□A□□□CA□□ECHA□C□F□□□C□□□□E□ □□

RÍO DE JANEIRO 6-10 NOVEMBER 2023

Happy Birthday Constantino

2003

2013

2023

MUTABILITY AND ENTROPY: APPROACHES TO COMPLEX SYSTEMS.

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- (h) Department of Physics, Universidad Santa María, Valparaíso, Chile.

BA□C DEFI□□□□□;C□A□□CA□□□G □□□E□; □□□□A□□□

□□□□□□□□□□□□□□□□□□□□□: $$U(T) = \sum_{i=1}^{W} e_i \, p(e_i(T))$$

□□□□□□□□□□□□□□: $$C_V(T) = \frac{dU(T)}{dT}$$

E□□□□□□ $$S(T) = \int_0^T \frac{dC_V(T')}{dT'} dT' \quad ; \quad S(0) = 0$$

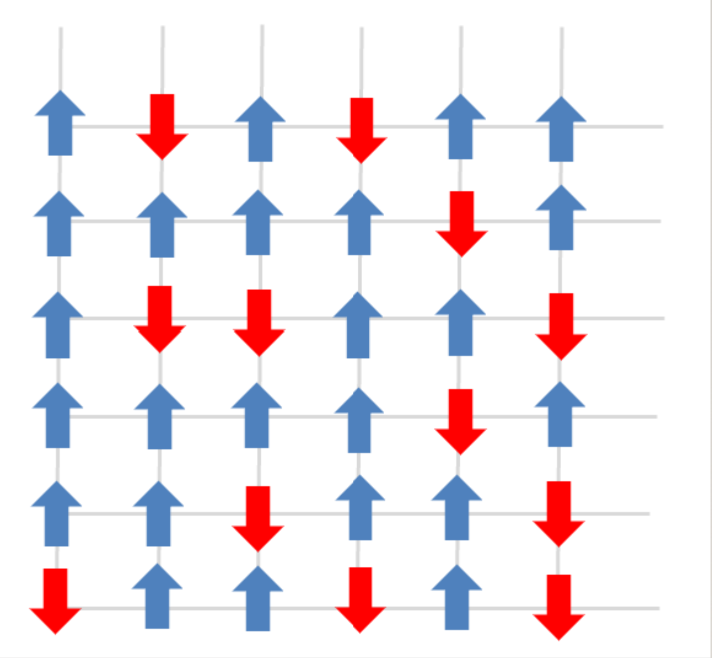
□□□□□□□□□□□□□□: $$M(T) = \sum_{i=1}^{N} S_i$$

□□□□□□□□□□□□□□: $$\chi(T) = \frac{1}{k_B T}\left(\langle M^2 \rangle - \langle M \rangle^2\right)$$

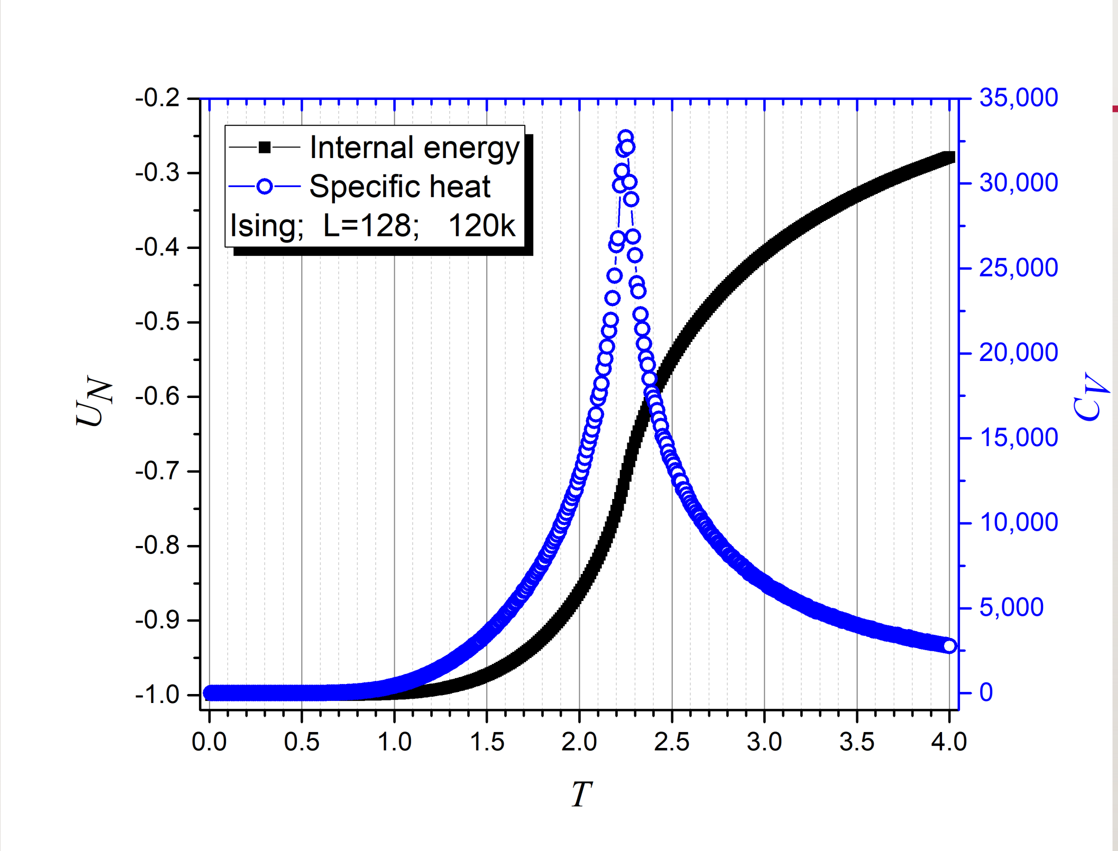
$$k_B = 1$$

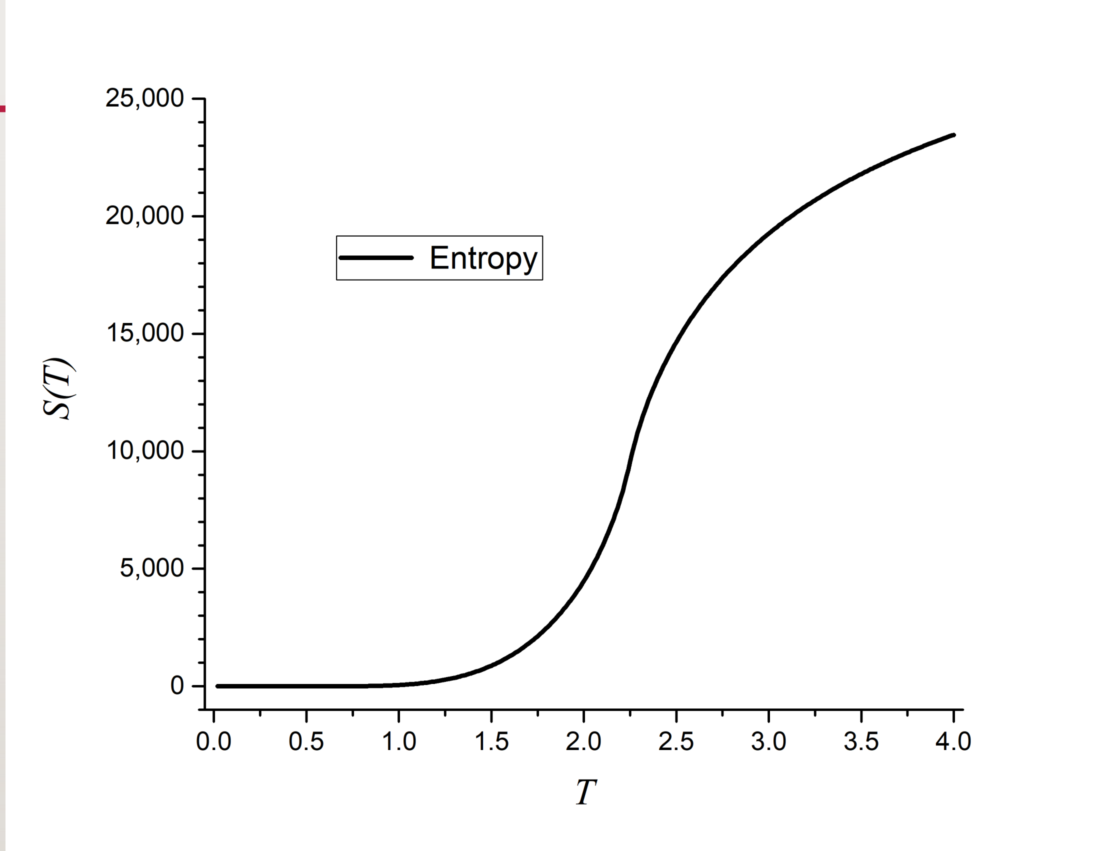
$$H = -J \sum_{k,l=1}^{L^2} S_k S_l$$

- Random initial pick
- One MC step= L^2 attemps
- If U(l+1)≤U(l) accept
- If U(l+1)>U(l), then if exp{-[U(l+1)-U(l)]/T} >random, accept (Metropolis)
- 120,000 MC steps

