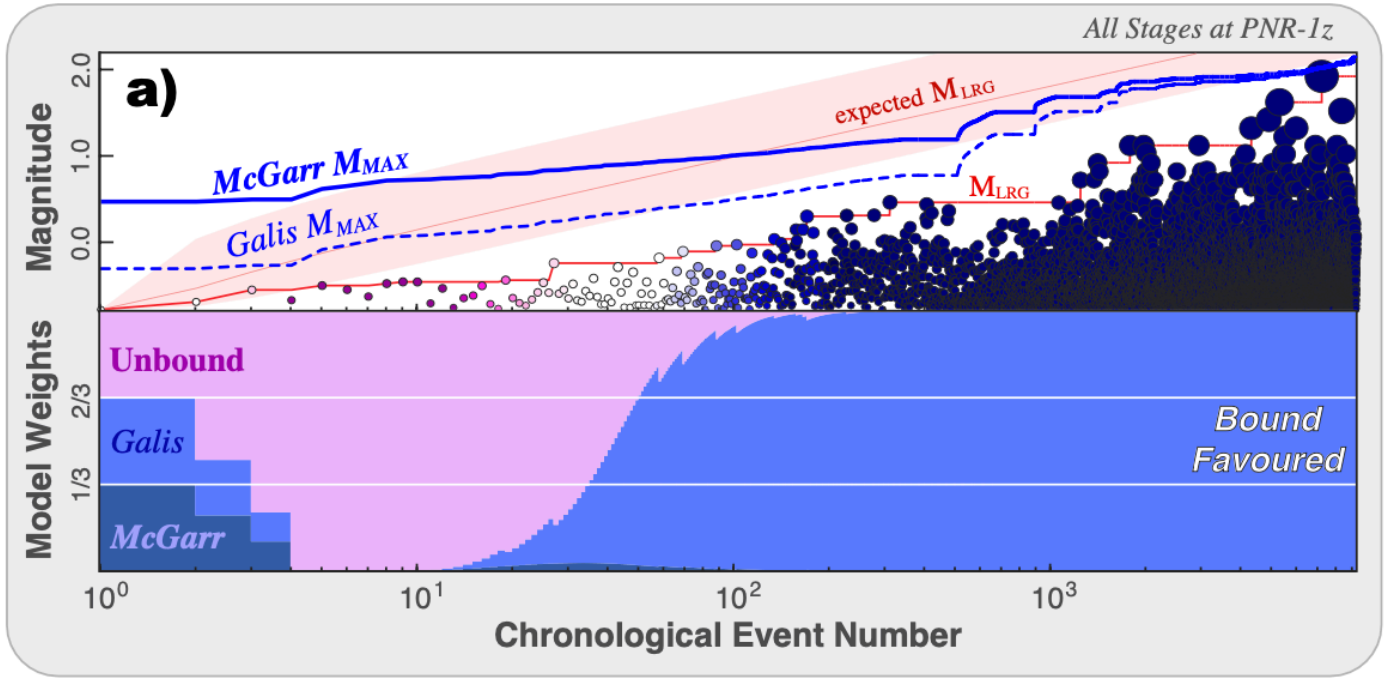
CAP at PNR-1z

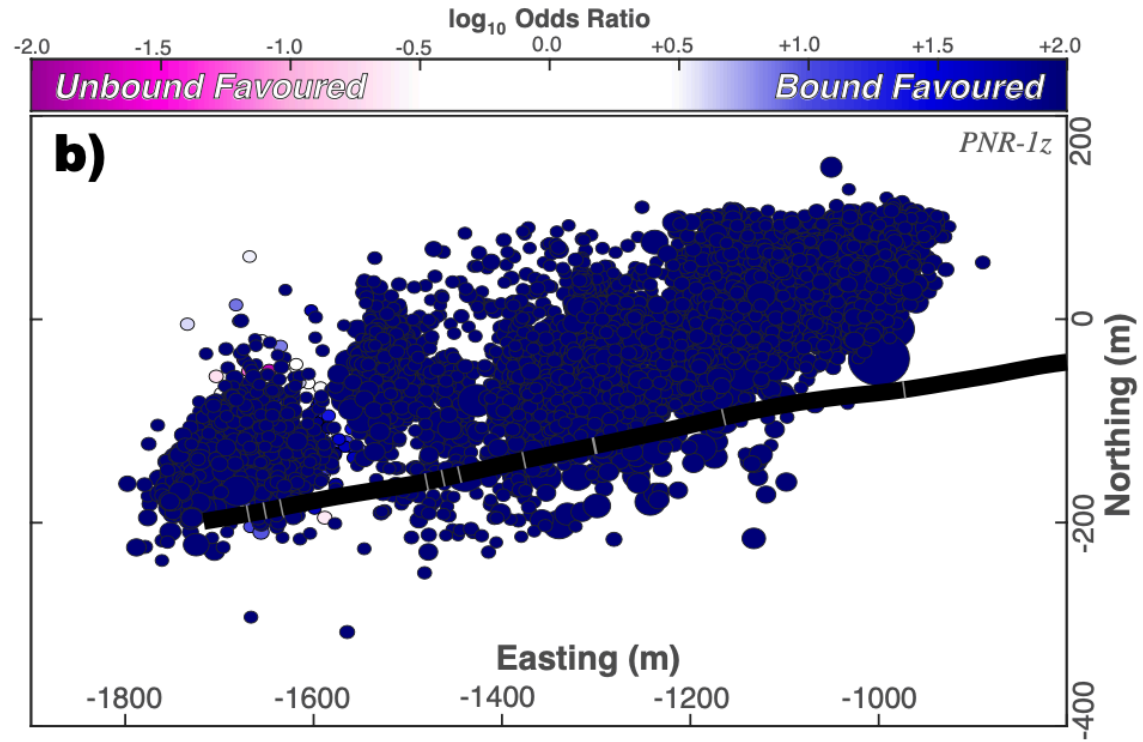
- Handle entire sequence as single, connected cluster.
- Serious evidence for bound M_{MAX}.
  - Deficient in large events.
  - 99.86% confident via KS-test.
  - Small error (<0.01) via MLE-test.
  - >100x odds ratio via EW-test.
- Earthquakes were managed (M_L 1.6).



Case		Simple tests		CAP-tests			
Location	Cluster	*b*-value	δM_{LRG}	KS-test	MLE-test	EW-test	M_{MAX} model
PNR-1z	*All*	1.21±0.05	-0.57	99.86%	<0.01	>100	Galis

CAP at PNR-1z



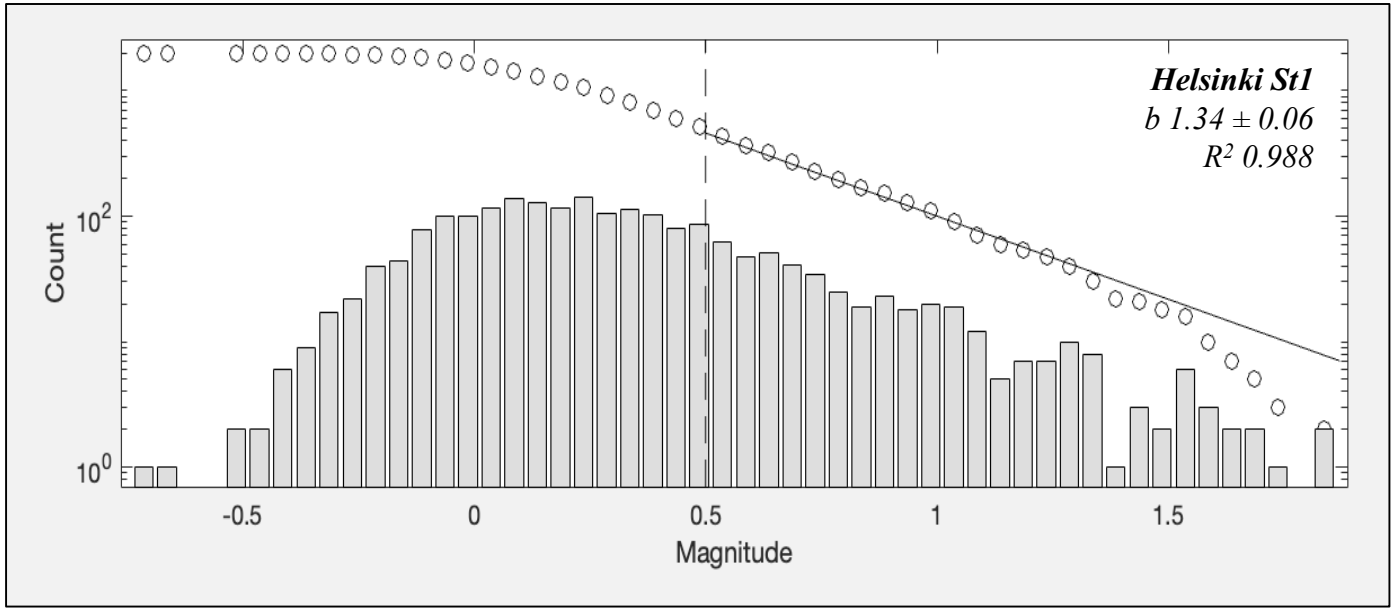


PNR-1z	*All*	1.21±0.05	-0.57	99.86%	<0.01	>100	Galis

- >100x odds ratio via EW-test.
- Earthquakes were managed (M_L 1.6).

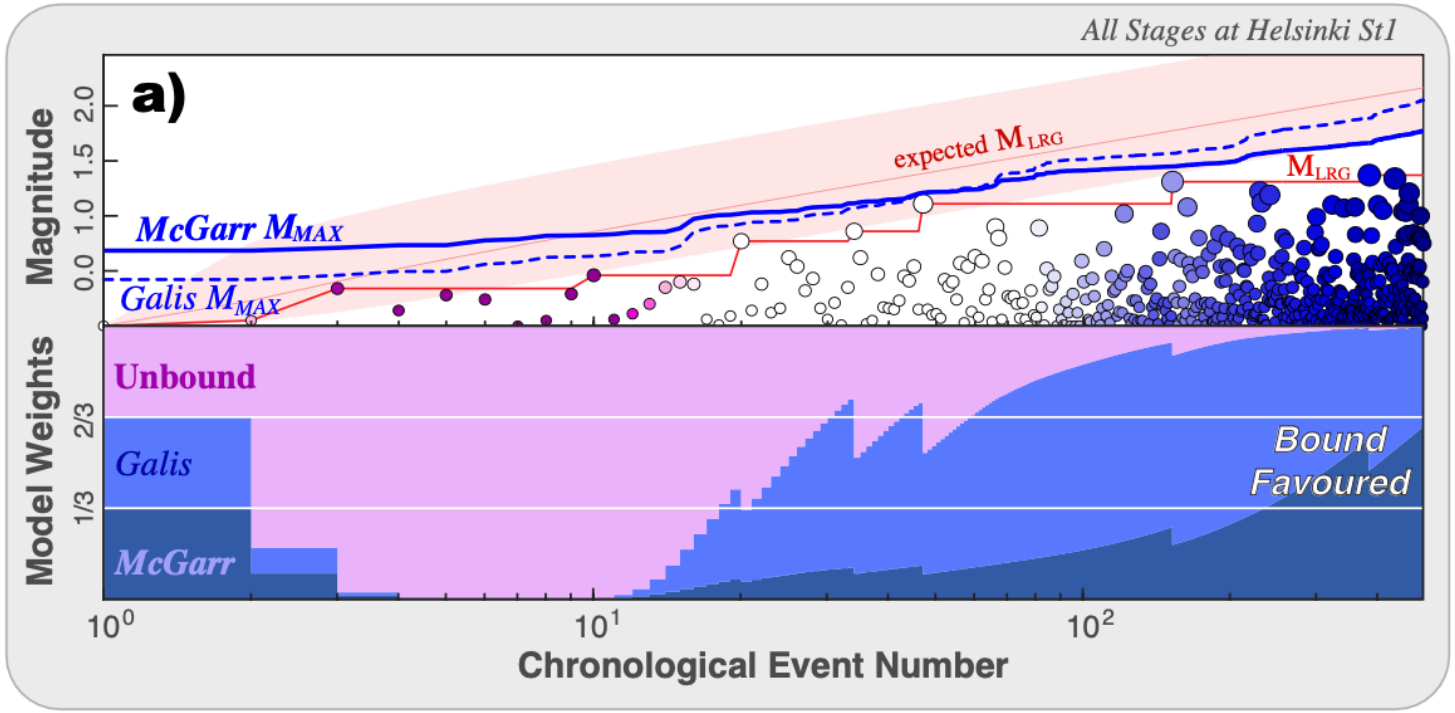
CAP at St1 (2019)

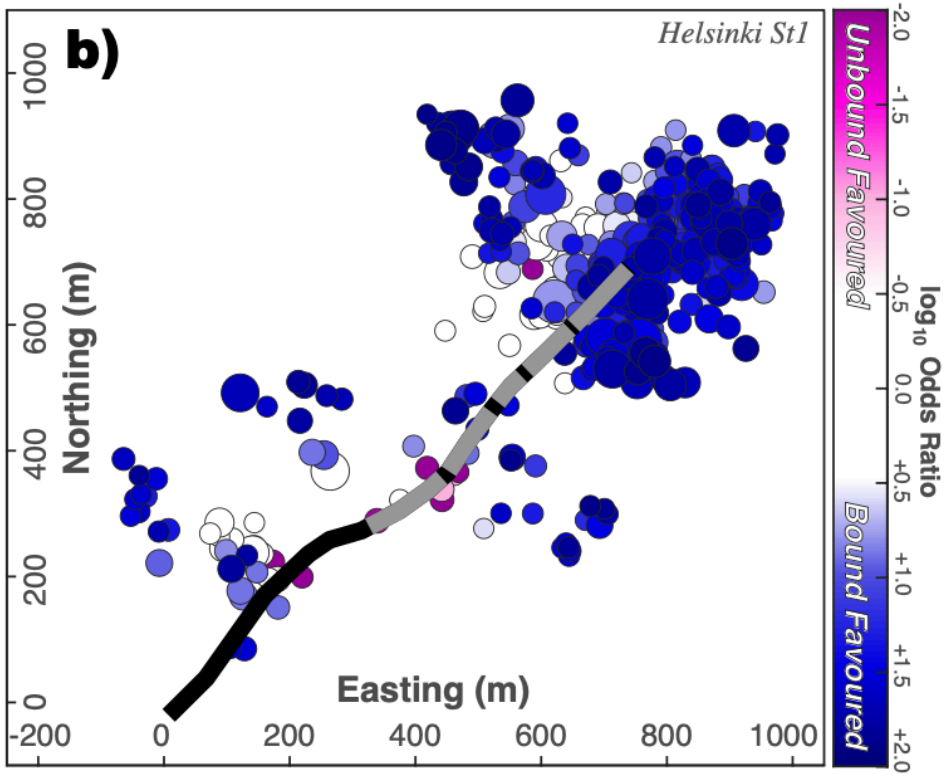
- Handle entire sequence as single, connected cluster.
- Serious evidence for bound M_{MAX}.
  - Deficient in large events.
  - 98.44% confident via KS-test.
  - Small error (0.02) via MLE-test.
  - 60x odds ratio via EW-test.
- Earthquakes were managed (M_W 1.9).