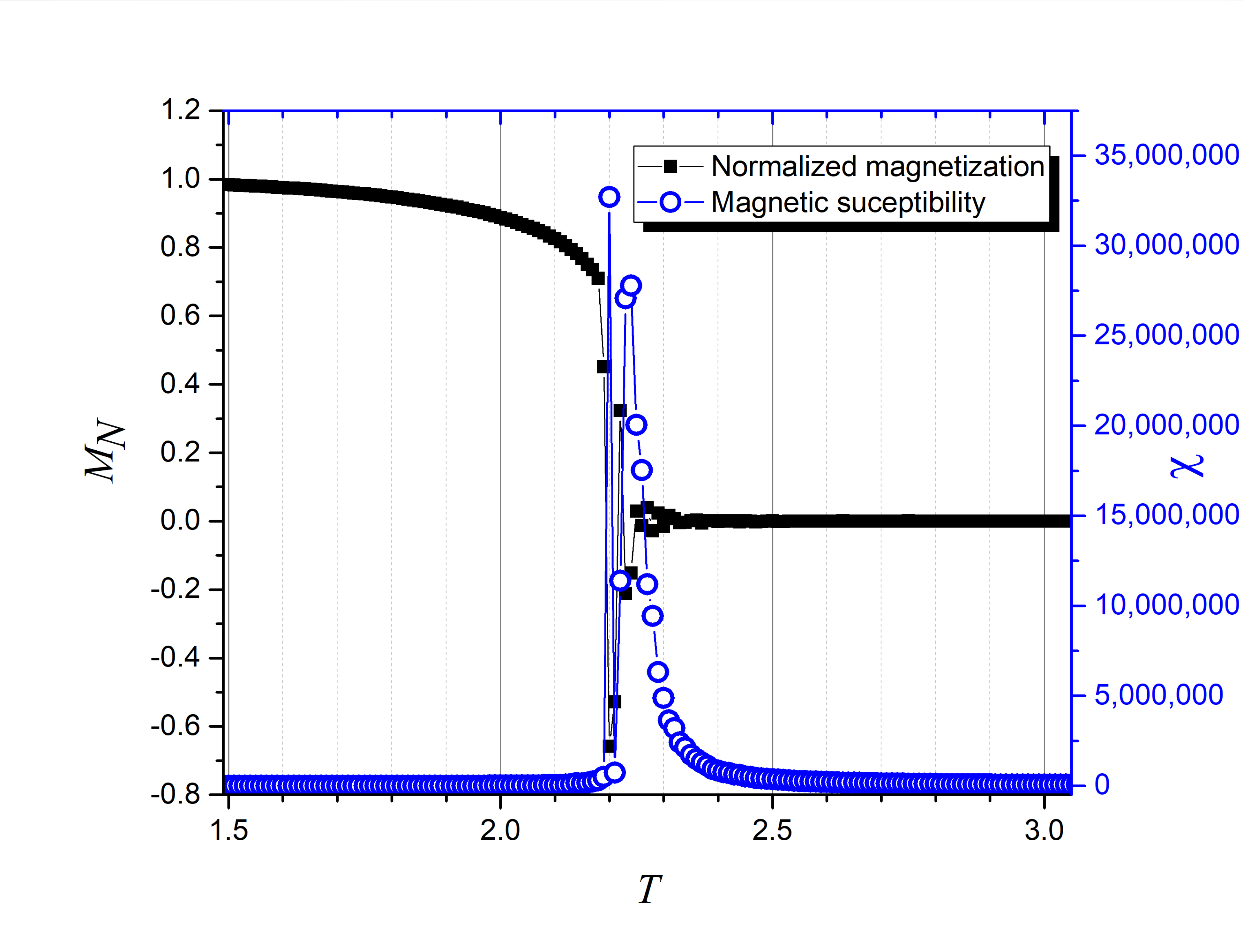


I□□□G: E□E□G□, □□ECIFIC HEA□, E□□□□□□





I□□□G: □AG□E□I□A□I□□, □AG□E□IC □□□CE□□IBI□I□□



Ergodicity breaking

[illegible]HA[illegible] E[illegible]

- [illegible] R=120,000 [illegible].
- A [illegible] f_i [illegible] U_i.
- [illegible] p_i [illegible] $p_i = f_i/R$.
- Leading to the Shannon entropy *h(T)* summing over the microstates (*i*) or the levels (*j*):

$$h(T) = -\sum_{i}^{microstates} p_i \ln(p_i) = -\sum_{j}^{levels} f_j\, p_j \ln(p_j) \quad ; \quad p_i = p_j \quad ; \quad \sum_{i}^{levels} f_i = R$$

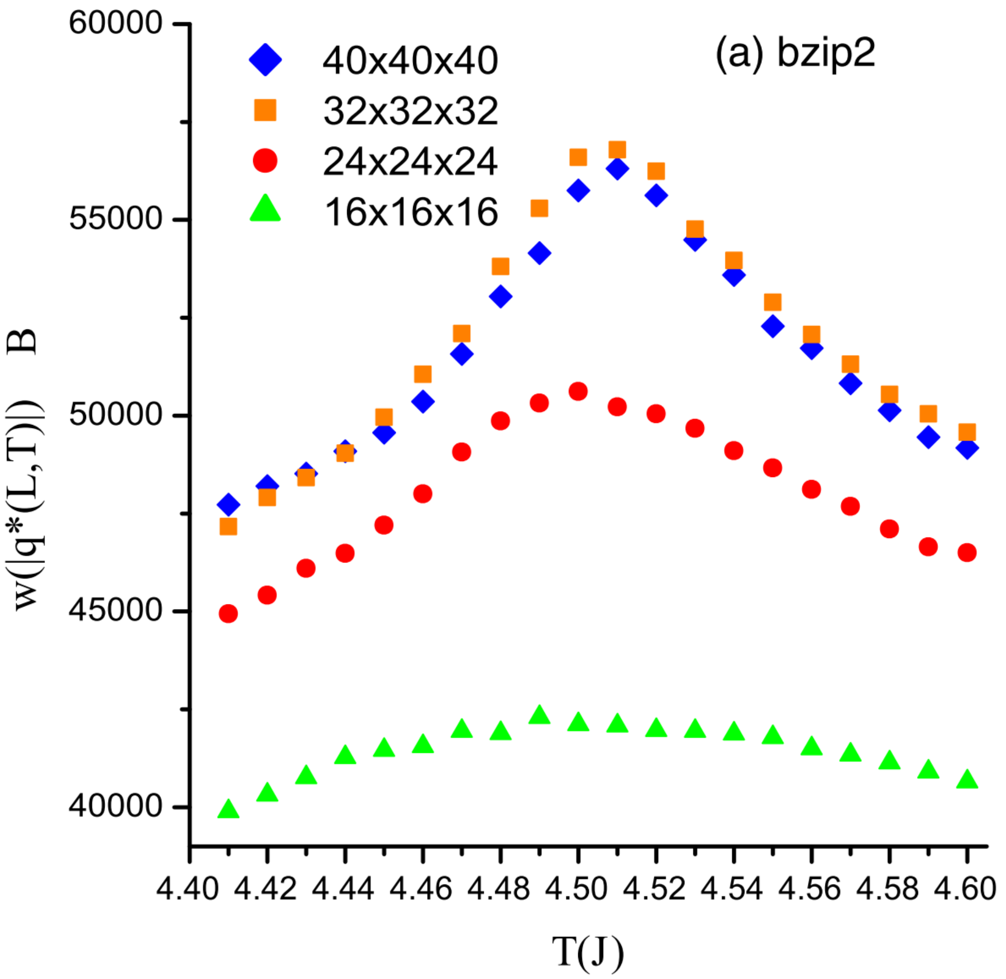
[illegible]ABI[illegible] ([illegible]E[illegible] F[illegible] [illegible]F E[illegible]?)

- A [illegible] ( ) [illegible]
- [illegible] w [illegible]
- [illegible] w^*
- [illegible] ζ [illegible] w^*/w
- Any compressor could be used here, but not all give the same results. Optimization!!

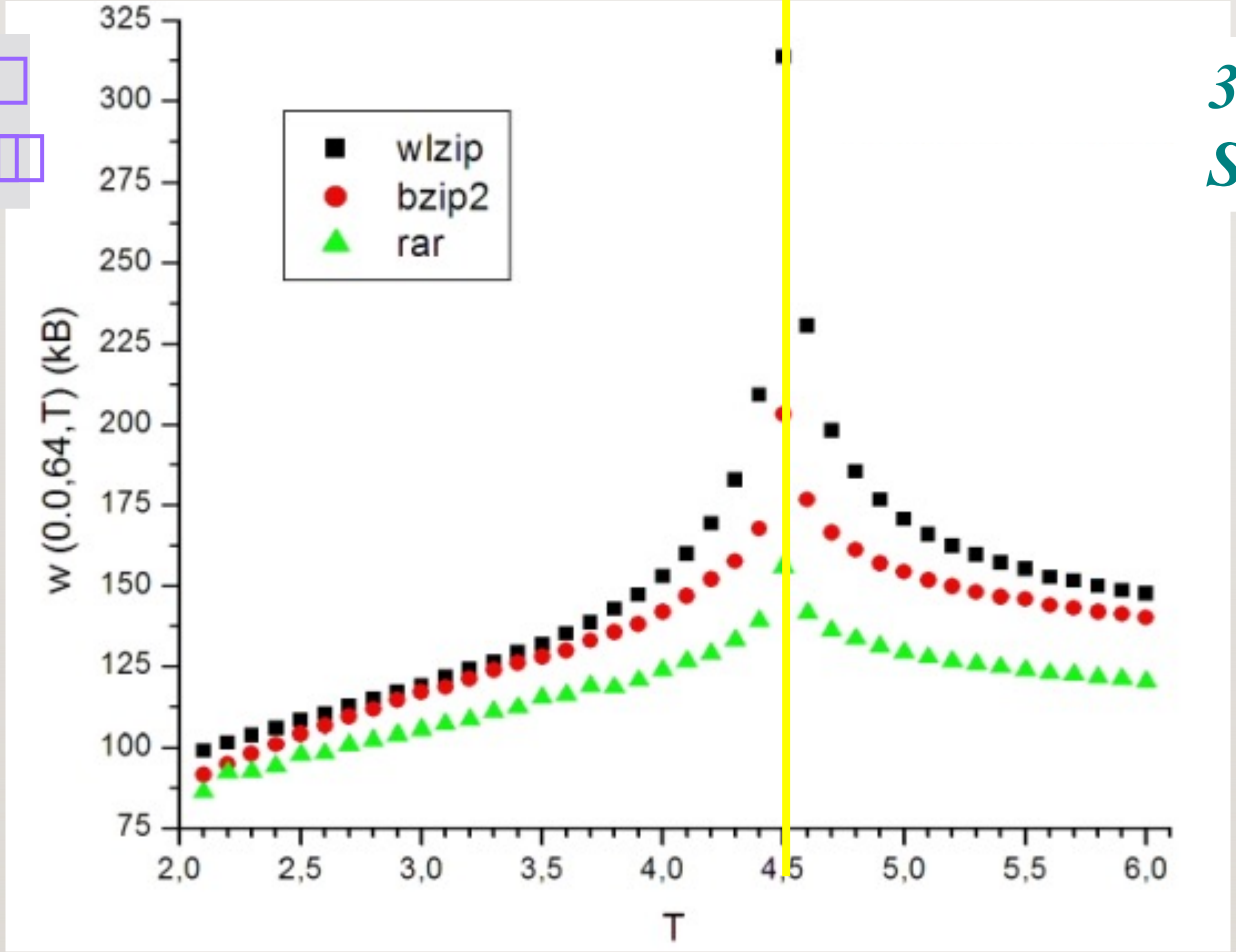
$$(\mu = \vartheta =)\ \zeta = \frac{w^*}{w}$$

[illegible]

3D I□□□G □□DE□(□C=4.507□)



[illegible]