Case		Simple tests		CAP-tests			
Location	Cluster	*b*-value	δM_{LRG}	KS-test	MLE-test	EW-test	M_{MAX} model
St1	*All*	1.34±0.06	-0.67	98.44%	0.02	~60	McGarr/Galis

CAP at St1 (2019)

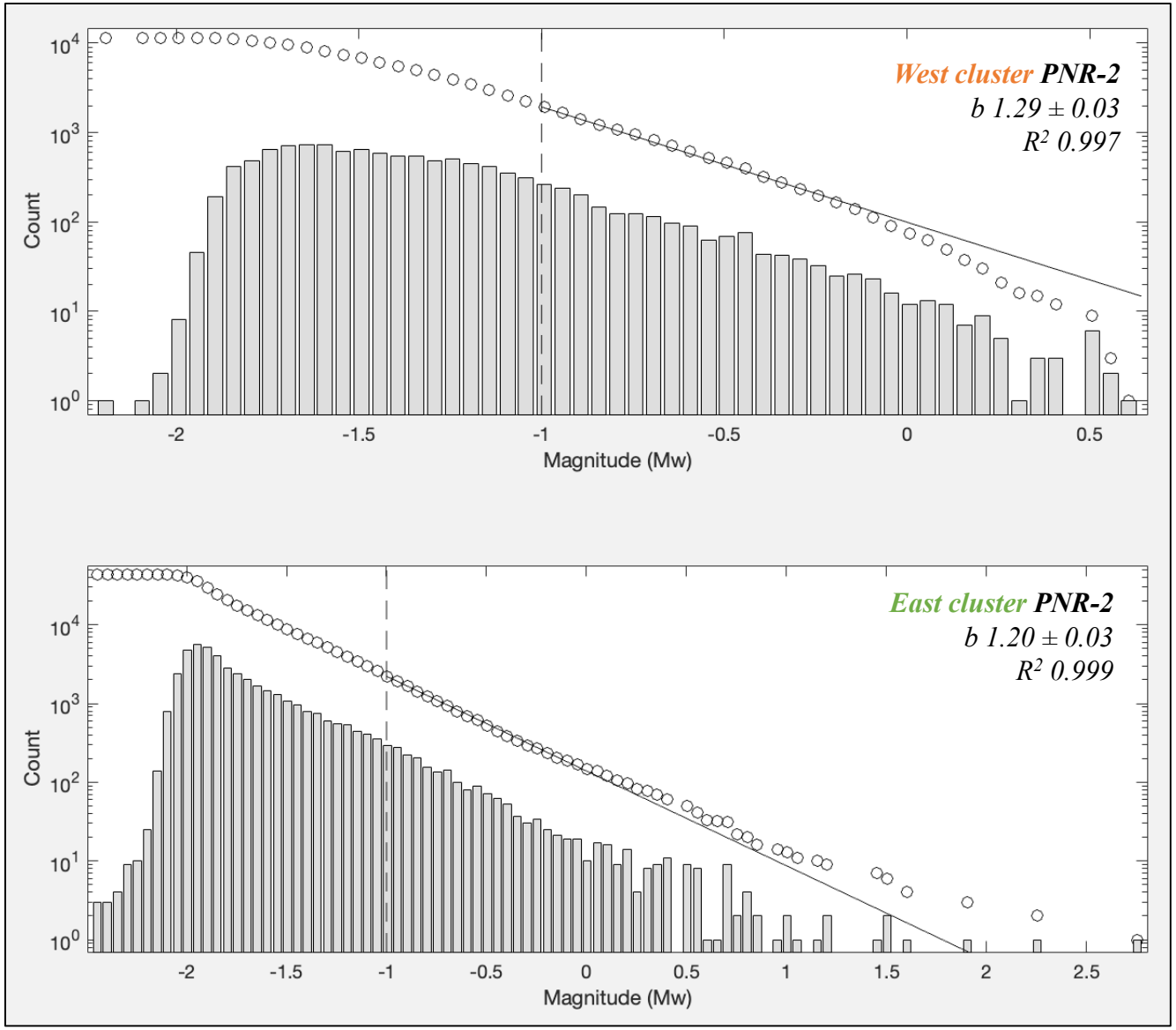




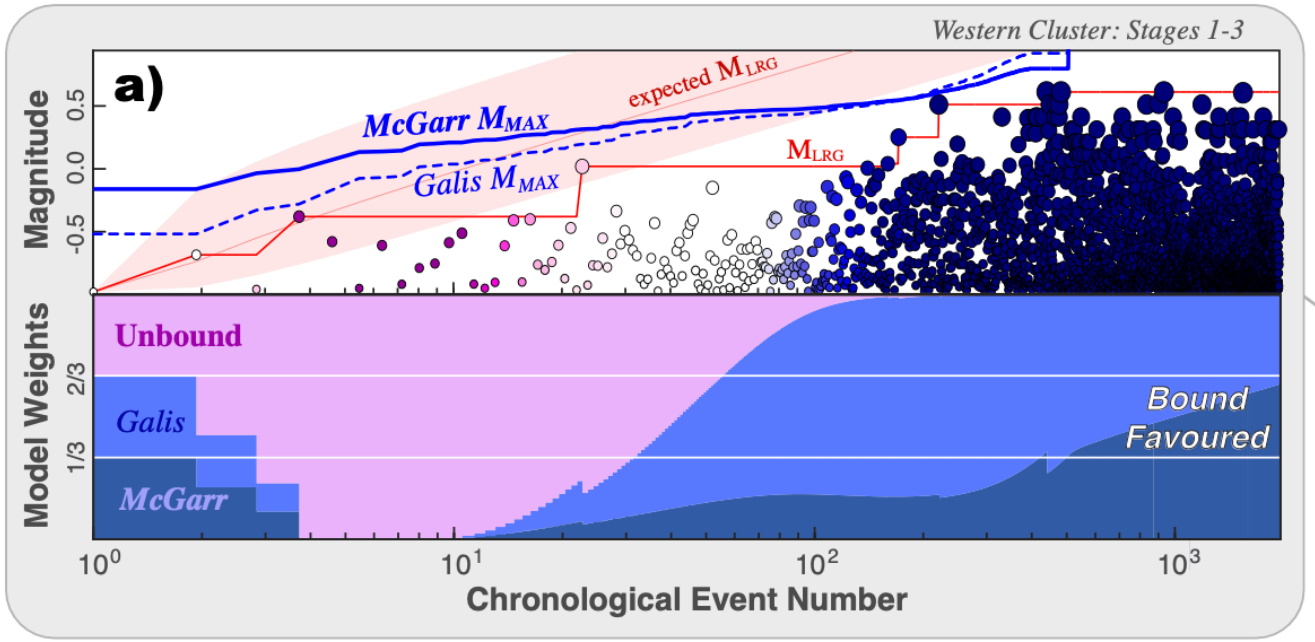
- Cox odds ratio via LW-test.
- Earthquakes were managed (M_w 1.9).

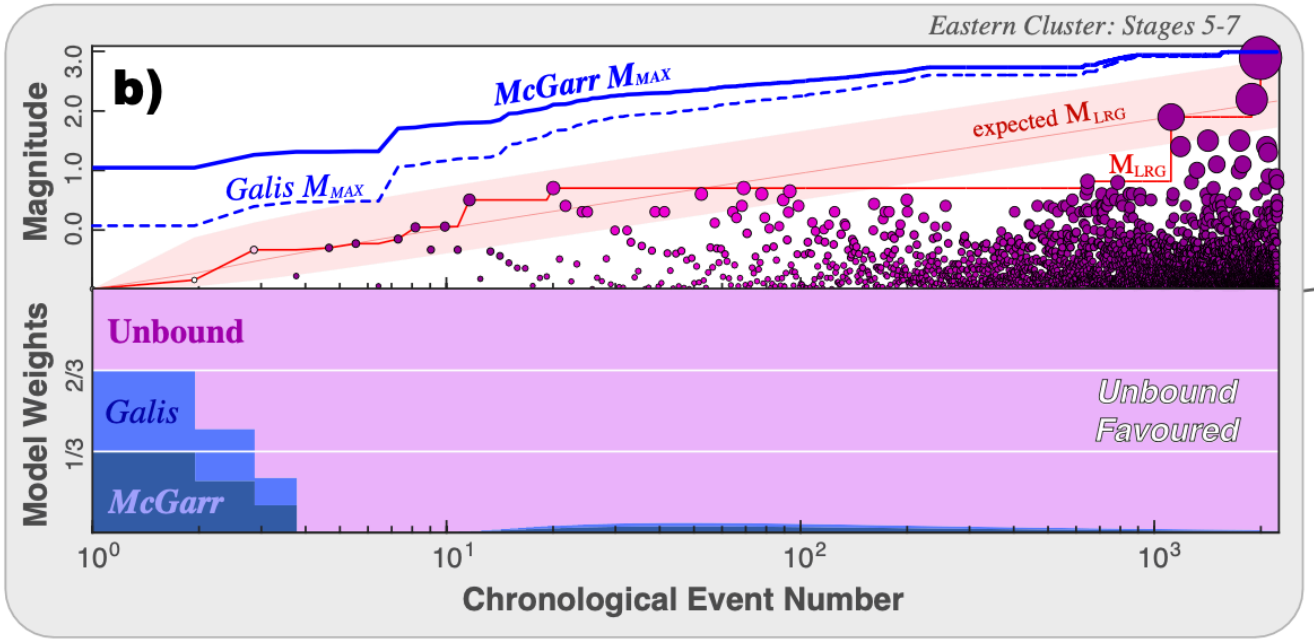
CAP at PNR-2

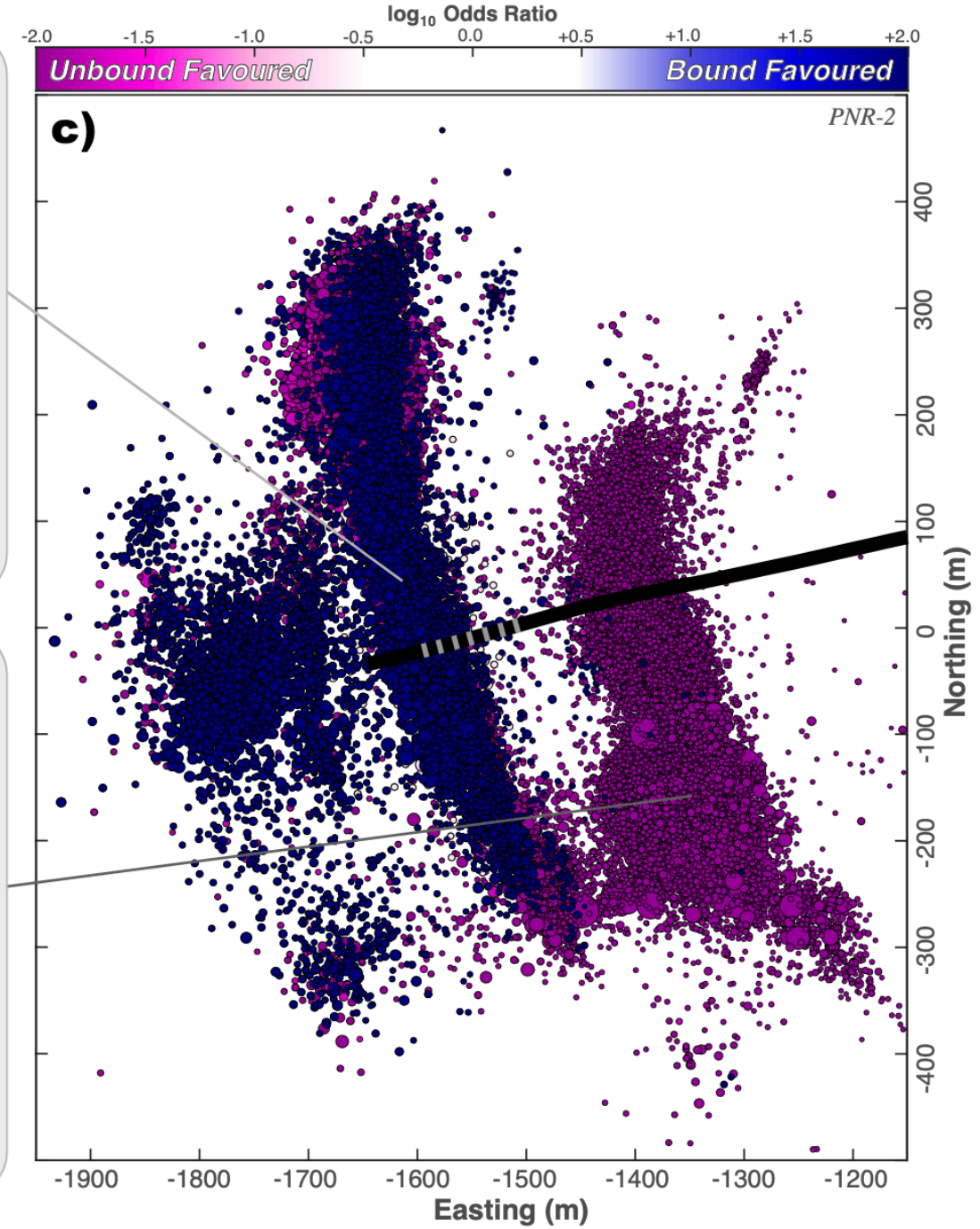
- Handle as two independent clusters (E & W), separated by stage 4.
- Bound M_{MAX} at W-cluster.
  - Deficient in large events.
  - >99.99% conf, <0.01 M, >100x b.
- Unbound M_{MAX} at E-cluster.
  - Overabundance of large events.
  - 33.7% conf, ~2.5 M, 0.01x b.
- E-clust caused moratorium (M_L 2.9).



Case		Simple tests		CAP-tests			
Location	Cluster	*b*-value	δM_{LRG}	KS-test	MLE-test	EW-test	M_{MAX} model
PNR-2	*West*	1.21±0.05	-1.24	>99.99%	<0.01	>100	McGarr/Galis
PNR-2	*East*	1.14±0.04	+0.84	33.7%	~2.50	0.01	Unbound

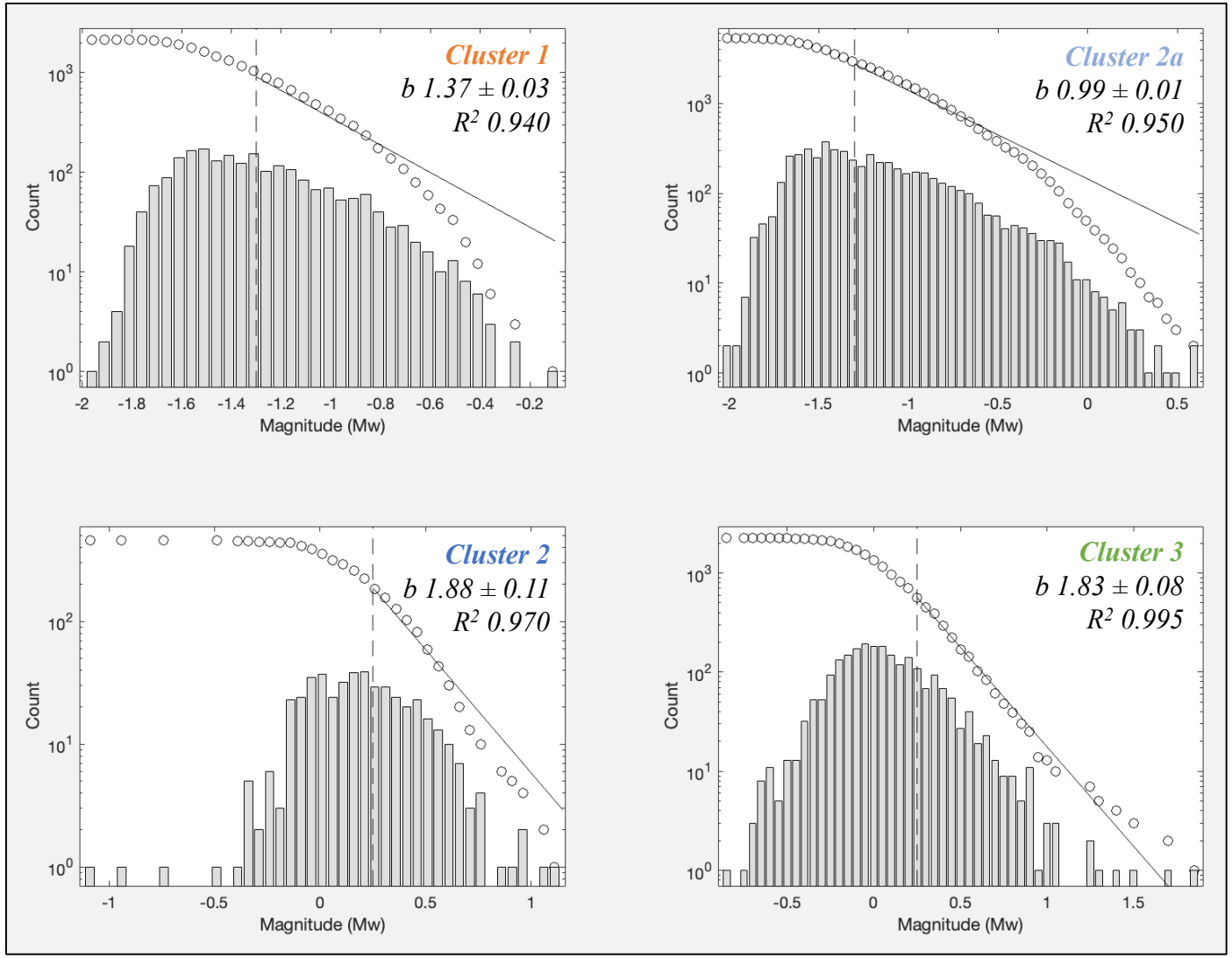

Western Cluster: Stages 1-3
a)
McGarr M_{MAX}
expected M_{LRG}
Galis M_{MAX}
M_{LRG}
Magnitude
0.5
0.0
-0.5
Unbound
Galis
McGarr
Bound Favoured
Model Weights
2/3
1/3
10^0
10^1
10^2
10^3
Chronological Event Number