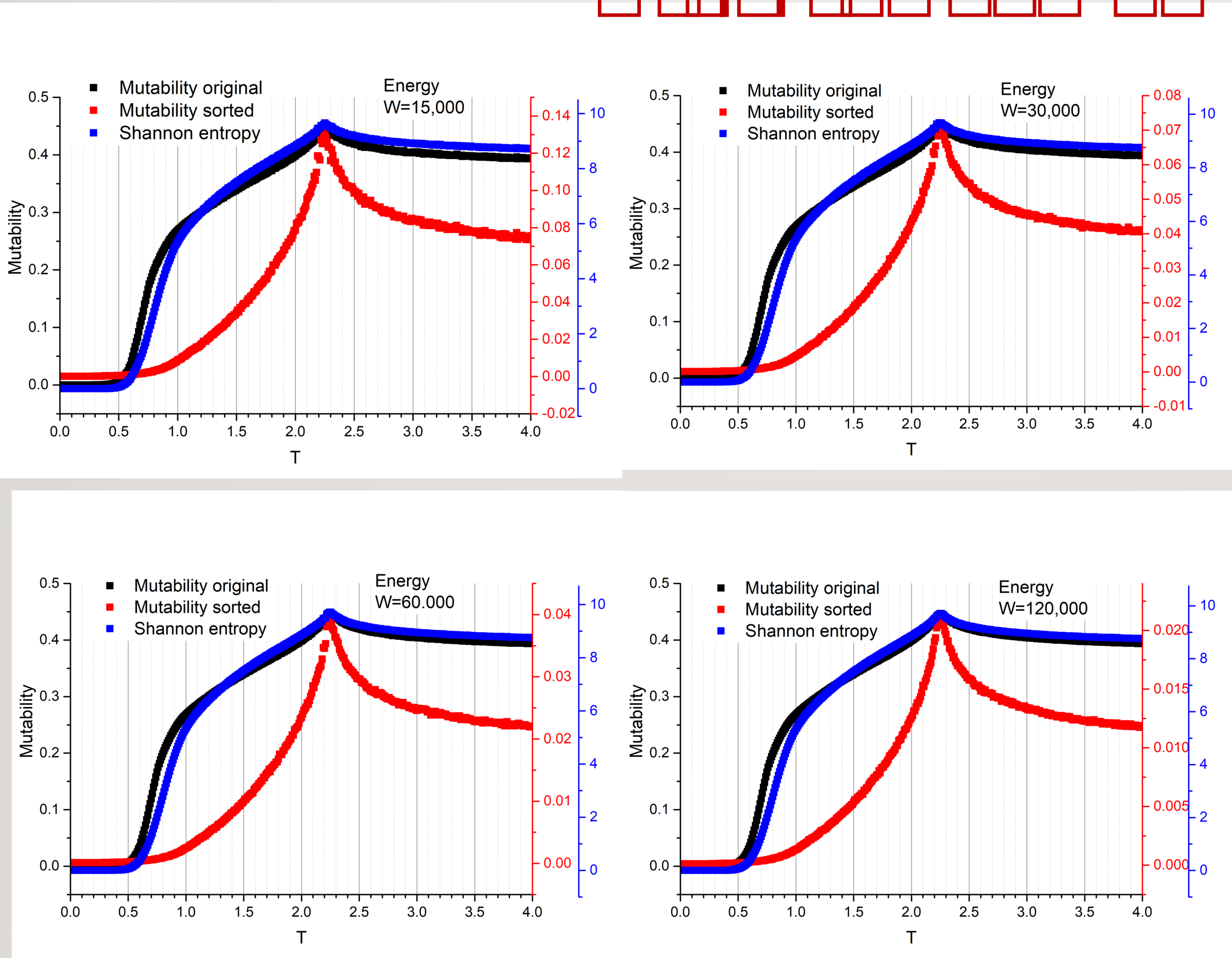


3D Ising ferromagnet
*Size 64*64*64*

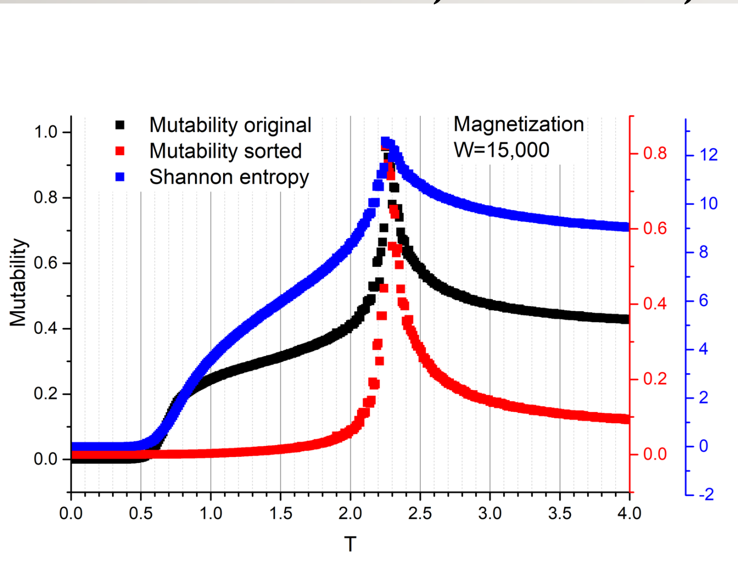
[illegible]

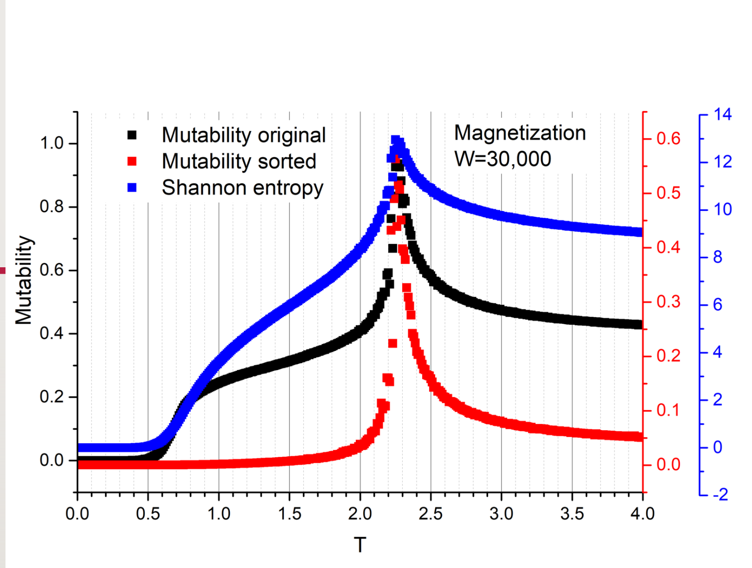
□E□□□□F□□2D, □=128 BA□ED □□E□E□G□□E□□E□CE;

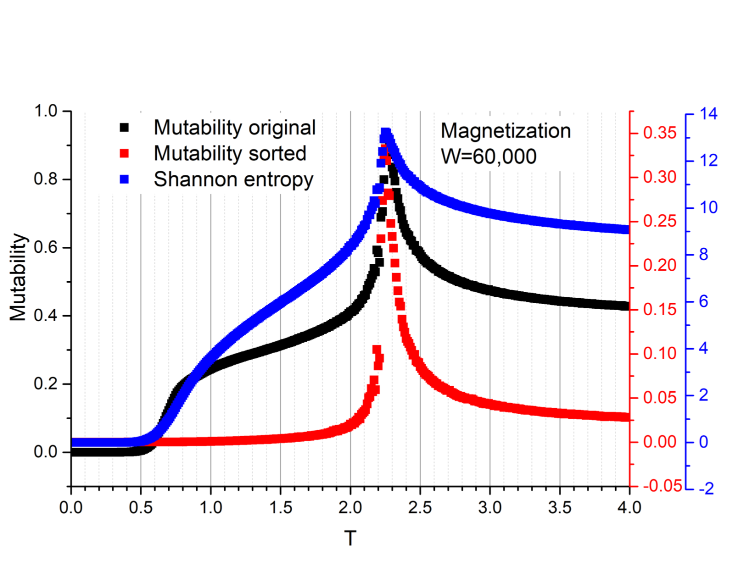
□ □□□F□□□ □□□ □□

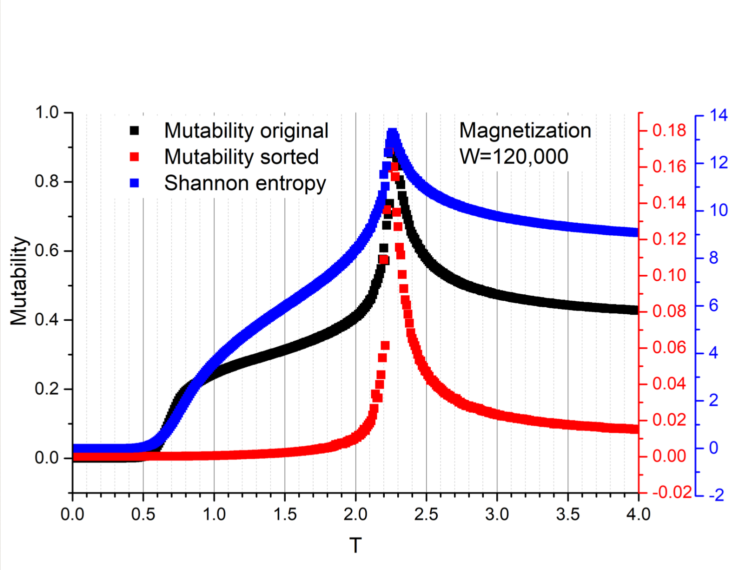


I□□G 2D; □=128, BA□ED □□ □AG□E□I□A□I□□ □E□□E□CE□









[illegible]

- [illegible]
- [illegible]
- [illegible]

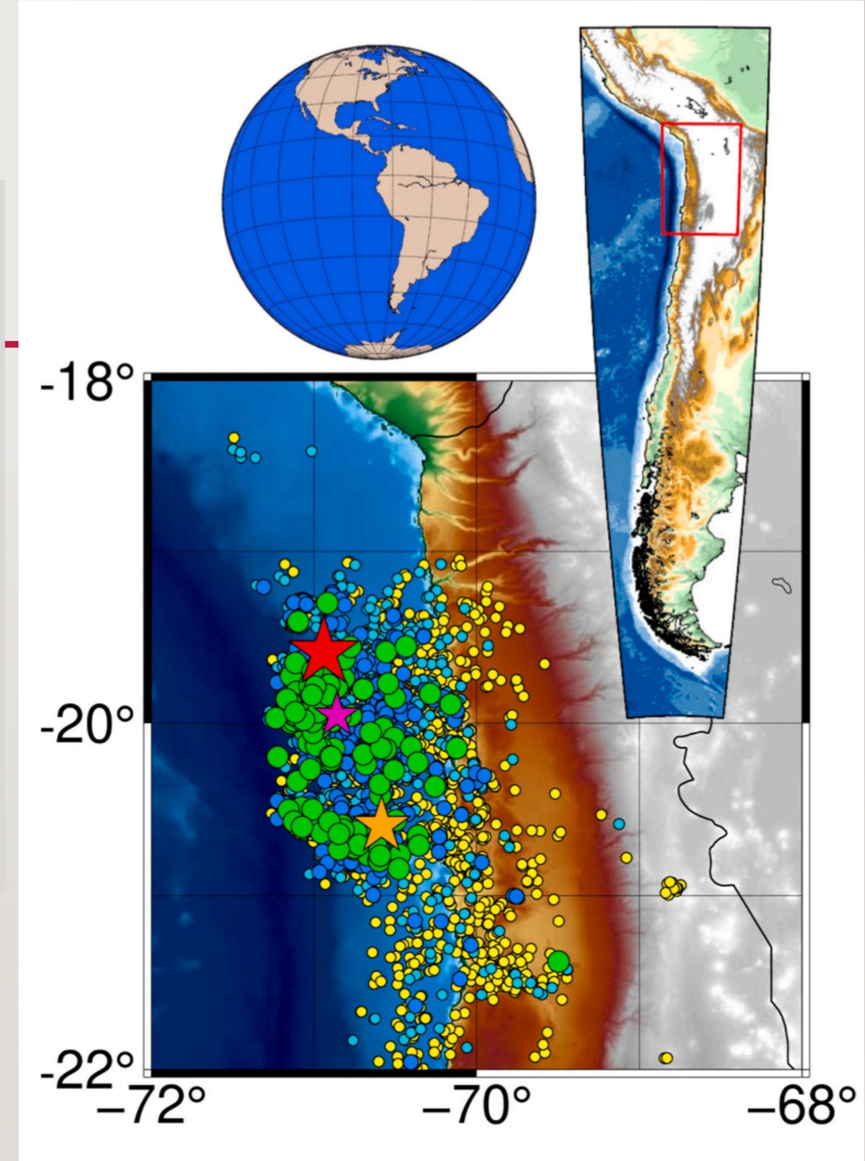
APPLICATION TO REAL DATA SEQUENCES (WITH THE COLLABORATION OF GONZALO SARAVIA)

- [illegible]-[illegible]: C[illegible] [illegible] (E[illegible] 23 (2021) 1019) ([illegible], F. [illegible]; [illegible] F[illegible])
- [illegible]: ζ [illegible] ([illegible] E 101 (2020) 022104, (A. [illegible]-[illegible], [illegible]; [illegible] A[illegible]) [illegible] A, [illegible], D[illegible])
- [illegible] ([illegible] A[illegible]. [illegible] H[illegible] 10 (2016) 217-223).
- C[illegible]/[illegible] 2 [illegible] ([illegible], 2023) ([illegible] C[illegible] B[illegible], A. [illegible]-[illegible] A[illegible])
- [illegible] ([illegible] E[illegible] 126 (2018) 724-735; [illegible]. [illegible]; [illegible] D[illegible] DE).
- E[illegible] 3 [illegible]: ([illegible]) E[illegible] 25 (2023) 1947; [illegible]) [illegible] H[illegible] E[illegible] 23 (2023) 1911-1920; [illegible]) C[illegible], [illegible] F[illegible] 165 (2022) 112874, [illegible] D[illegible] CH; A[illegible] A[illegible] E[illegible]).
- A[illegible].

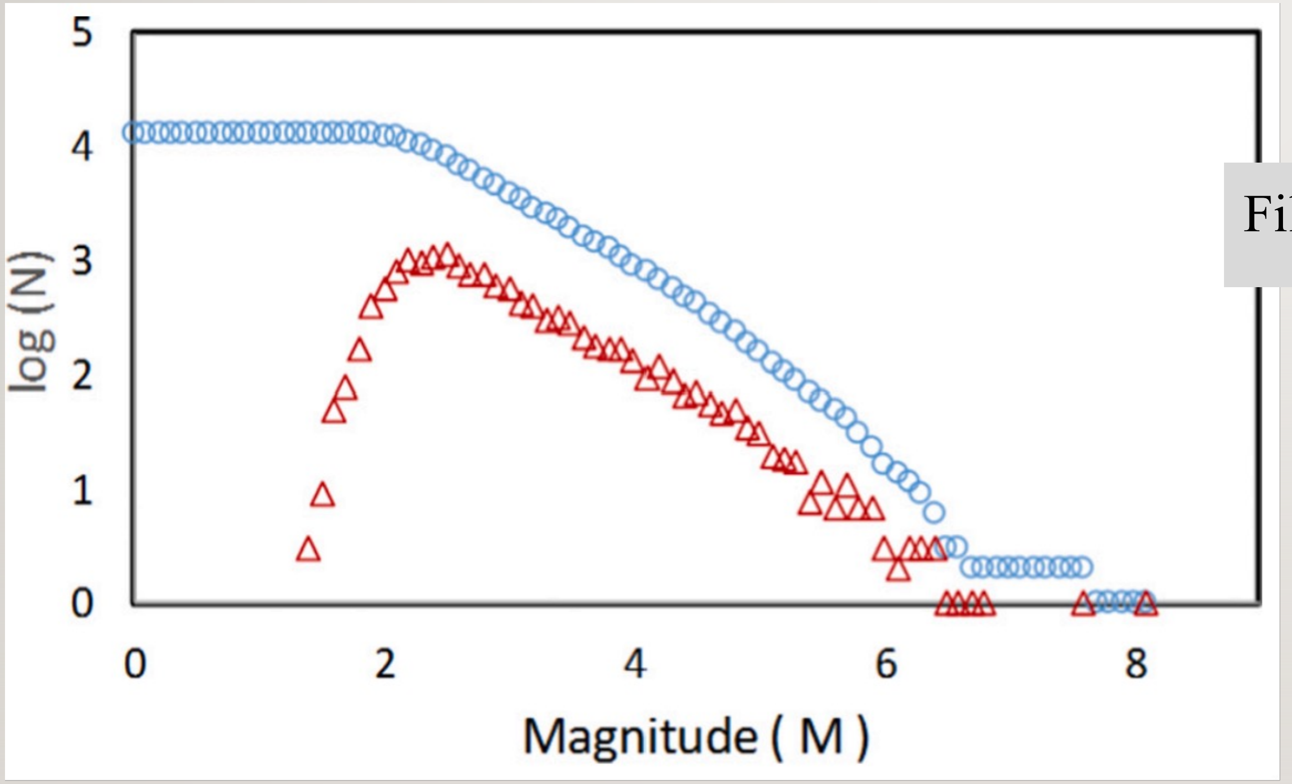
DEFINITION OF THE SEISMIC SEQUENCE

- Seisms related to the **Mw 8.1 Iquique earthquake**, on April 1, 2014.
- Use the Integrated Plate Boundary Observatory Chile (IPOC) catalog, which sets dates: from 2007.01.01 up to 2014.12.31 (Filter #1).
- Filter # 2: Seisms within rectangle 18-24S and 68-72W.
- List of seisms Mw6.3 and larger, within these conditions:

Year	Month	Day	Magnitude	Latitude	Longitude	Depth
2014	**3**	**16**	☆ **6.6**	**-19.95476**	**-70.85965**	**17.86**
2014	**3**	**17**	**6.4**	**-19.97812**	**-70.95194**	**21.09**
2014	*3*	*22*	*6.3*	*-19.74193*	*-71.03003*	*46.32*
2014	**4**	**1**	★ **8.1**	**-19.58927**	**-70.94021**	**19.91**
2014	4	3	6.4	-20.23952	-70.68120	24.34
2014	**4**	**3**	☆ **7.6**	**-20.59462**	**-70.58543**	**21.96**
2014	4	4	6.3	-20.59444	-70.70383	22.50
2014	4	11	6.3	-20.70646	-70.72461	20.72

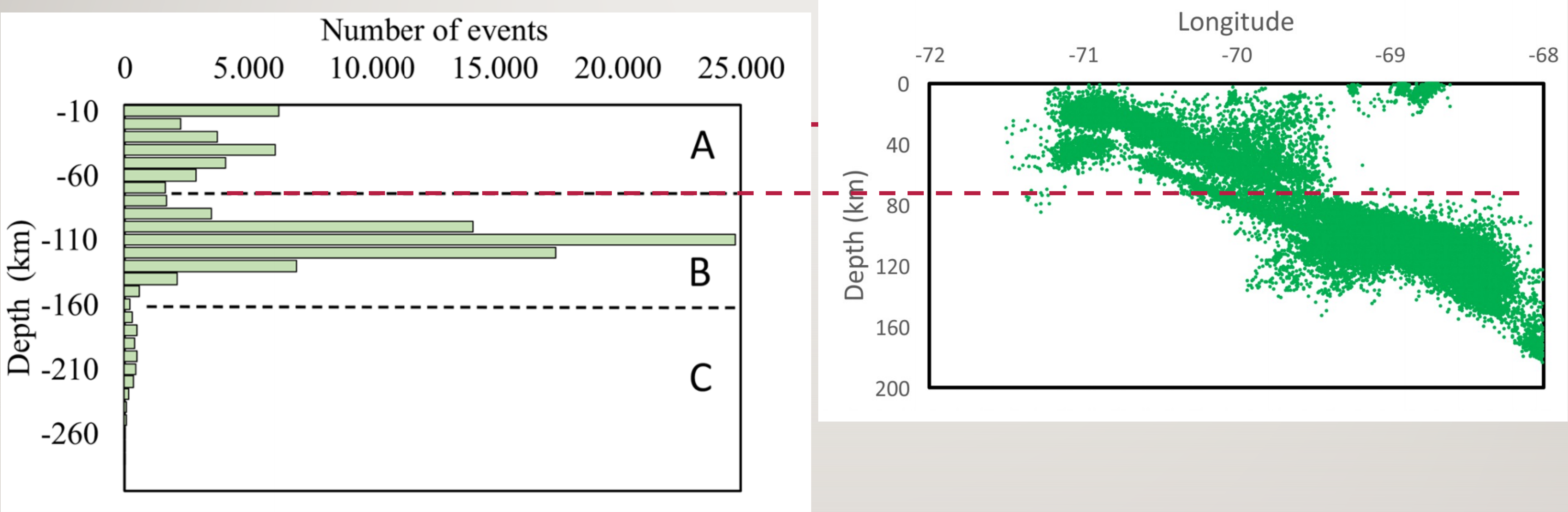


□AG□I□□DE ,□I□E (2014) A□D G□□E□BE□G-□ICH□E□



Filter # 3: Seisms with magnitude Mw over 2.2.

DE□□H B□I□□C (□EF□) ; □□BD□C□□□□ □□□□G □A□□□DE (□IGH□)



Filter #4: Seisms with depth up to 70 km are left for the analisis

The total number of seisms after the 4 filters is 10640.

HA[illegible]D[illegible]G [illegible]F DA[illegible]A

- D[illegible].
- [illegible]
- D[illegible]

□□A□□□□□E□□□□□□□□A□D EA□□H□□A□E□

(□□□ADA□A. A□D □□□□□□□G□-C□□□A, □.: □□□-E□□E□□□E E□□□□□□A□D F□AG□E□□□A□E□□□□I□□E□AC□□□□ □□DE□ F□□EA□□H□□A□E□C□□□□□□. □□□□□I□EA□□C□I., 117, 106906, H□□□□://D□I.□□G/10.1016/□C□□□□.2022.106906, 2023.)

Tsallis entropy has been expressed as

$$S_T = \frac{1}{q-1}\left[1 - \sum_{i}^{\Omega} p_i^q\right] ,$$

where q has to be evaluated for each system. For our seismic distribution we can assign a probability $p(M_i)$ to each magnitude according to the distribution for the 10640 entries. Then we can make use of direct relationships from statistical physics:

$$S(T) = -\sum_{M_0}^{M_{Max}} p(M_i)\ Log(p(M_i));$$

$$\sum_{M_0}^{M_{Max}} p(M_i) = 1;$$

$$\bar{M} = \sum_{M_0}^{M_{Max}} M_i\, p(M_i)$$

The combination of these three conditions by means of Lagrange multipliers and the physical conditions imposed by the Gutenberg Richter method can lead to get the value of q

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□□□□A□□□F □□□E □□□□□□ED □□A□□E□

Autores	Región	q
Sotolongo y Posadas 2004	Sur Península Ibérica (Andalucía)	1,6
	Península Ibérica	1,64
	California	1,65
Silva et al. 2006	Samambaia - Brazil	1,6
	New Madrid - USA	1,63
	Anatolian - Turkey	1,71
Darooneh y Mehri, 2010	Irán	1,78
	California	1,81
Telesca 2010	L'Aquila Italia (Periodo 1)	1,48
	L'Aquila Italia (Periodo 2)	1,74
	L'Aquila Italia (Periodo 3)	1,7
Telesca 2011	California	1,54
Valverde-Esparza et al. 2012	Jalisco (México)	1,7
	Michoacan (México)	1,69
	Oaxaca (México)	1,63
	Guerrero (México)	1,64

[illegible]HA[illegible] E[illegible]

- [illegible] p_i [illegible].
- A [illegible].
- I[illegible].