Eastern Cluster: Stages 5-7
b)
McGarr M_{MAX}
Galis M_{MAX}
expected M_{LRG}
M_{LRG}
Magnitude
3.0
2.0
1.0
0.0
Unbound
Galis
McGarr
Unbound Favoured
Model Weights
2/3
1/3
10^0
10^1
10^2
10^3
Chronological Event Number

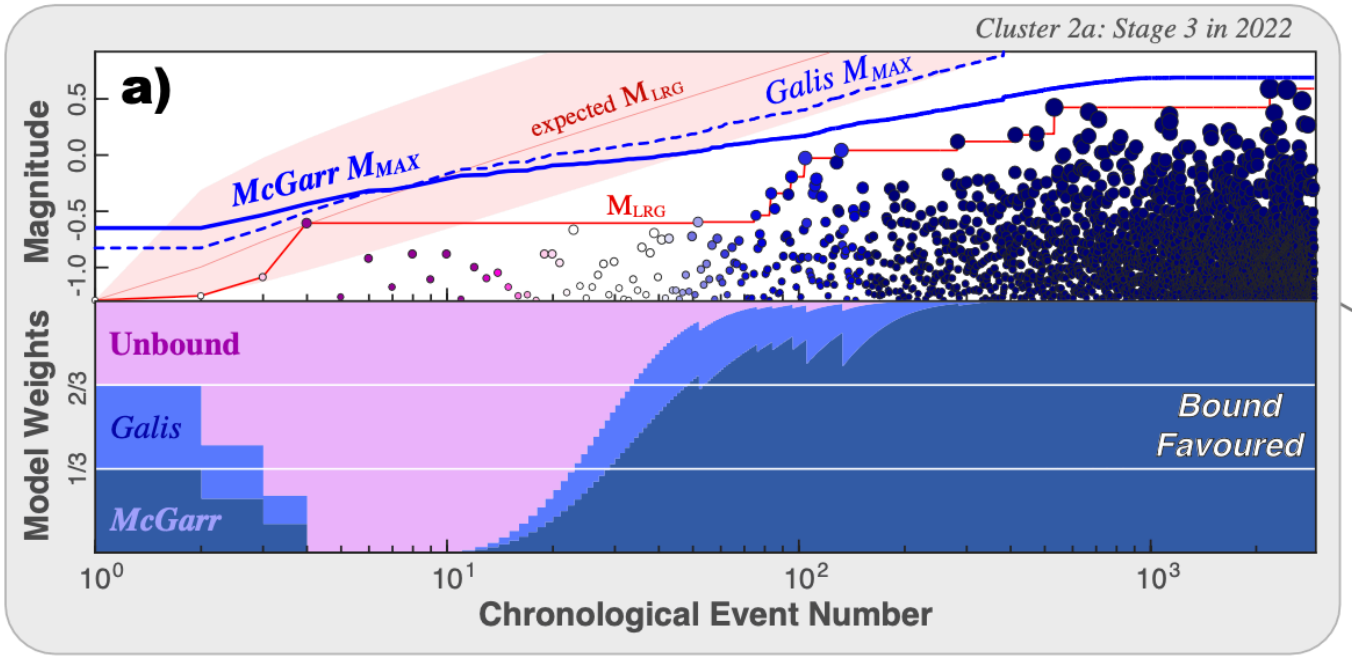

$\log_{10}$ Odds Ratio
-2.0
-1.5
-1.0
-0.5
0.0
+0.5
+1.0
+1.5
+2.0
Unbound Favoured
Bound Favoured
c)
PNR-2
400
300
200
100
0
-100
-200
-300
-400
Northing (m)
-1900
-1800
-1700
-1600
-1500
-1400
-1300
-1200
Easting (m)

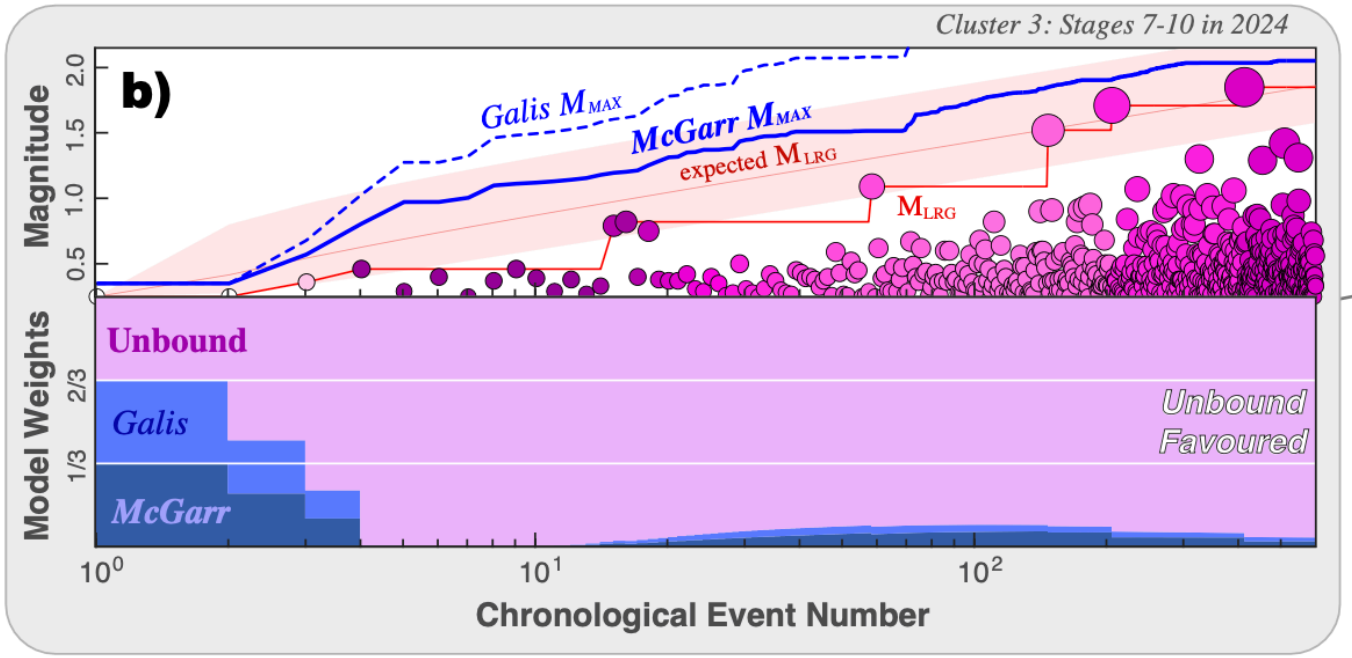
CAP at FORGE

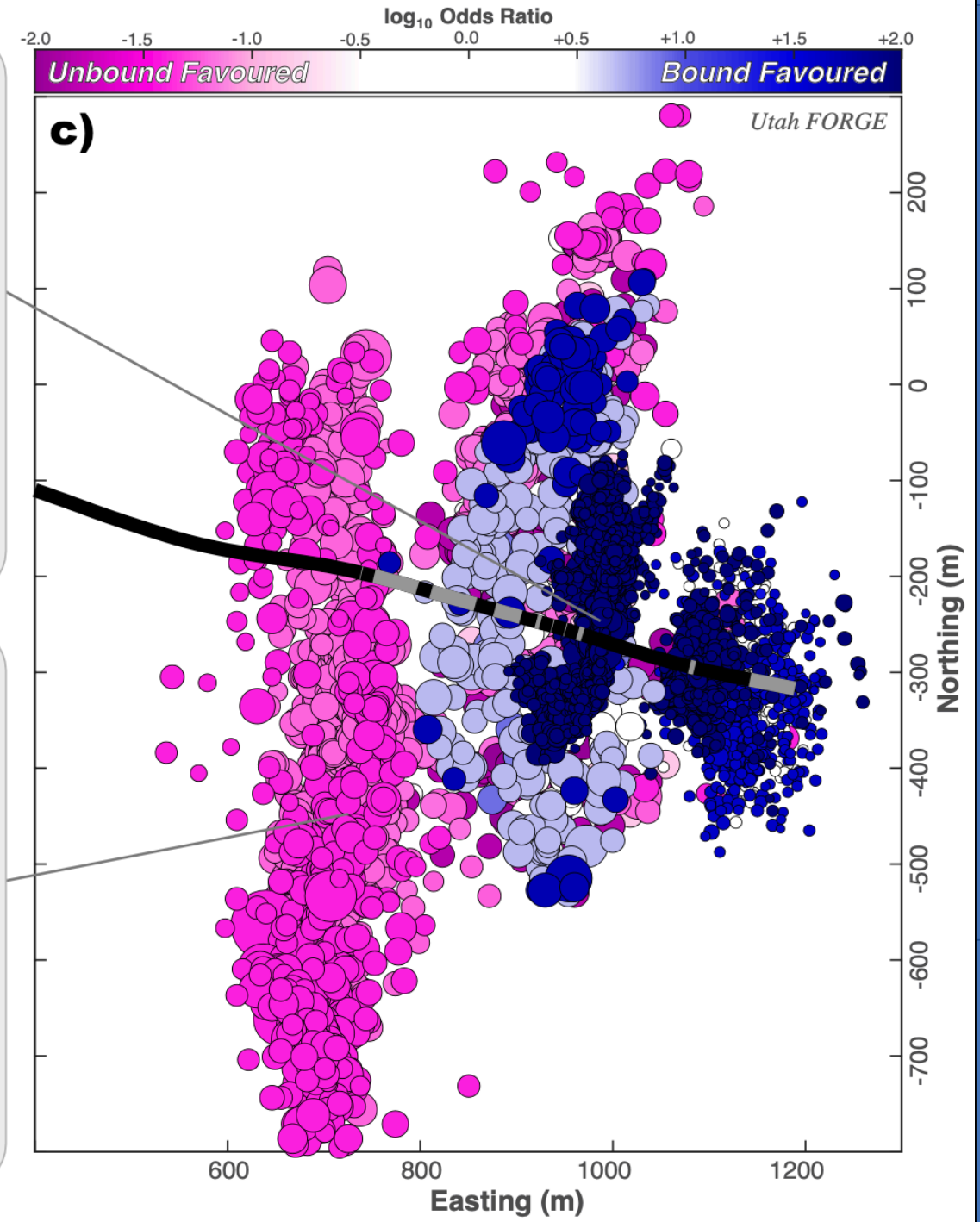
- Handle as four clusters (E & W): s1-s2, s3-2022, s3-s6, s7-s10.
- Bound M_{MAX} at clusters 1-2.
  - Deficient in large events.
  - 99% conf, <0.01 M, 26-100x b.
- Unbound M_{MAX} at cluster 3.
  - Overabundance of large events.
  - 65.3% conf, ~1.5, 0.02x b.
- Largest event observed in cluster 3.



Case		Simple tests		CAP-tests			
Location	Cluster	*b*-value	δM_{LRG}	KS-test	MLE-test	EW-test	M_{MAX} model
FORGE	*1*	1.43±0.06	-0.90	>99.99%	<0.01	>100	McGarr
FORGE	*2a*	1.01±0.02	-1.50	>99.99%	<0.01	>100	McGarr
FORGE	*2*	1.88±0.11	-0.28	98.99%	<0.01	~26	Galis
FORGE	*3*	1.83±0.10	+0.11	65.34%	~1.53	0.02	Unbound


Cluster 2a: Stage 3 in 2022
a)
Magnitude
McGarr M_{MAX}
expected M_{LRG}
Galis M_{MAX}
M_{LRG}
Model Weights
Unbound
Galis
McGarr
Bound Favoured
Chronological Event Number


Cluster 3: Stages 7-10 in 2024
b)
Magnitude
Galis M_{MAX}
McGarr M_{MAX}
expected M_{LRG}
M_{LRG}
Model Weights
Unbound
Galis
McGarr
Unbound Favoured
Chronological Event Number

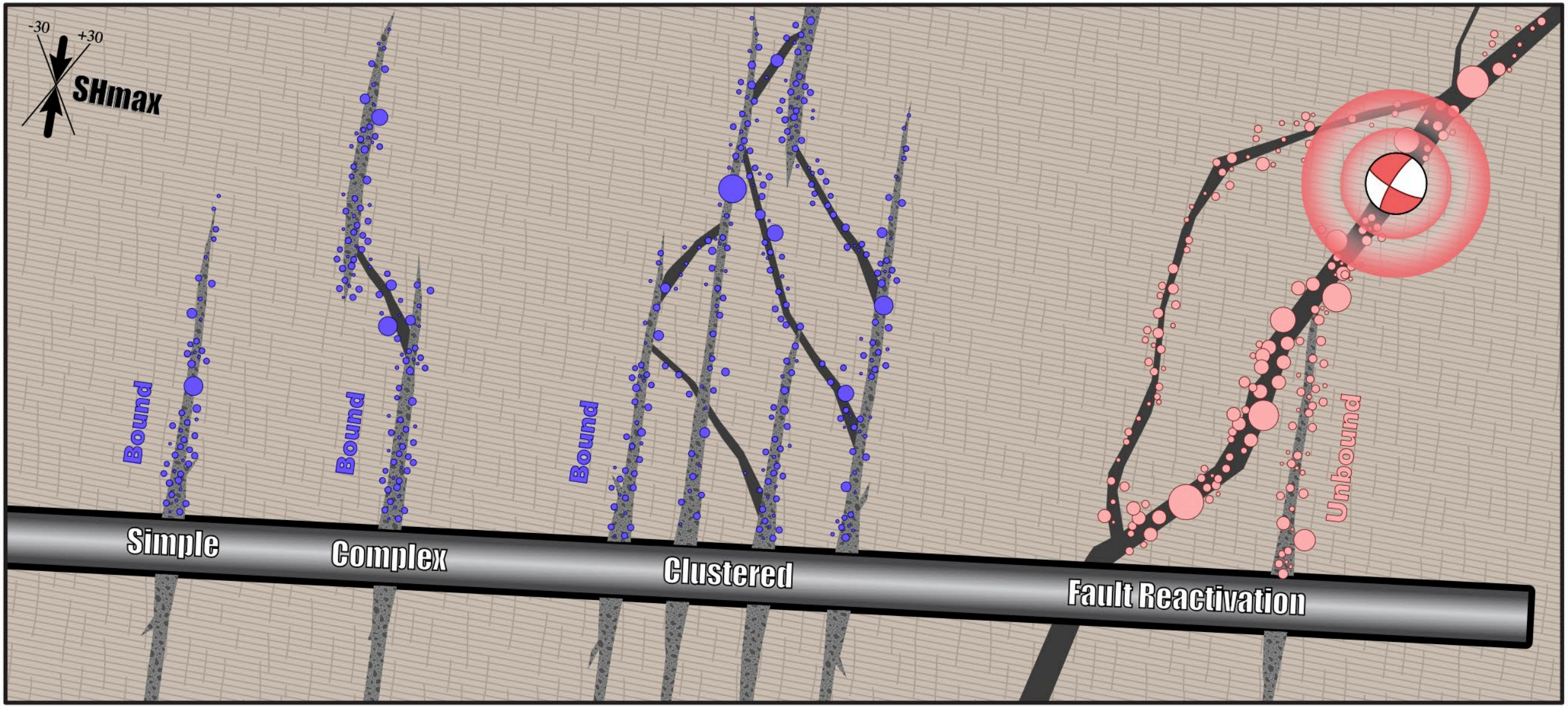

$\log_{10}$ Odds Ratio
Unbound Favoured
Bound Favoured
c)
Utah FORGE
Easting (m)
Northing (m)

Physical Interpretation

- Dependence on clustering of stages.
  - The role of hydraulic connectivity.
- Insights driven by sensitivity testing.
  - PNR-1z remains bound when truncating end stages (less conf).
  - PNR-1z becomes unbound/mixed when truncating start stages.
- Inferences for pre-existing faults.