2.4
4.0
3.8
4.0
2,2
4.6
3.5
2.9
2.2
3.0
4.1
3.1
3.1
4.3
4.3
3.6
5.5
3.5
2.4
3.5
2.7
2.5
2.2
2.5
2.3
2.5
2.6
3.3
2.4
2.9
2.6
2.8
2.3
2.2
2.2
2.4
3.8
4.1
2.8
2.4
2.5
2.2
2.5
2.8
2.3
2.5
3.4
4.0
4.0
2.9

=50 F

01,2014, 6.6

w

w^*

$$h(T) = -\sum_{j=1}^{beans} p_j(T) f_j \, Log\left(p_j(T)\right)$$

$$\zeta = \frac{w^*}{w}$$

[illegible] AF [illegible] E [illegible] G

[illegible] =50 [illegible] F [illegible] 01,2014, [illegible] :

2.2, 2.2, 2.2, 2.2, 2.2, 2.2, 2.3, 2.3, 2.3, 2.4,
2.4, 2.4, 2.4, 2.4, 2.5, 2.5, 2.5, 2.5, 2.5, 2.5,
2.6, 2.6, 2.7, 2.8, 2.8, 2.8, 2.9, 2.9, 2.9, 3.0,
3.1,3.1, 3.3, 3.4, 3.5, 3.5, 3.5, 3.6, 3.8, 3.8,
4.0, 4.0, 4.0, 4.0, 4.1, 4.1, 4.3, 4.3, 4.6, 5.5

j	M	Map	f_j	$p_j = f_j/R$
1	2.2	0,6	6	0.1200
2	2.3	6,3	3	0.0600
3	2.4	9,5	5	0.1000
4	2.5	14,6	6	0.1200
5	2.6	20,2	2	0.0400
6	2.7	22	1	0.0200
7	2.8	23,3	3	0.0600
8	2.9	26,3	3	0.0600
9	3.0	29	1	0.0200
10	3.1	30,2	2	0.0400
11	3.3	32	1	0.0200
12	3.4	33	1	0.0200
13	3,5	34,3	3	0.0600
14	3.6	37	1	0.0200
15	3.8	38,2	2	0.0400
16	4.0	40,4	4	0.0800
17	4.1	44,2	2	0.0400
18	4.3	46,2	2	0.0400
19	4.6	48	1	0.0200
20	5.5	49	1	0.0200

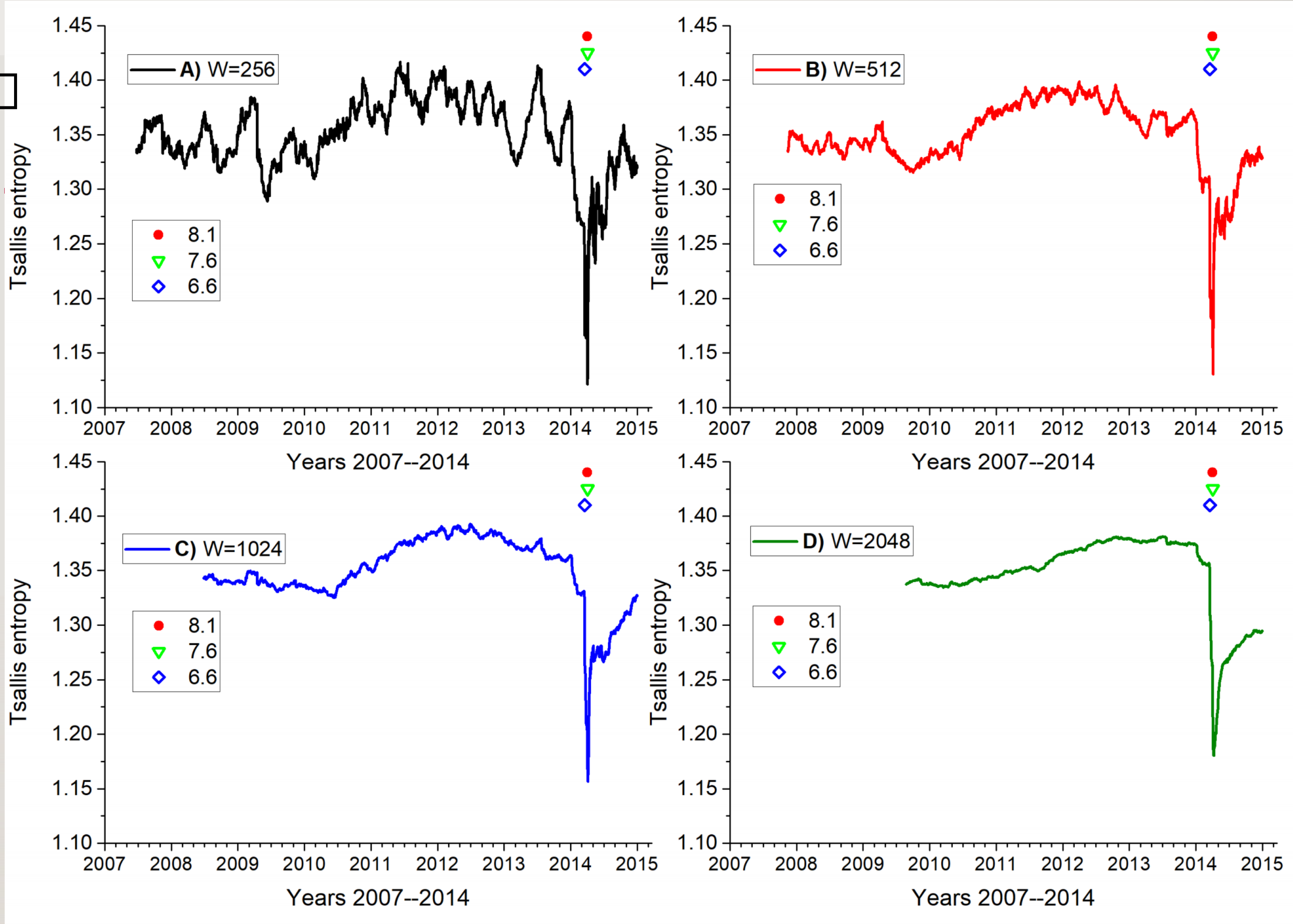
[illegible]A[illegible]A[illegible]F [illegible]ABI[illegible](D[illegible]A[illegible]ICA[illegible]E[illegible]?)

- [illegible], [illegible] , [illegible]
- [illegible], [illegible]
- F[illegible], [illegible]
- I[illegible], [illegible]3 [illegible] $\zeta_{[illegible]}$=0.85, $\zeta_{[illegible]}$= 0.90*, [illegible] $\zeta_{[illegible]}$= 0.78 , [illegible]

Citation: Pasten, D.; Vogel, E.E.; Saravia, G.; Posadas, A.; Sotolongo, O. Tsallis Entropy and Mutability to Characterize Seismic Sequences: The Case of 2007–2014 Northern Chile Earthquakes. *Entropy* **2023**, *25*, 1417. https://doi.org/10.3390/e25101417

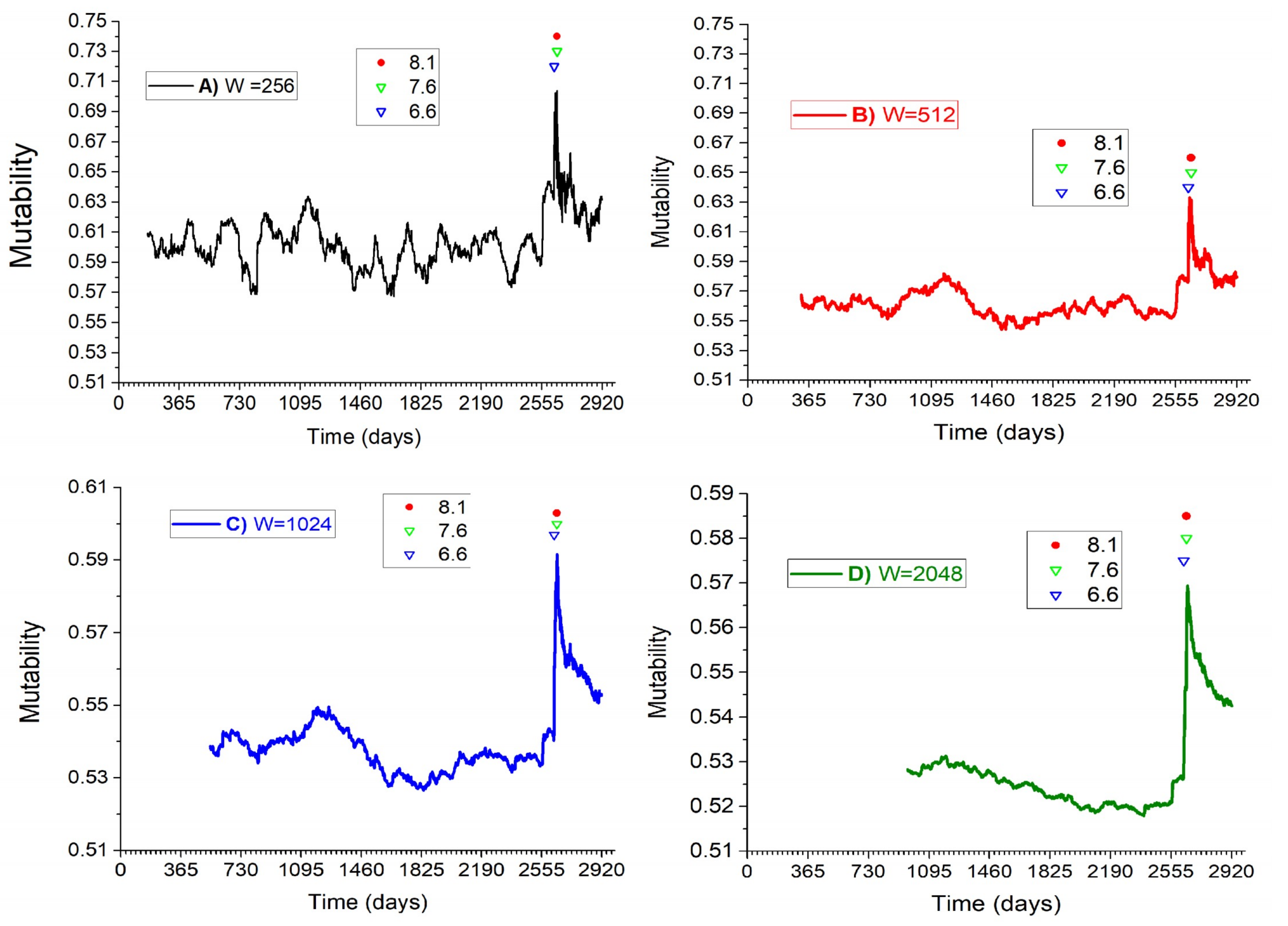
□A□□□E□□□□□□□□I□□□□E (I□□C DA□A)

- □□□□□□(□□□□□□)□□□□□□□ □ □□□□□□□□□□□.
- W=256 □ 2048.
- □□.
- □□□□□□□□□□□□□□□□□□□□2007-14.
- B□□□□□□□□□□□□□ S_T □□□□□□□□□□□□□□□□□□□□□□□□2014.04.01



ABI I E

- =256 2048.
- 2007-14.
- B ζ 2014.04.01
- S_T:
- S_T , , .
- : .