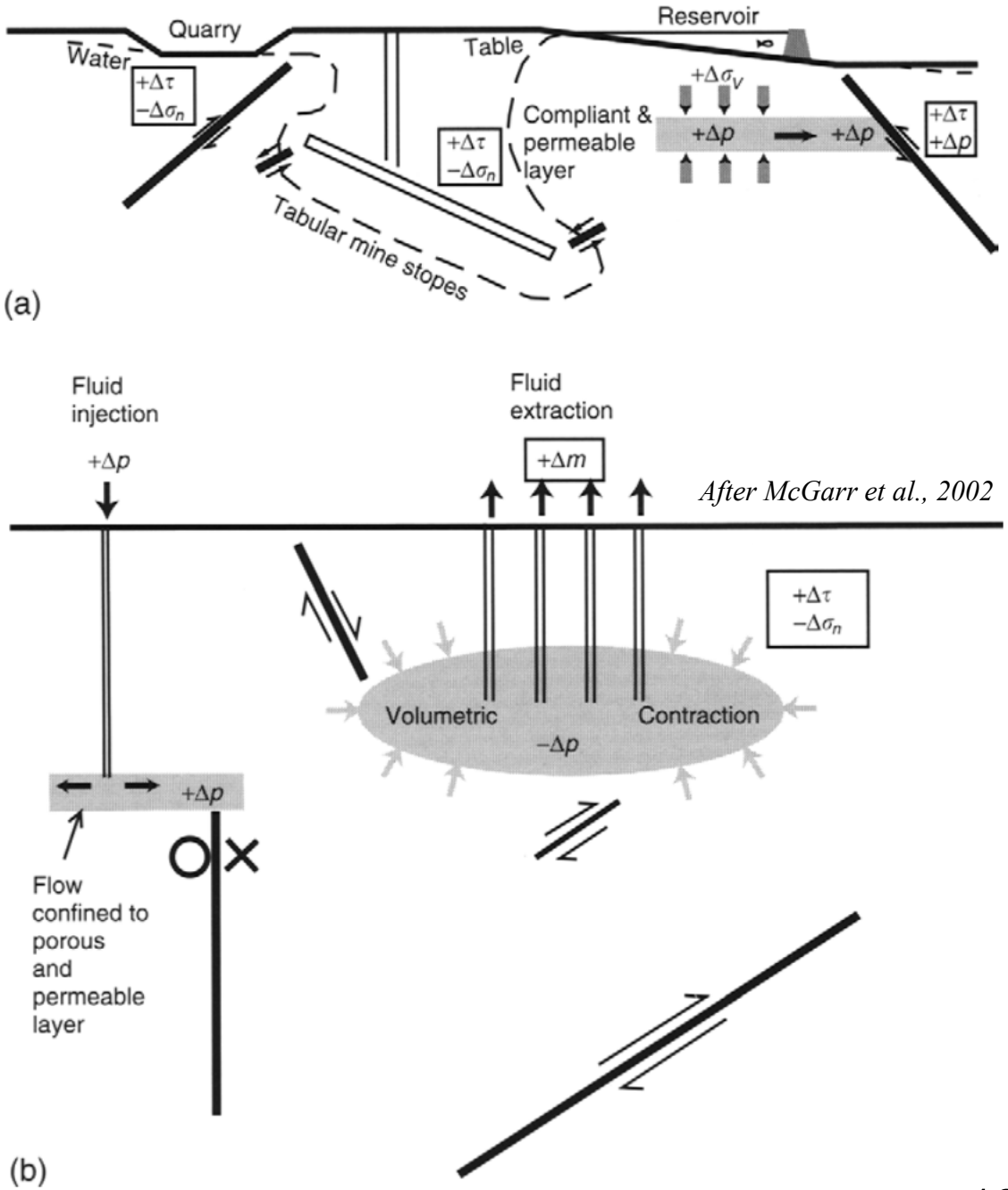
Cluster Definition		KS-test	MLE-test	EW-test	M_{LRG}
Start Stage	End Stage			odds ratio	
1	1	>99.99%	<0.01	~27	0.44 M_W
1	2	>99.99%	<0.01	~2.6	0.44 M_W
1	3	>99.99%	<0.01	>100	0.70 M_W
1	12	>99.99%	<0.01	>100	0.90 M_W
1	13	>99.99%	<0.01	>100	0.90 M_W
1	14	>99.99%	<0.01	>100	1.10 M_W
1	18	93.05%	<0.01	>100	1.10 M_W
1	22	>99.99%	<0.01	>100	1.10 M_W
1	30	>99.99%	<0.01	>100	1.30 M_W
1	31	>99.99%	<0.01	>100	1.40 M_W
1	32	99.56%	<0.01	>100	1.60 M_W
1	35	99.80%	<0.01	>100	1.60 M_W
1	37	>99.99%	<0.01	>100	1.60 M_W
1	38	99.62%	<0.01	~93	1.90 M_W
1	39	99.88%	<0.01	~63	1.90 M_W
1	40	99.80%	<0.01	~85	1.90 M_W
1	41	99.86%	<0.01	~45	1.90 M_W

Cluster Definition		KS-test	MLE-test	EW-test	M_{LRG}
Start Stage	End Stage			odds ratio	
1	41	99.86%	<0.01	~45	1.90 M_W
2	41	99.50%	<0.01	~33	1.90 M_W
3	41	99.80%	<0.01	~35	1.90 M_W
12	41	98.20%	<0.01	~2.2	1.90 M_W
13	41	98.70%	<0.01	~25	1.90 M_W
14	41	97.80%	<0.01	~16	1.90 M_W
18	41	98.40%	<0.01	~1.4	1.90 M_W
22	41	94.26%	<0.01	~7.6	1.90 M_W
30	41	87.35%	<0.01	~1.1	1.90 M_W
31	41	58.90%	<0.01	~1.5	1.90 M_W
32	41	55.08%	0.02	~1.4	1.90 M_W
35	41	62.78%	<0.01	~1.5	1.90 M_W
37	41	52.25%	<0.01	~1.2	1.90 M_W
38	41	59.84%	0.04	~1.1	1.90 M_W
39	41	69.31%	0.01	~2.0	1.90 M_W
40	41	44.30%	0.02	~0.8	1.90 M_W
41	41	64.72%	0.01	~1.0	1.90 M_W


-30
+30
SHmax
Bound
Bound
Bound
Unbound
Simple
Complex
Clustered
Fault Reactivation

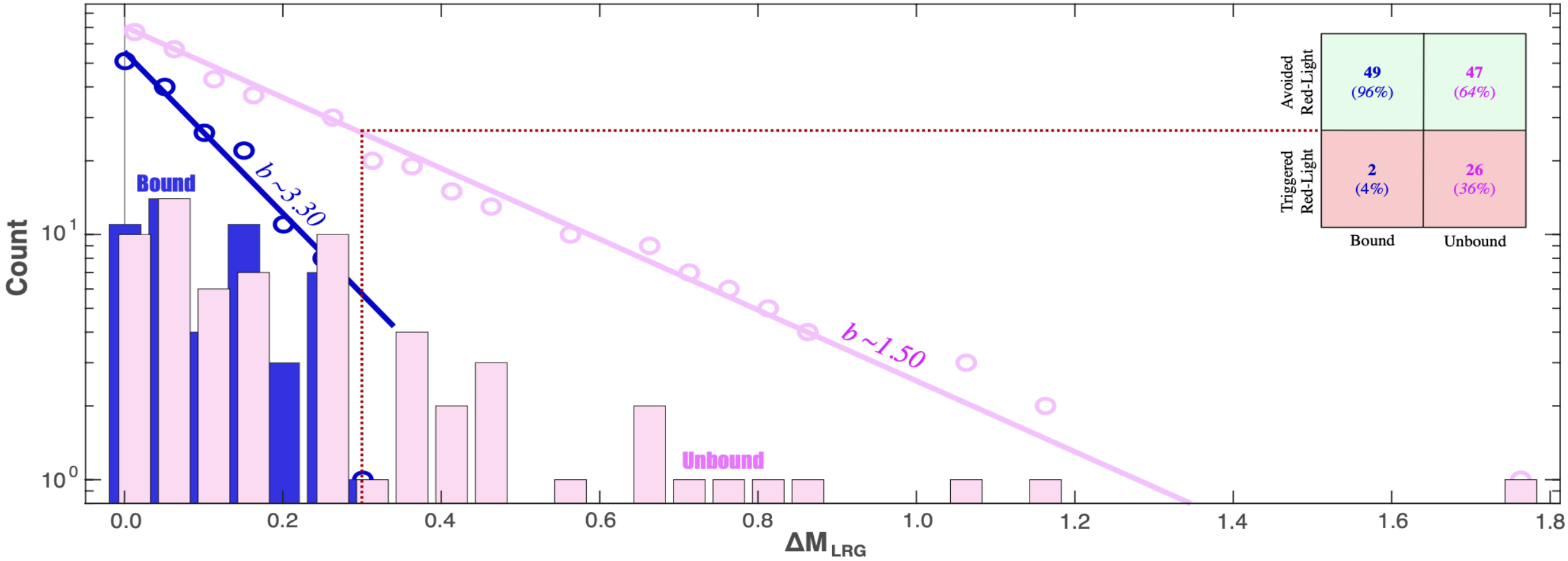
Induced Seismicity: Driven or triggered?

- Driven: controlled by anthropogenic subsurface stress changes.
- Triggered: small stress change releases stored tectonic stress.
- Unbound-triggered, Bound-driven.
- CAP-tests represent first test to separate these two categories.
- Test M_{MAX} models on driven cases.



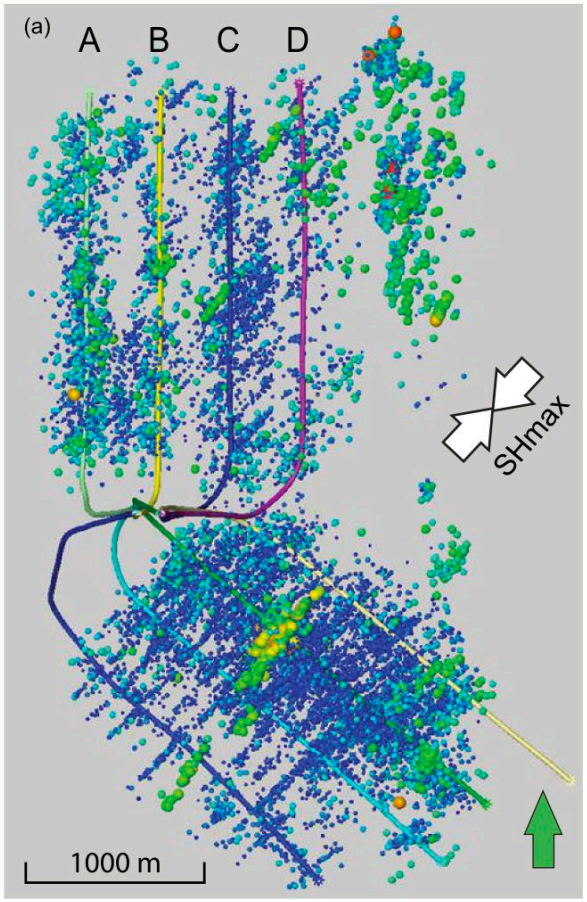
Practical Implications for Operations

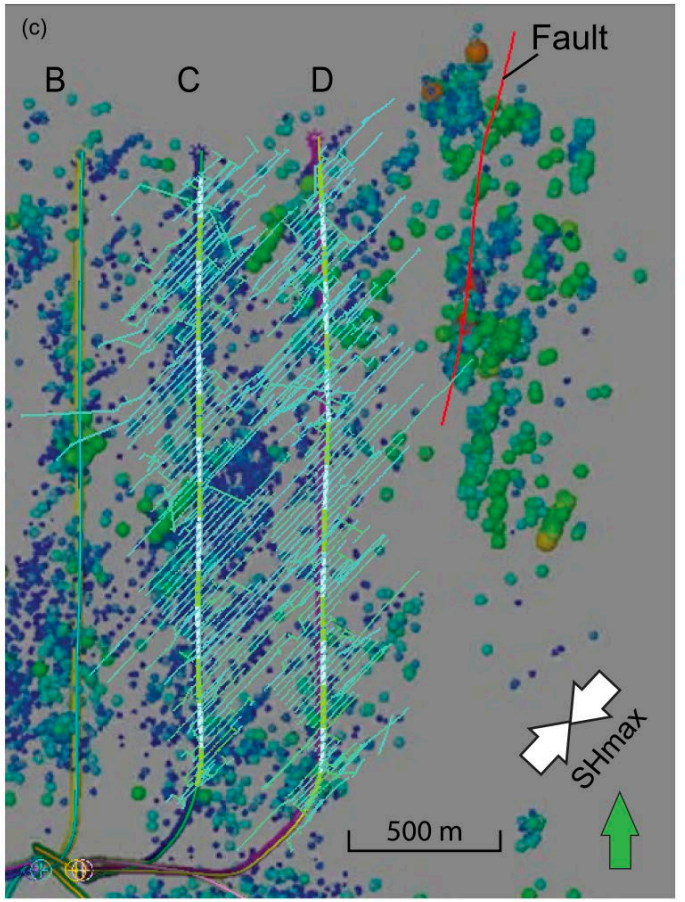
- Use EW-test (at 3x) to discern bound/unbound.
- Record all ΔM_{LRG} after EW-test results.



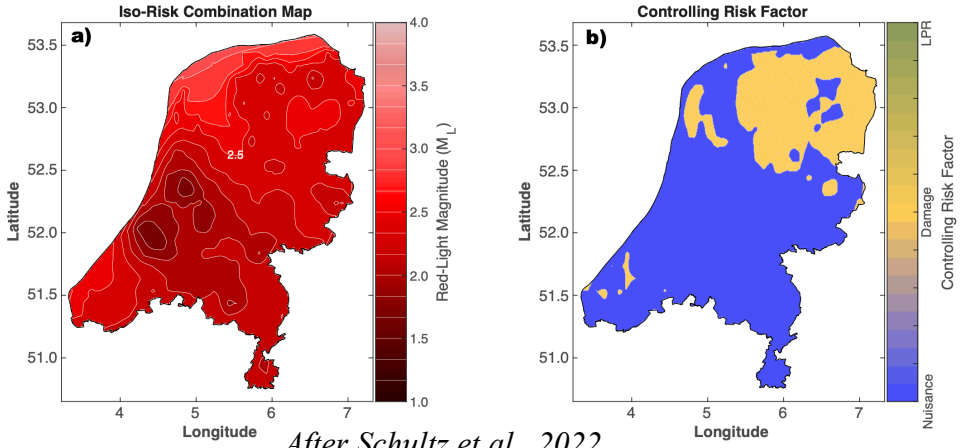
Operational Mitigation

- Additional tool to discern problematic stages in real-time.
- Changes reaction when approaching red-light:
  - Bound safer, unbound riskier.
- Divert injection away from faults that hamper resource production.