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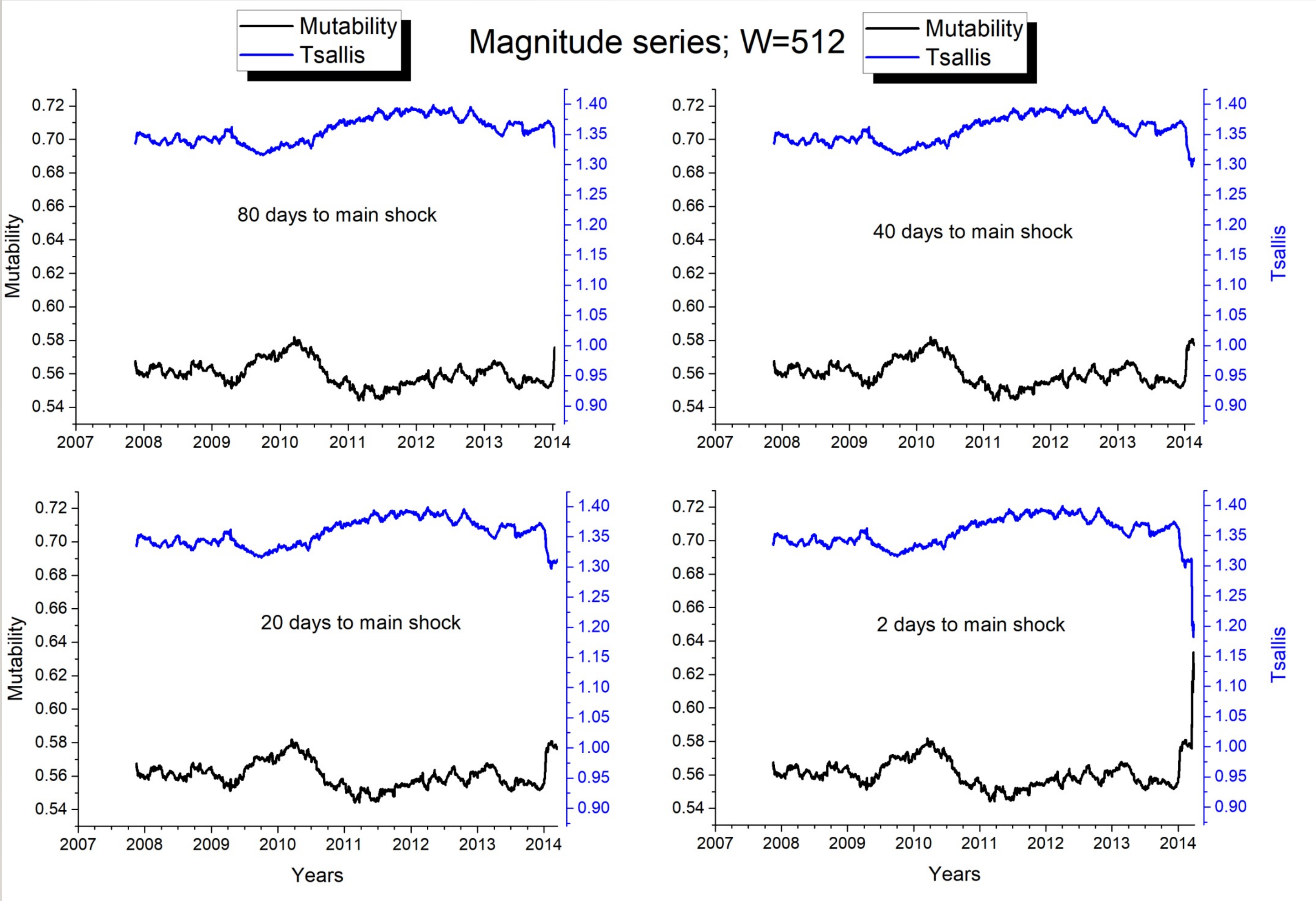
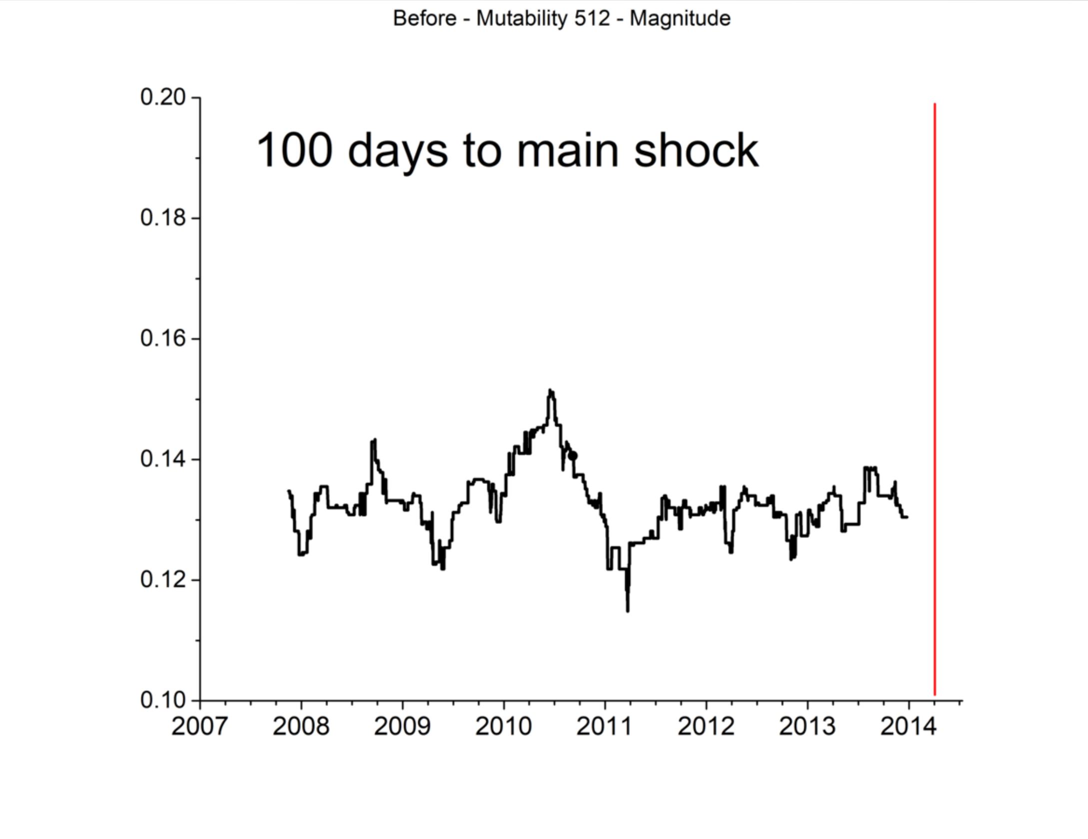

Magnitude series; W=512
Mutability
Tsallis
80 days to main shock
40 days to main shock
20 days to main shock
2 days to main shock
Mutability
Tsallis
Years
0.72
0.70
0.68
0.66
0.64
0.62
0.60
0.58
0.56
0.54
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
2007
2008
2009
2010
2011
2012
2013
2014

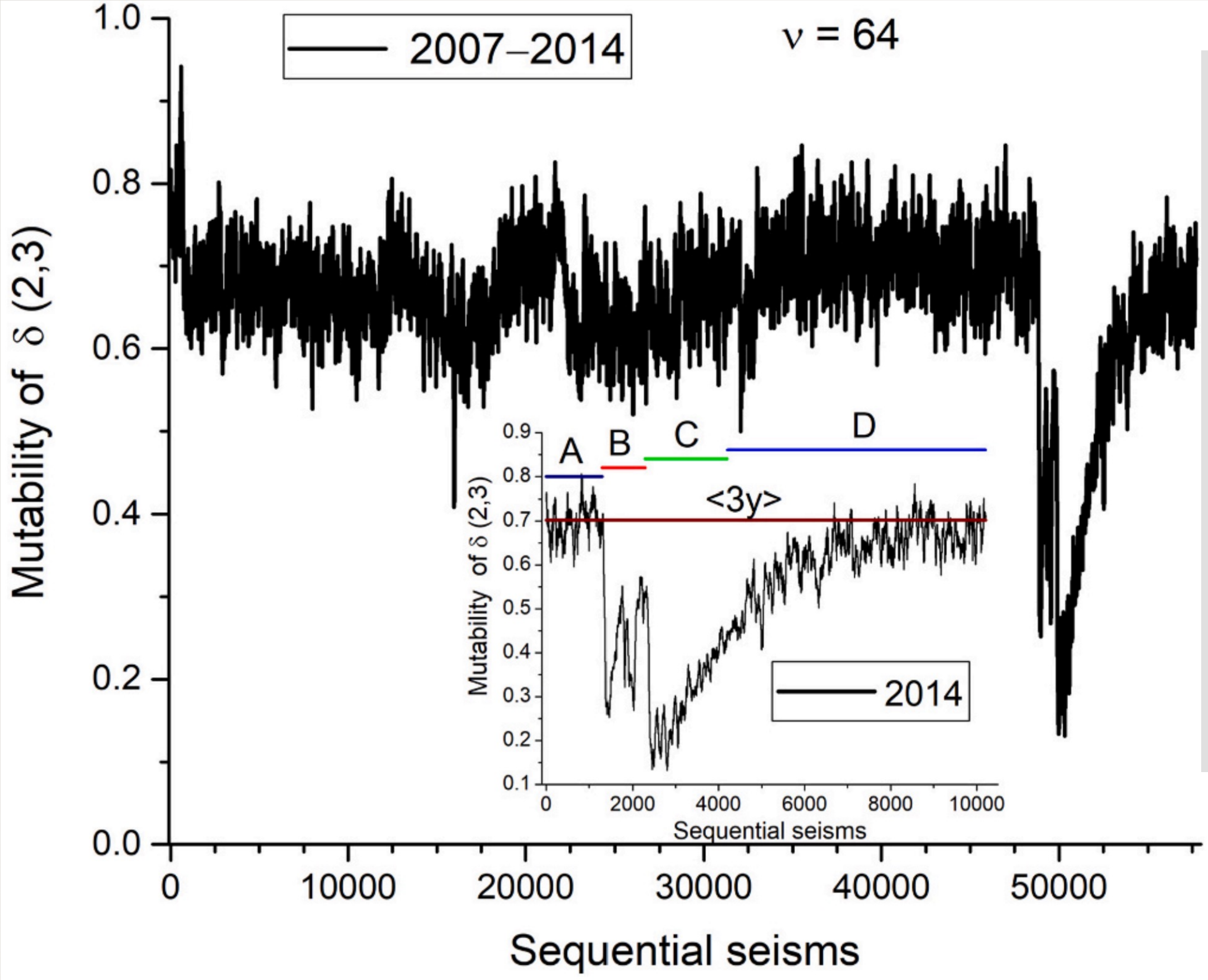

Before - Mutability 512 - Magnitude
100 days to main shock
0.20
0.18
0.16
0.14
0.12
0.10
2007
2008
2009
2010
2011
2012
2013
2014

[illegible]!