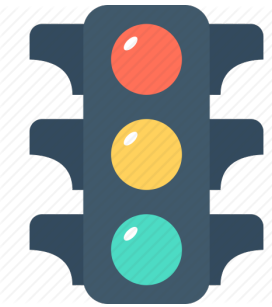




After Konstantinovskaya et al., 2021



After Schultz et al., 2022



Summary

- Applied a suite of tools for testing M_{MAX}.
- Able to clearly distinguish bound cases of IS.
- Significant cluster-to-cluster variability, inferences for causation via fault reactivation.
- Potential diagnostic tool, separating bound/unbound cases.
- Implications for real-time hazard/risk mitigation.

http://www.seismo.ethz.ch/en/about-us/all-employees/Ryan-Schultz/

Questions?

Schultz, Lanza, Dyer, …, & Wiemer (2024).

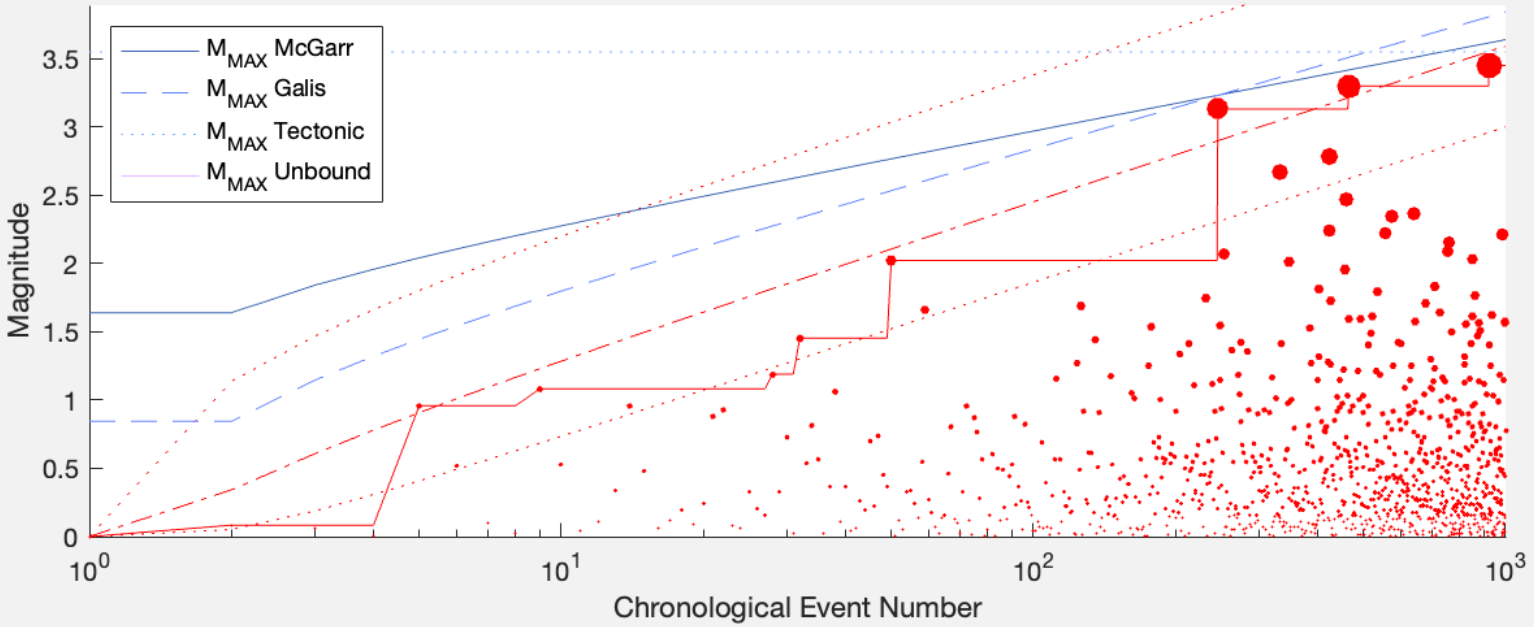
The bound growth of induced earthquakes could de-risk hydraulic fracturing,

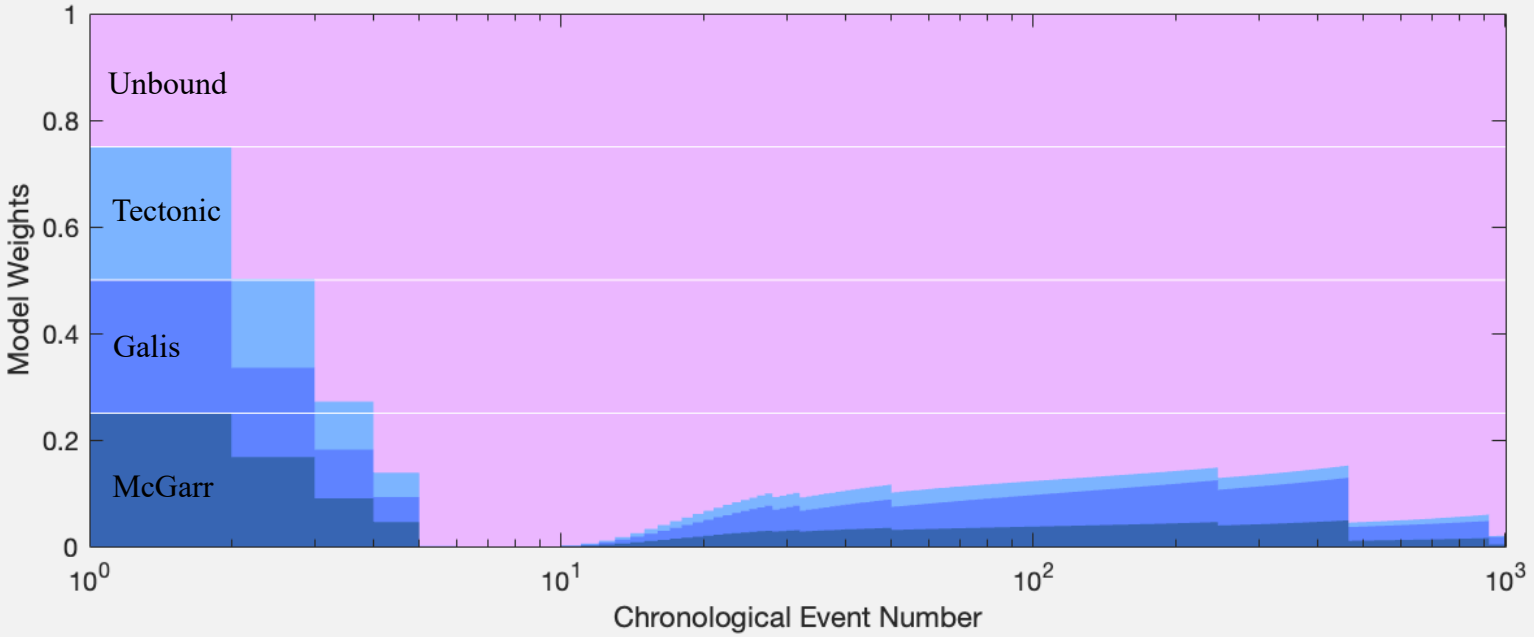
submitted,

doi: xx.

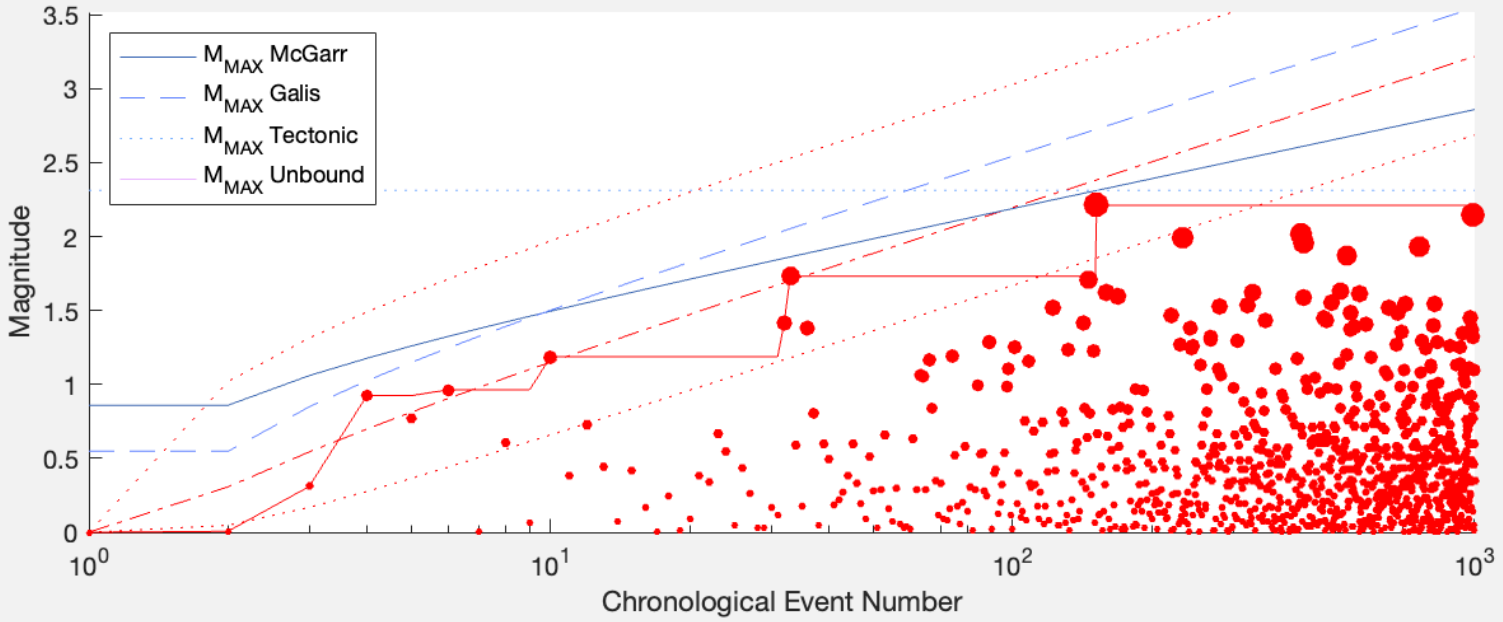
http://www.seismo.ethz.ch/en/about-us/all-employees/Ryan-Schultz/

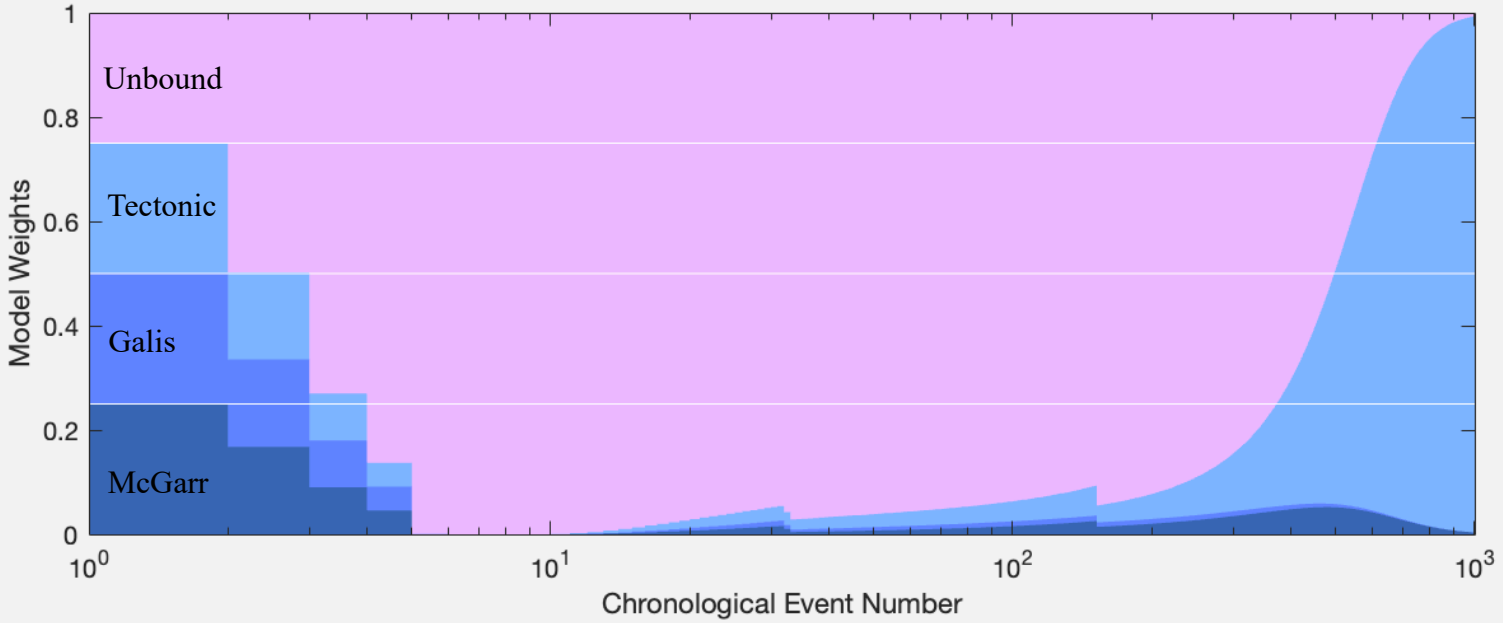
Synthetic (Unbound)



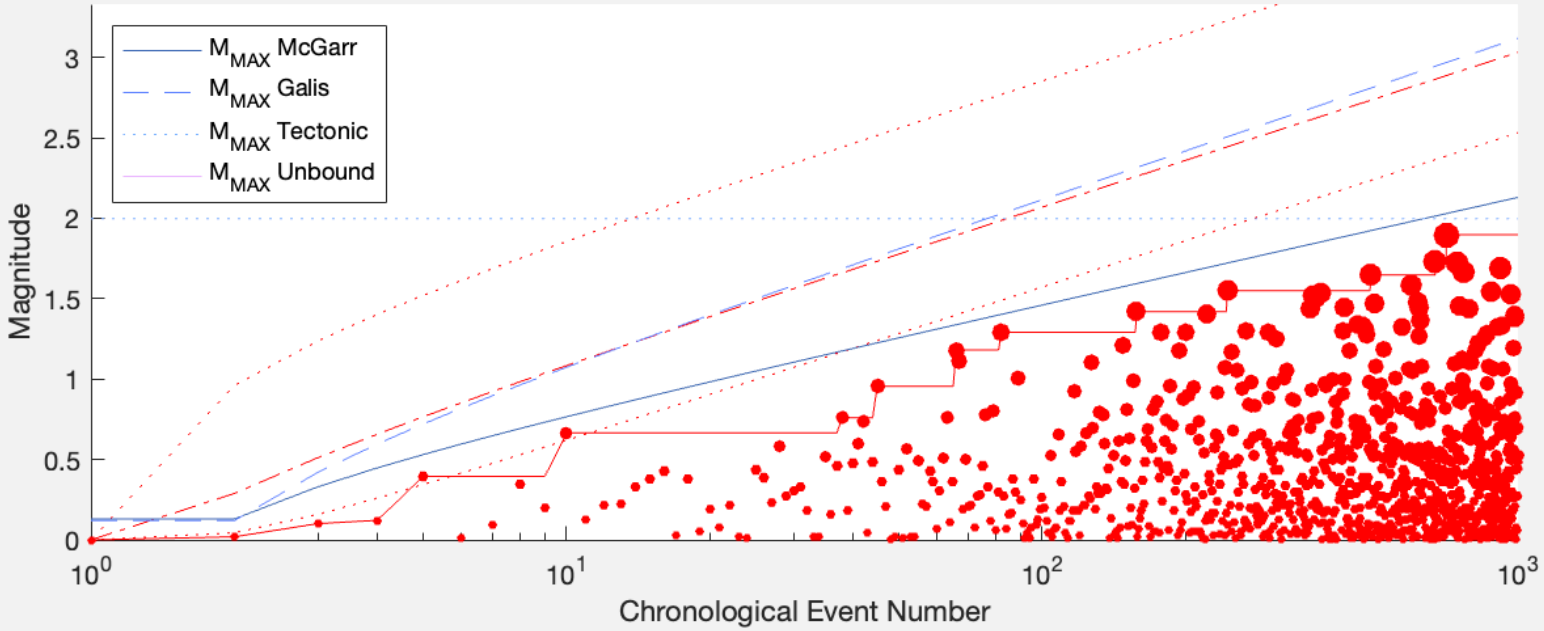


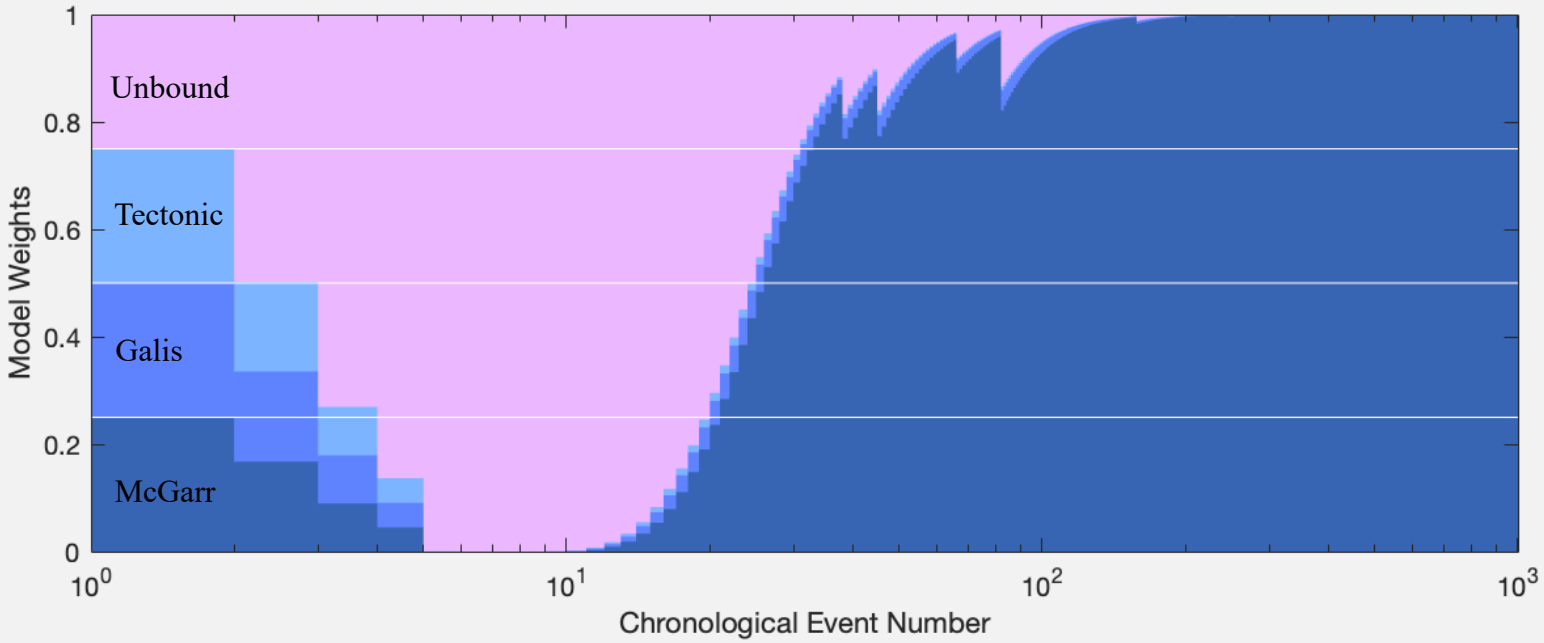
Synthetic (Tectonic)



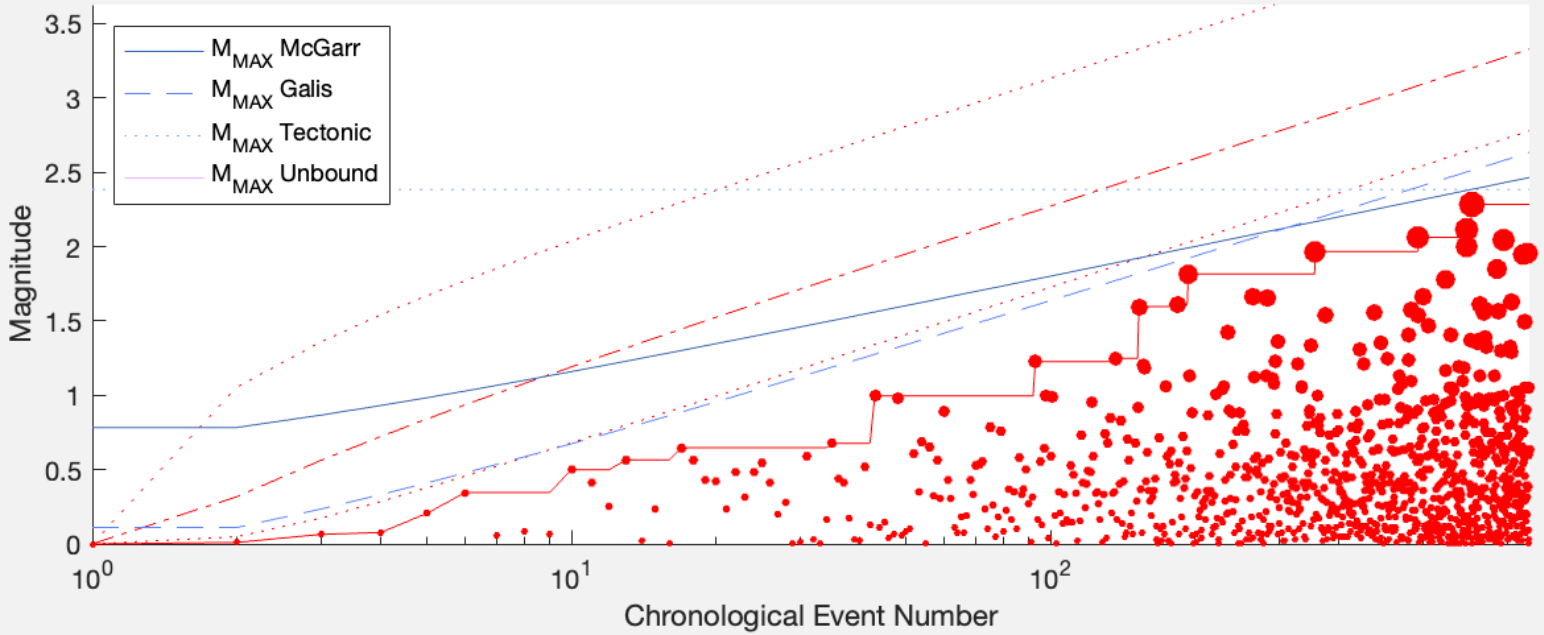


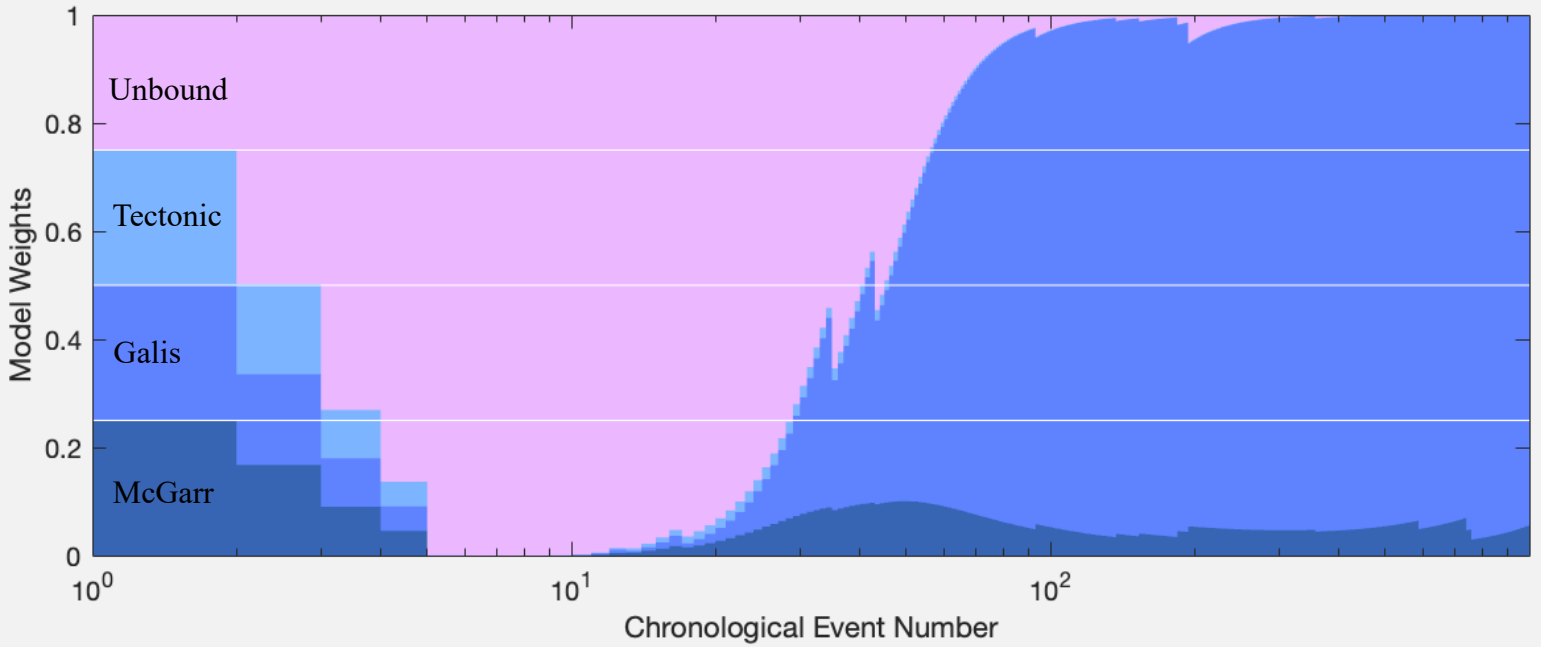
Synthetic (McGarr)



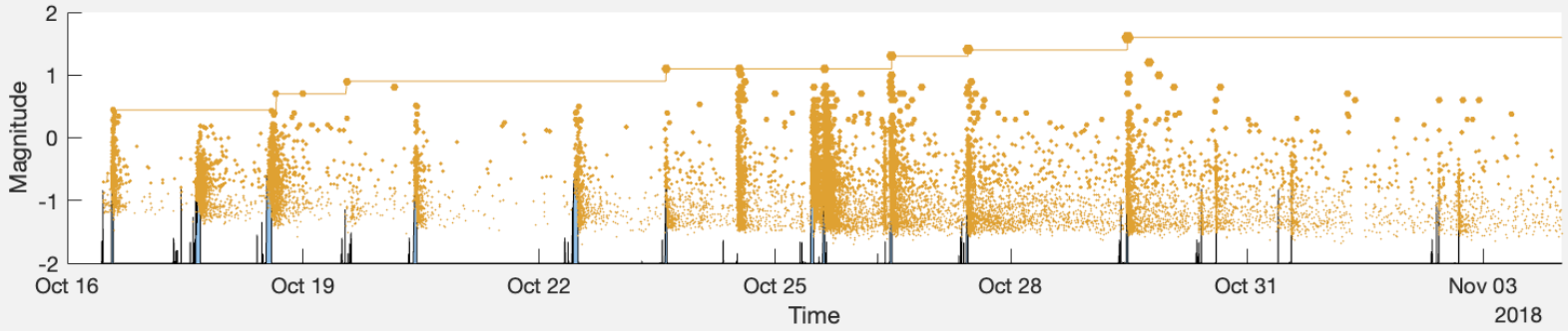


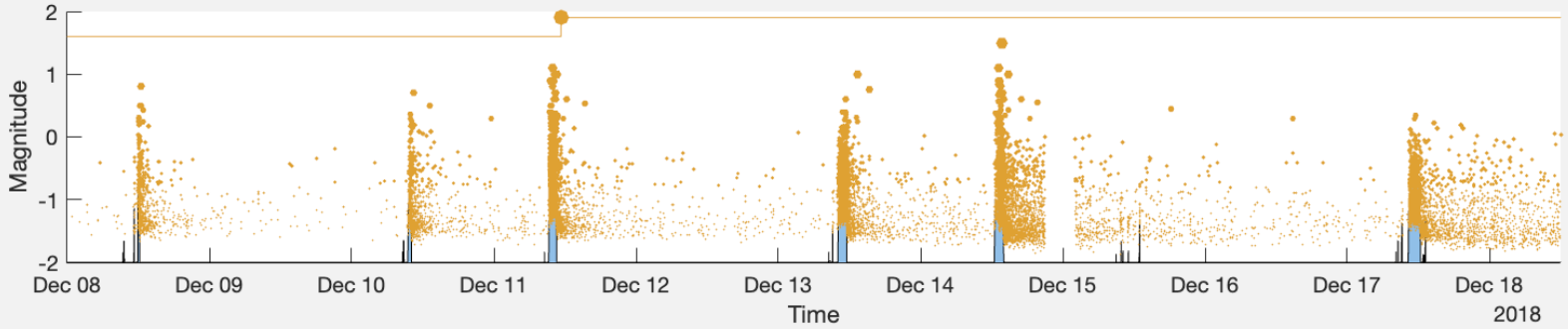
Synthetic (Galis)