A[illegible]E[illegible]A[illegible]E [illegible]E[illegible] BE [illegible]DIED

- [illegible]
- I[illegible]
- D[illegible]

[illegible]ABI[illegible] C[illegible]EC[illegible]I[illegible]E I[illegible]E[illegible]A[illegible]; [illegible]=64

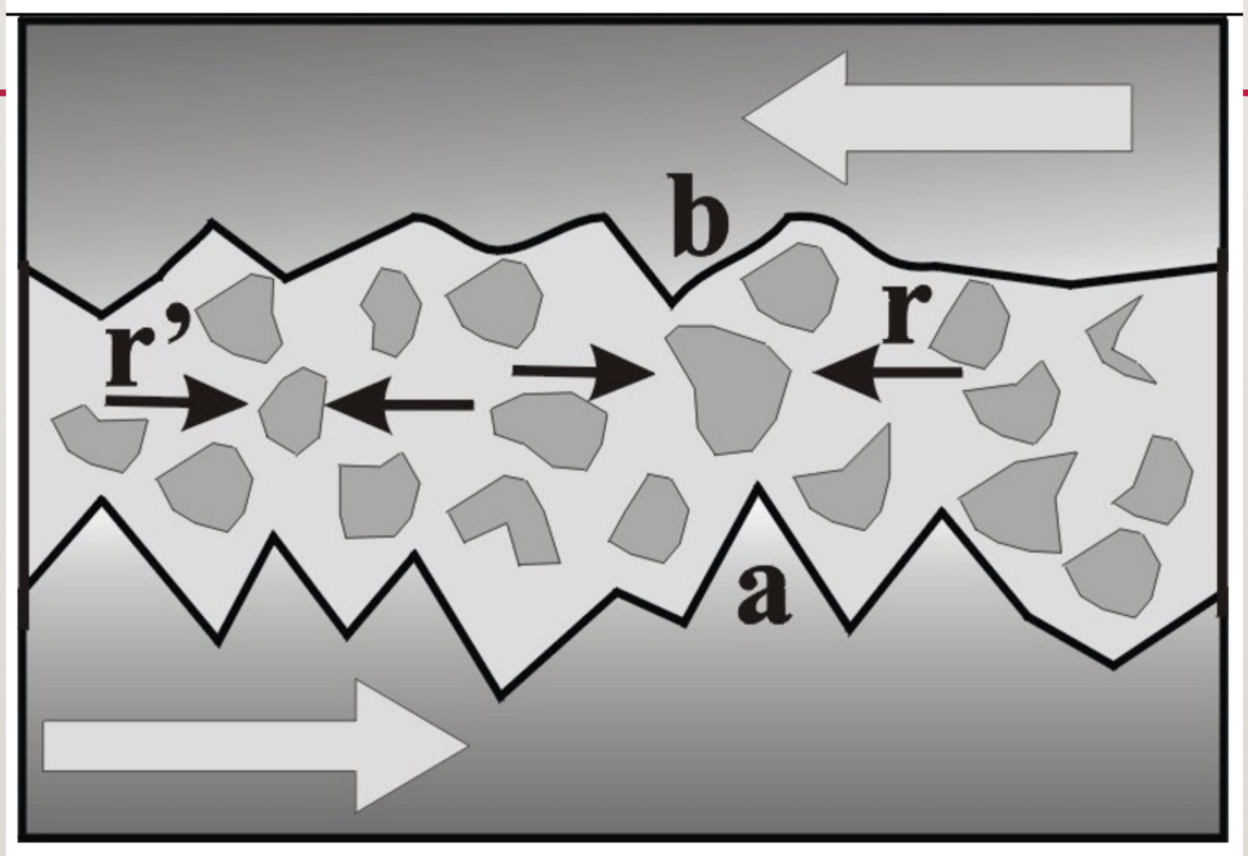


- [illegible]; [illegible]=64.
- I[illegible] I [illegible]: I [illegible]4 [illegible]0002 [illegible]2134
- A [illegible]2,3 [illegible].
- [illegible]

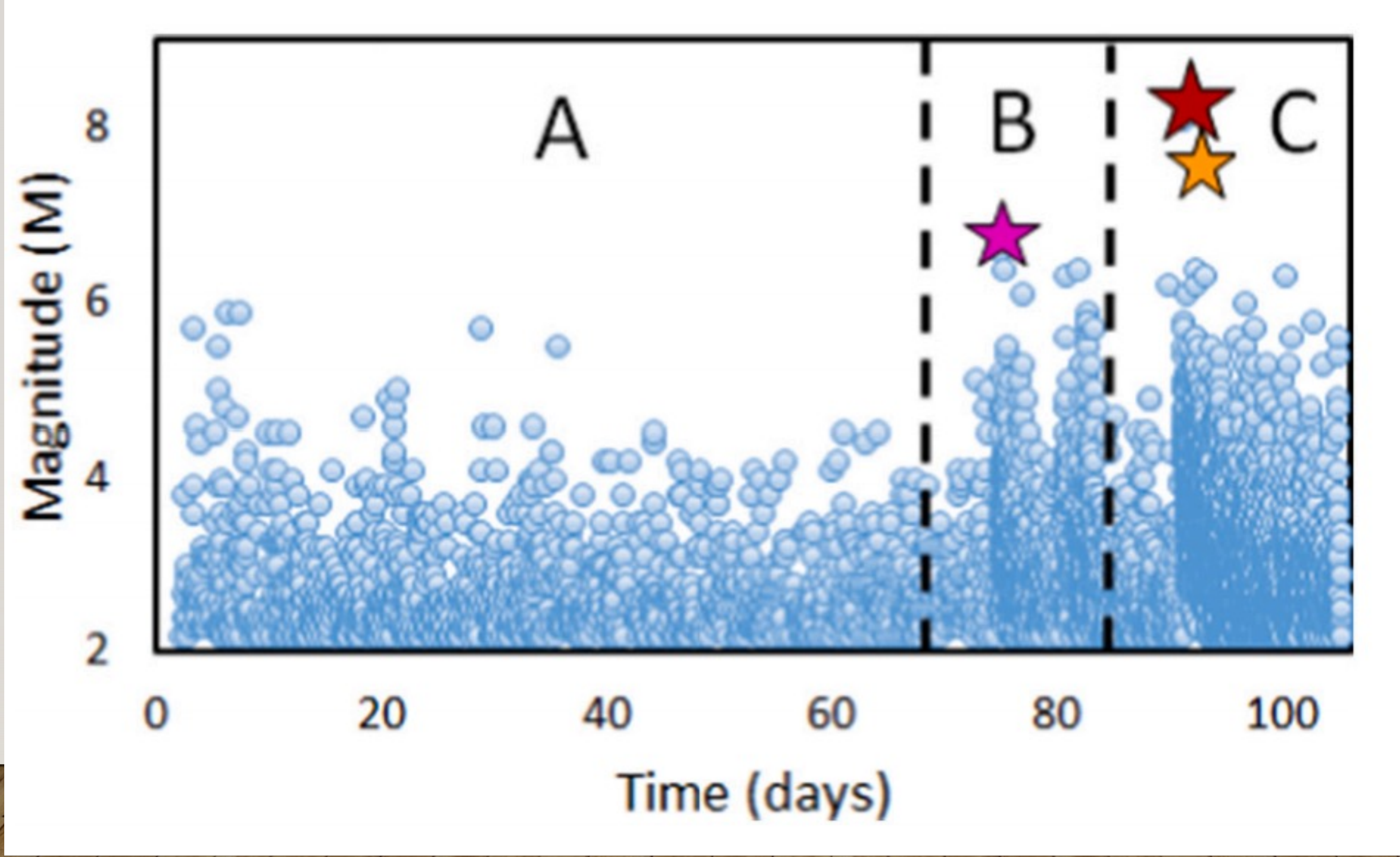
C□□C□□DI□G □E□A□□□;□EC□□□D (A□D □A□□)□A□□

- [illegible] ([illegible]?)
- [illegible] ([illegible]?)
- [illegible]. ([illegible])

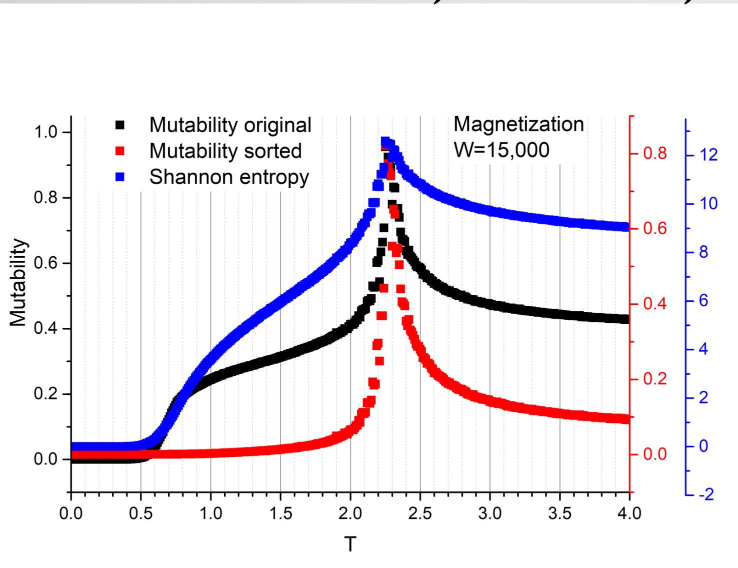
CA□□□□□ □F □□BD□C□□□□: E□□□□□□ACE DEC□EA□E

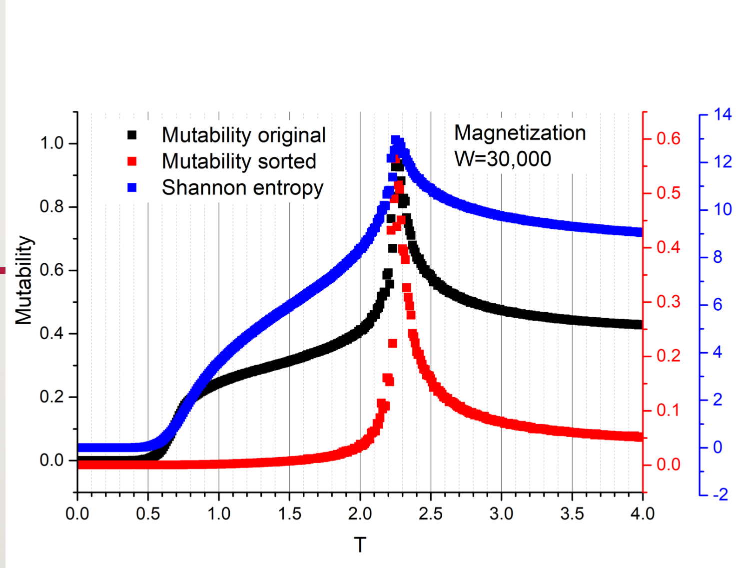


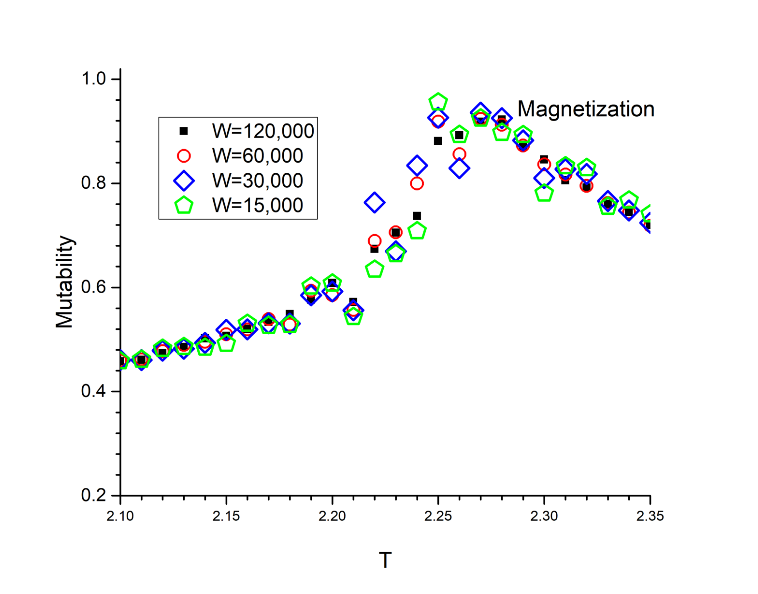
□AG□I□□DE □/□□□I□E DA□BEF□□E A□D AF□E□□□AI□ □EI□□