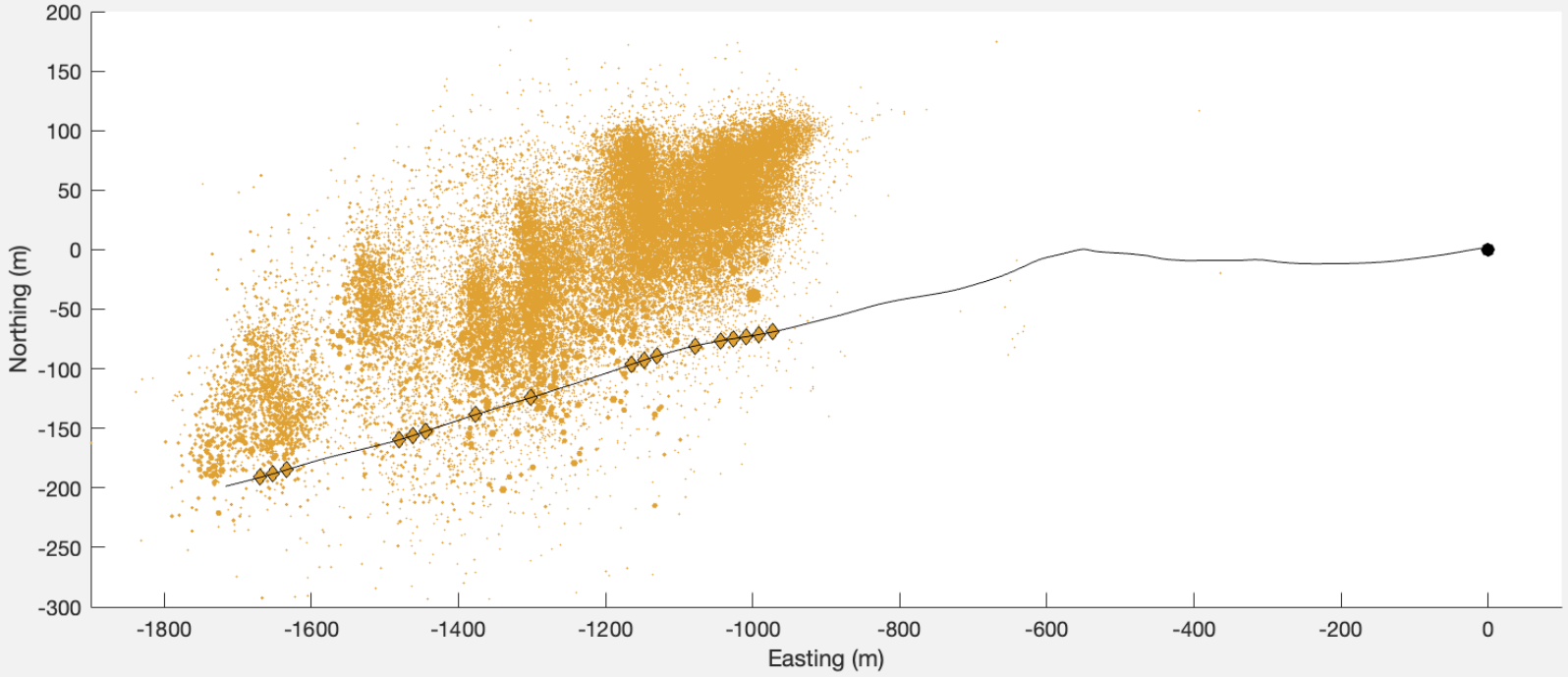




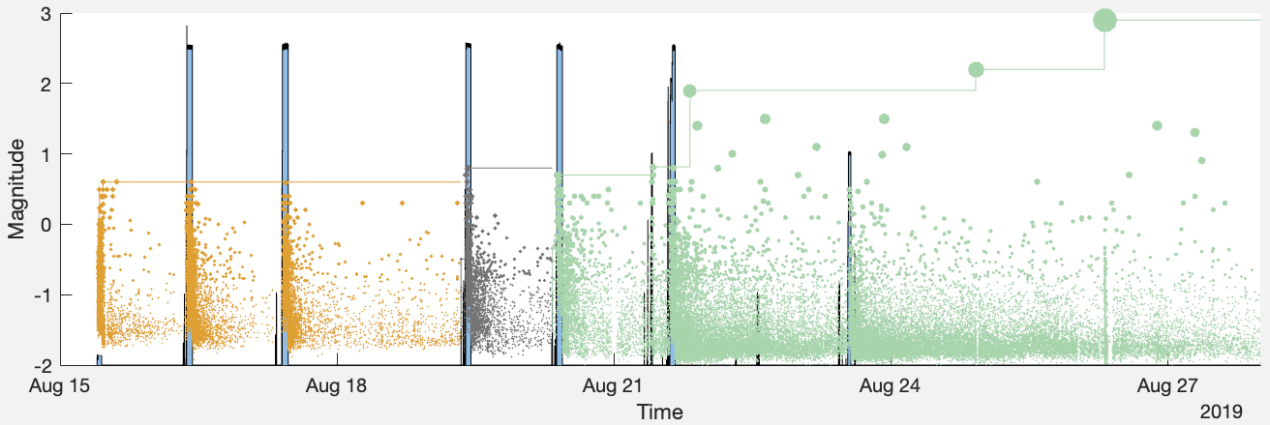
PNR-1z

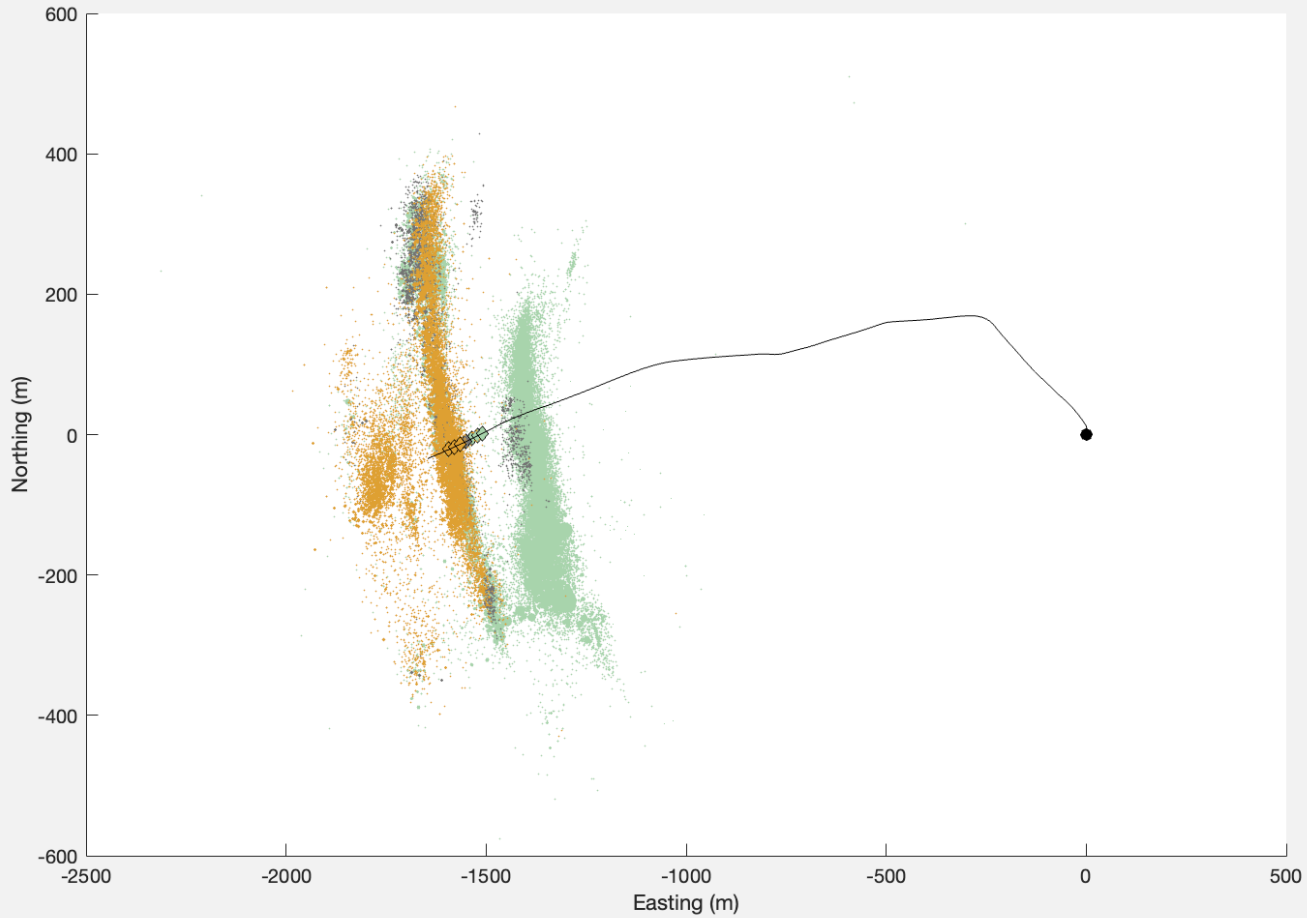

Magnitude
2
1
0
-1
-2
Oct 16
Oct 19
Oct 22
Oct 25
Oct 28
Oct 31
Nov 03
2018
Time


Magnitude
2
1
0
-1
-2
Dec 08
Dec 09
Dec 10
Dec 11
Dec 12
Dec 13
Dec 14
Dec 15
Dec 16
Dec 17
Dec 18
2018
Time

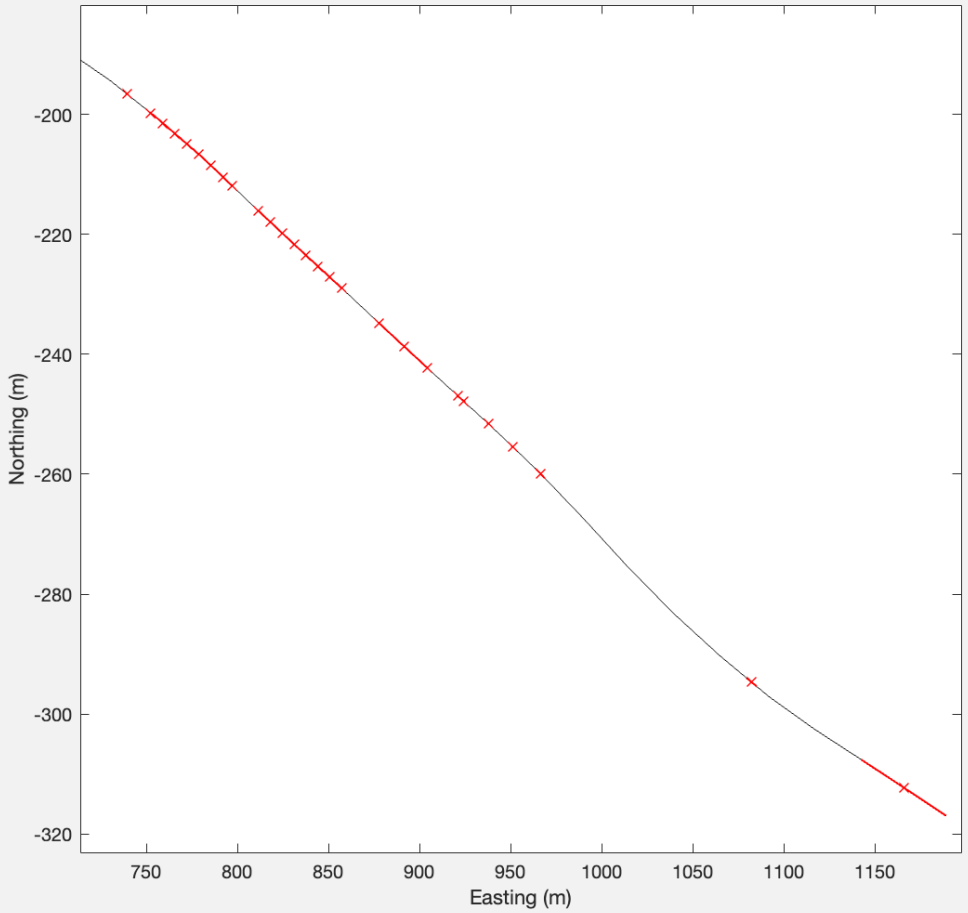

Northing (m)
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-1800
-1600
-1400
-1200
-1000
-800
-600
-400
-200
0
Easting (m)

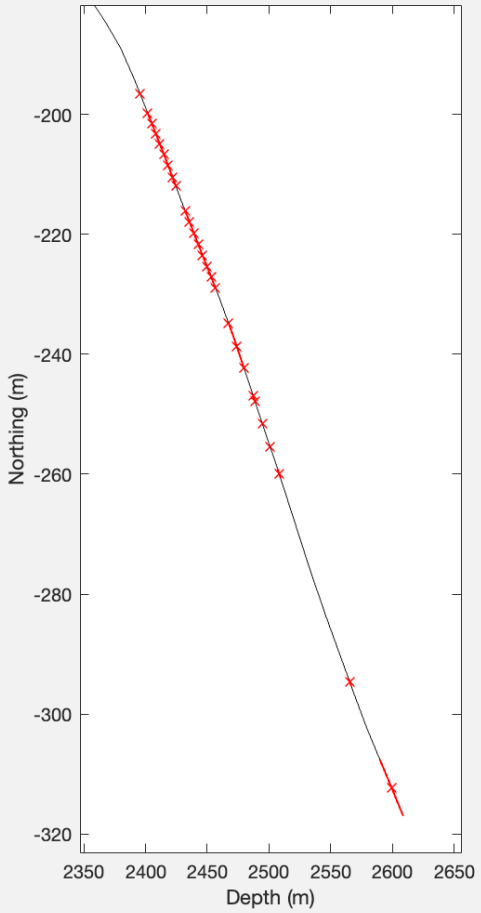
PNR-2

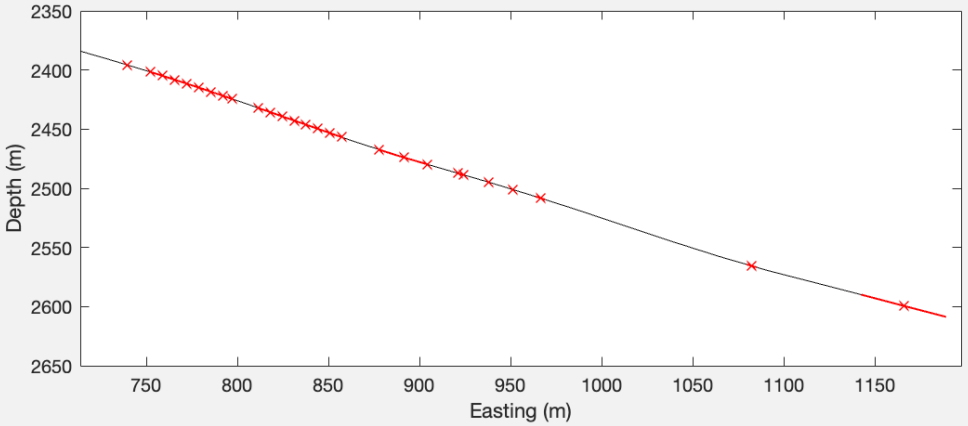

Magnitude
3
2
1
0
-1
-2
Aug 15
Aug 18
Aug 21
Aug 24
Aug 27
2019
Time


Northing (m)
600
400
200
0
-200
-400
-600
-2500
-2000
-1500
-1000
-500
0
500
Easting (m)

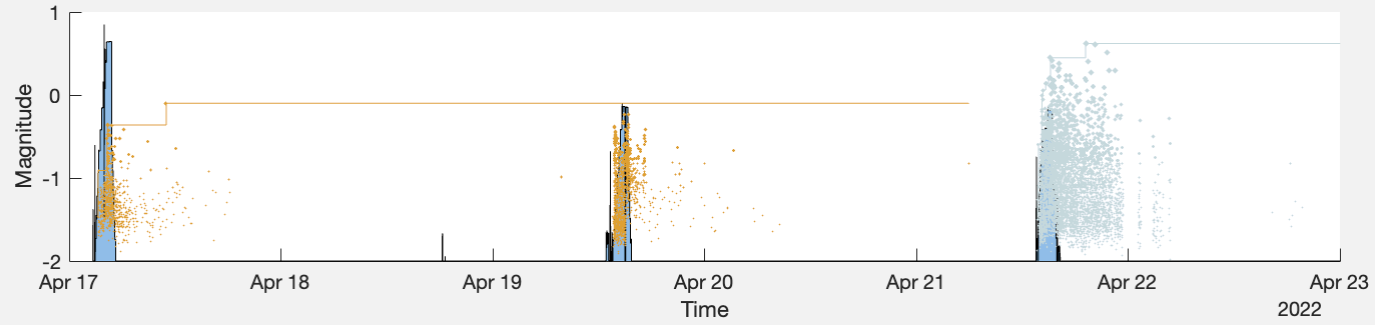
FORGE

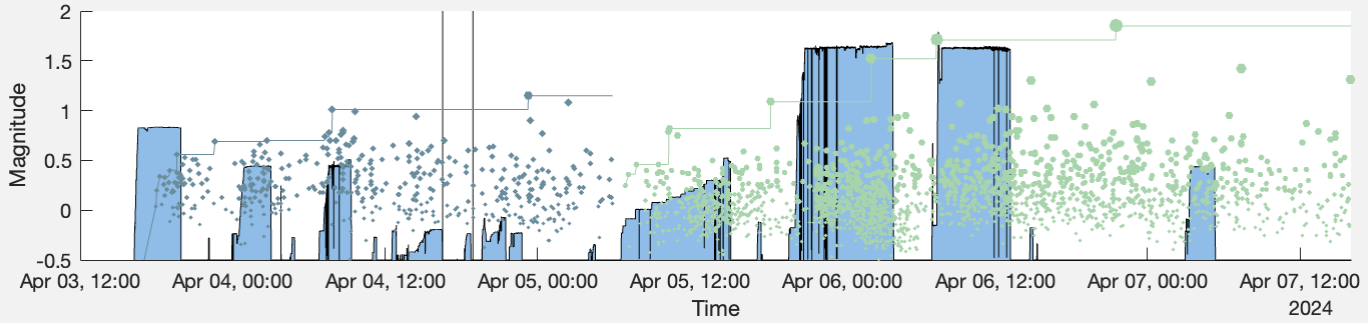

-200
-220
-240
-260
-280
-300
-320
Northing (m)
750
800
850
900
950
1000
1050
1100
1150
Easting (m)

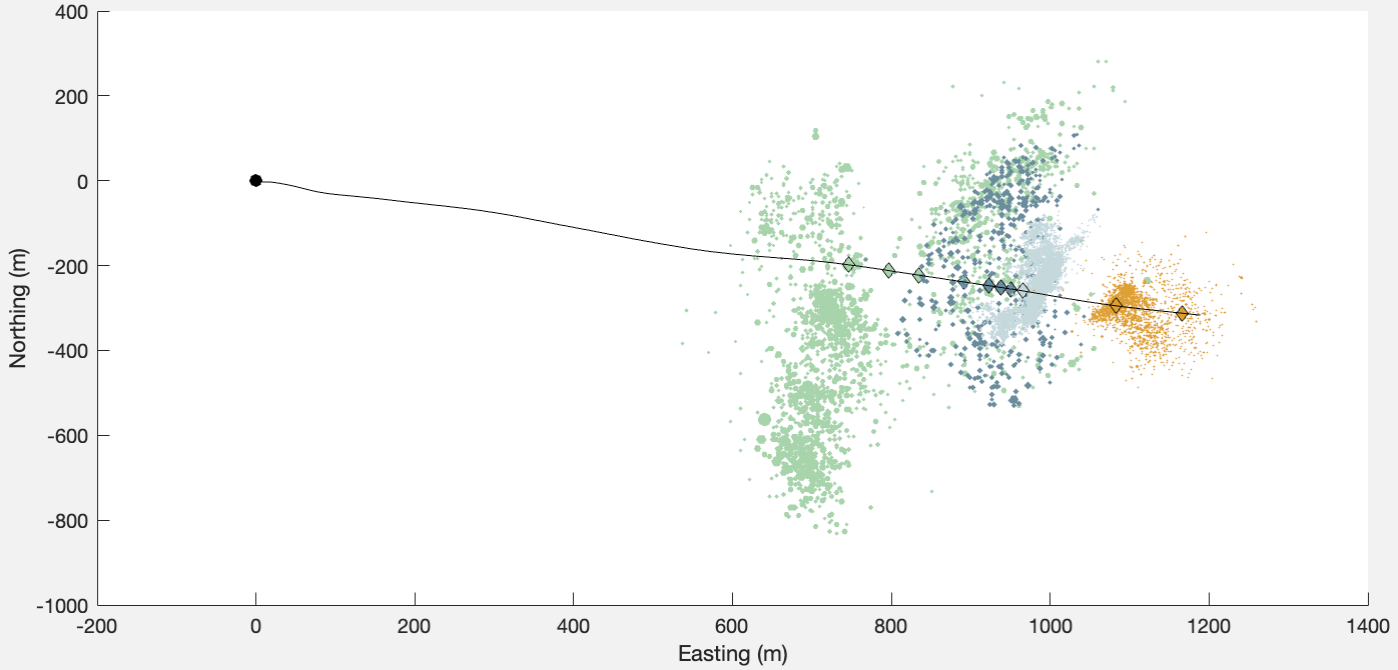

-200
-220
-240
-260
-280
-300
-320
Northing (m)
2350
2400
2450
2500
2550
2600
2650
Depth (m)


2350
2400
2450
2500
2550
2600
2650
Depth (m)
750
800
850
900
950
1000
1050
1100
1150
Easting (m)

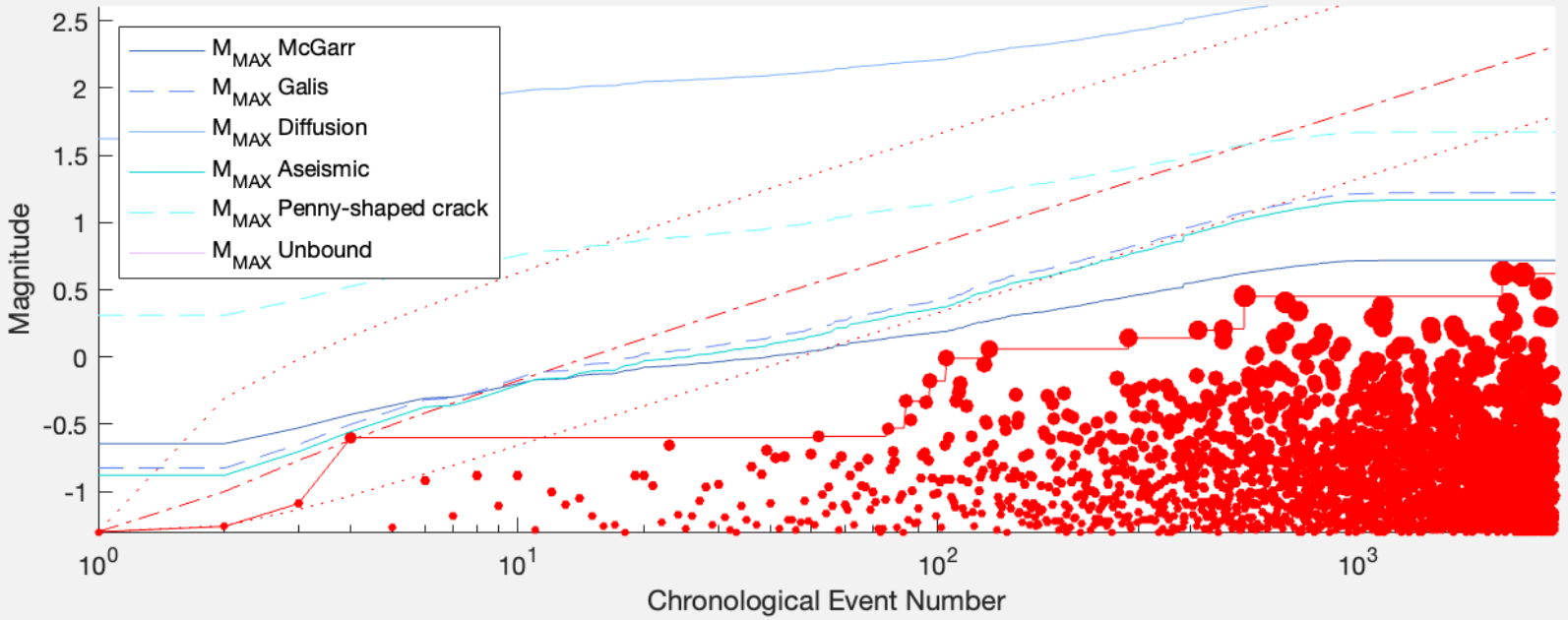
FORGE

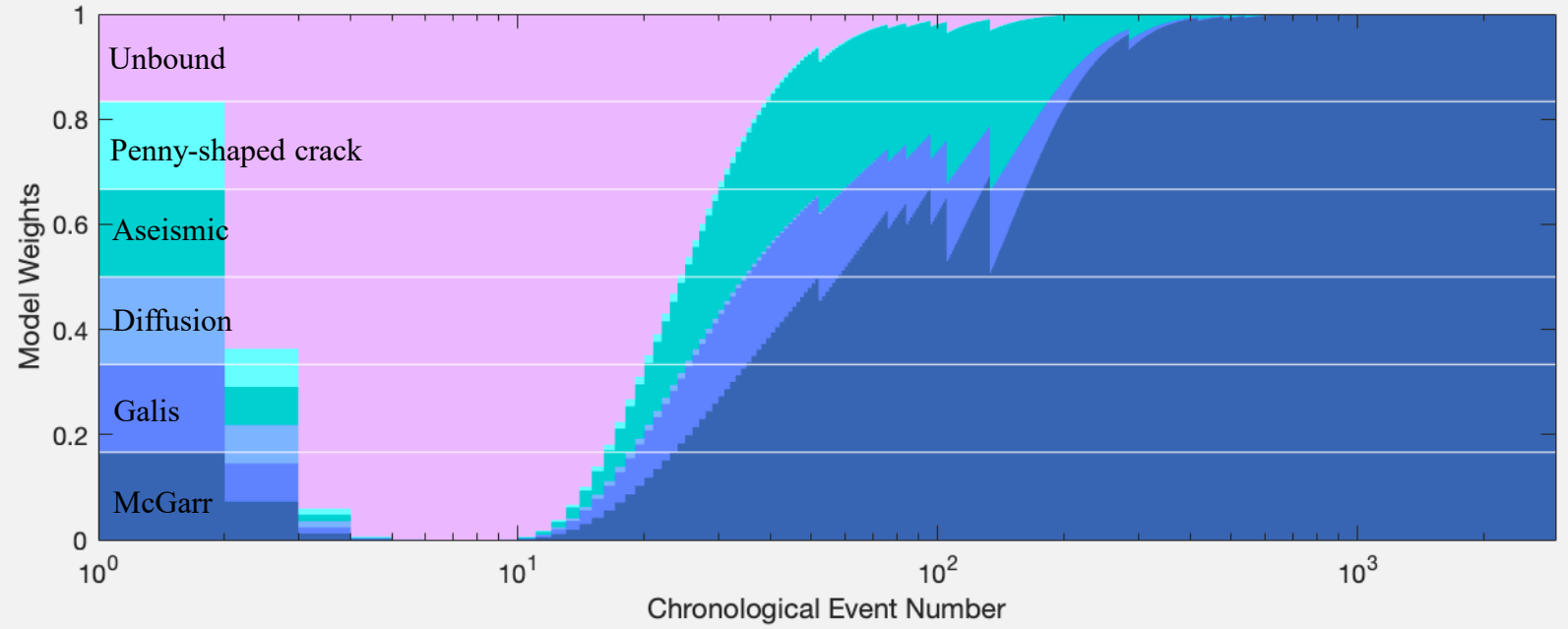

Magnitude
1
0
-1
-2
Apr 17
Apr 18
Apr 19
Apr 20
Apr 21
Apr 22
Apr 23
Time
2022


Magnitude
2
1.5
1
0.5
0
-0.5
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
Apr 06, 12:00
Apr 07, 00:00
Apr 07, 12:00
Time
2024

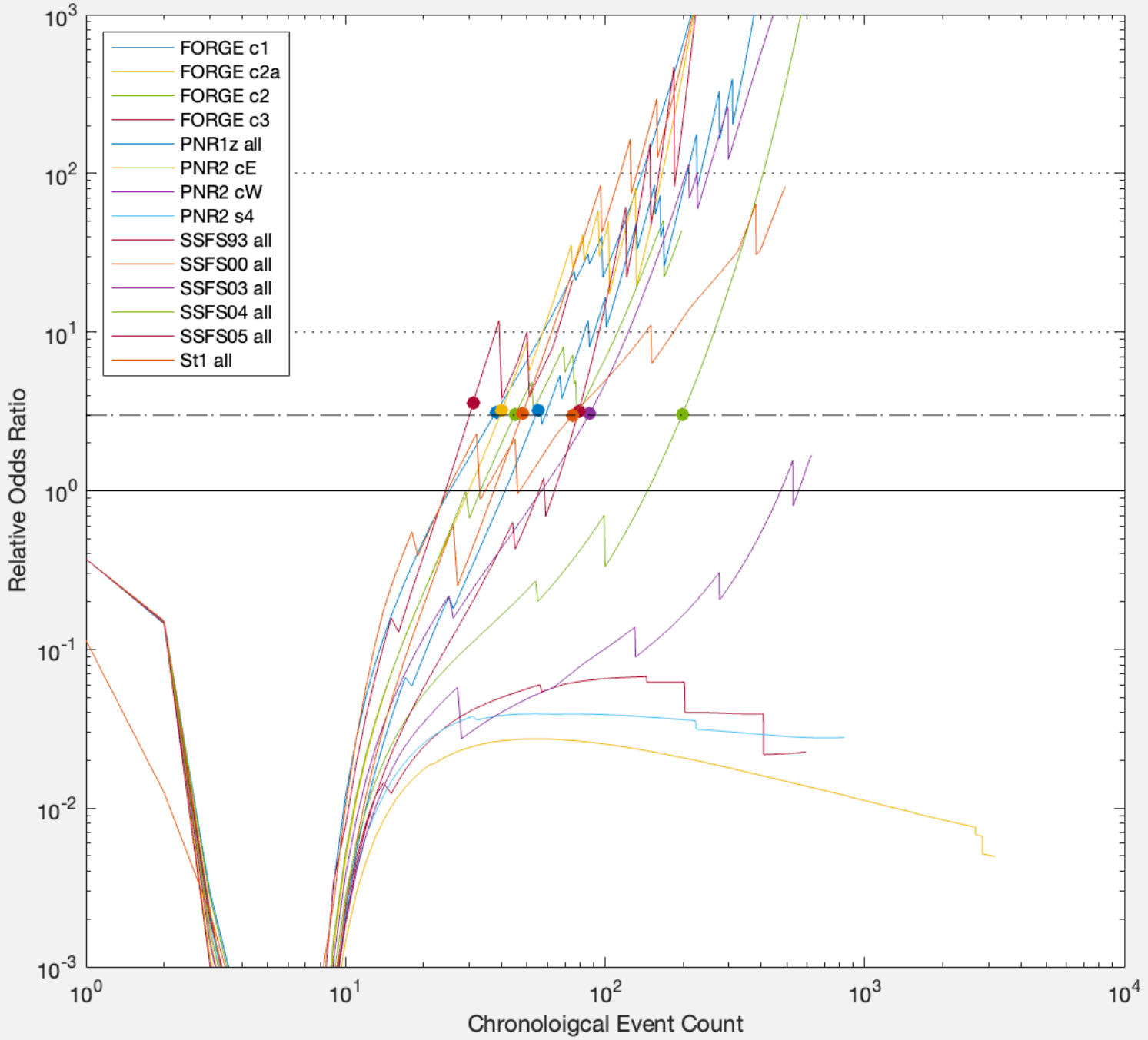

Northing (m)
400
200
0
-200
-400
-600
-800
-1000
-200
0
200
400
600
800
1000
1200
1400
Easting (m)

FORGE


M_{MAX} McGarr
M_{MAX} Galis
M_{MAX} Diffusion
M_{MAX} Aseismic
M_{MAX} Penny-shaped crack
M_{MAX} Unbound
Magnitude
2.5
2
1.5
1
0.5
0
-0.5
-1
10^0
10^1
10^2
10^3
Chronological Event Number


Unbound
Penny-shaped crack
Aseismic
Diffusion
Galis
McGarr
Model Weights
1
0.8
0.6
0.4
0.2
0
10^0
10^1
10^2
10^3
Chronological Event Number

FORGE


FORGE c1
FORGE c2a
FORGE c2
FORGE c3
PNR1z all
PNR2 cE
PNR2 cW
PNR2 s4
SSFS93 all
SSFS00 all
SSFS03 all
SSFS04 all
SSFS05 all
St1 all
Relative Odds Ratio
Chronoloigcal Event Count