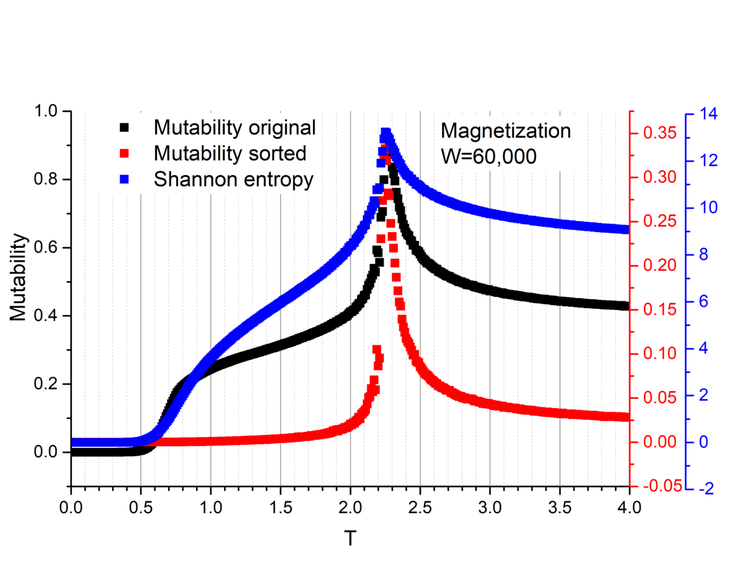


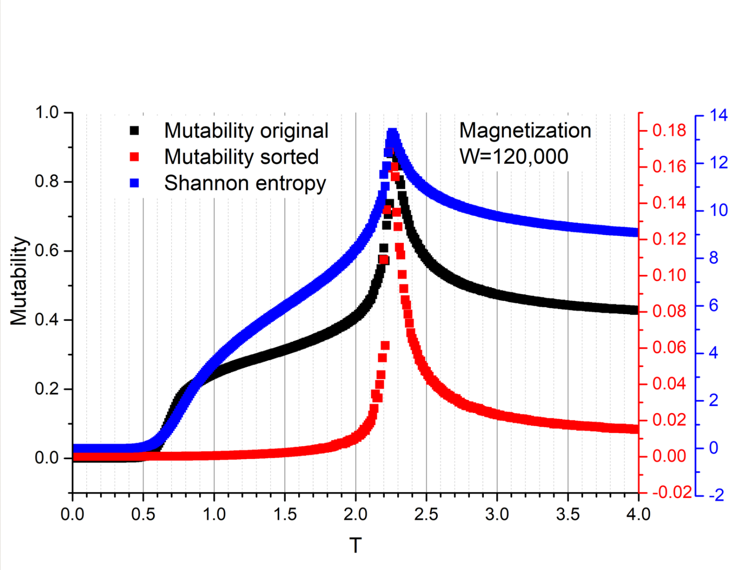
I□□G 2D; □=128, BA□ED □□ □AG□E□I□A□I□□ □E□□E□CE□



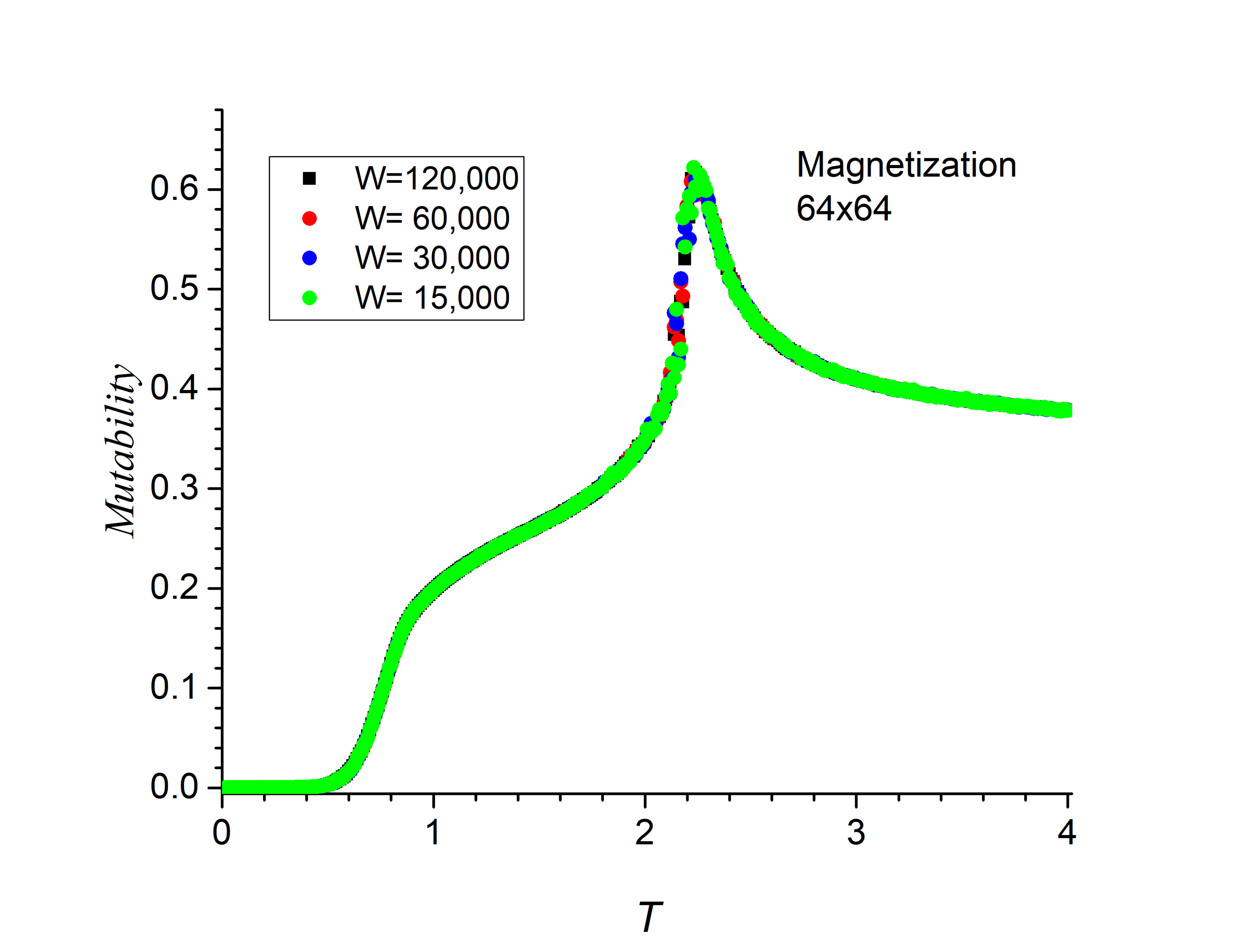


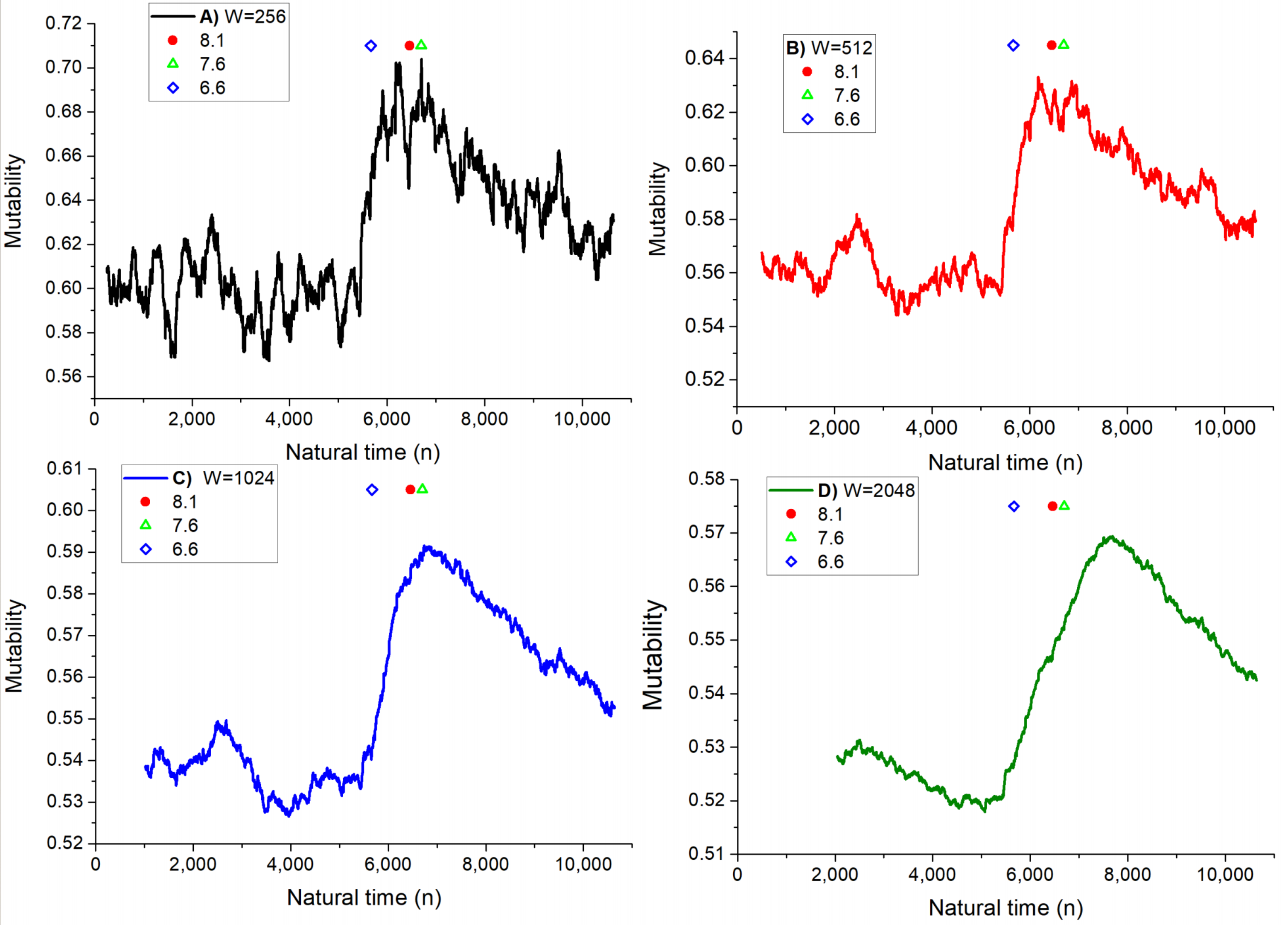


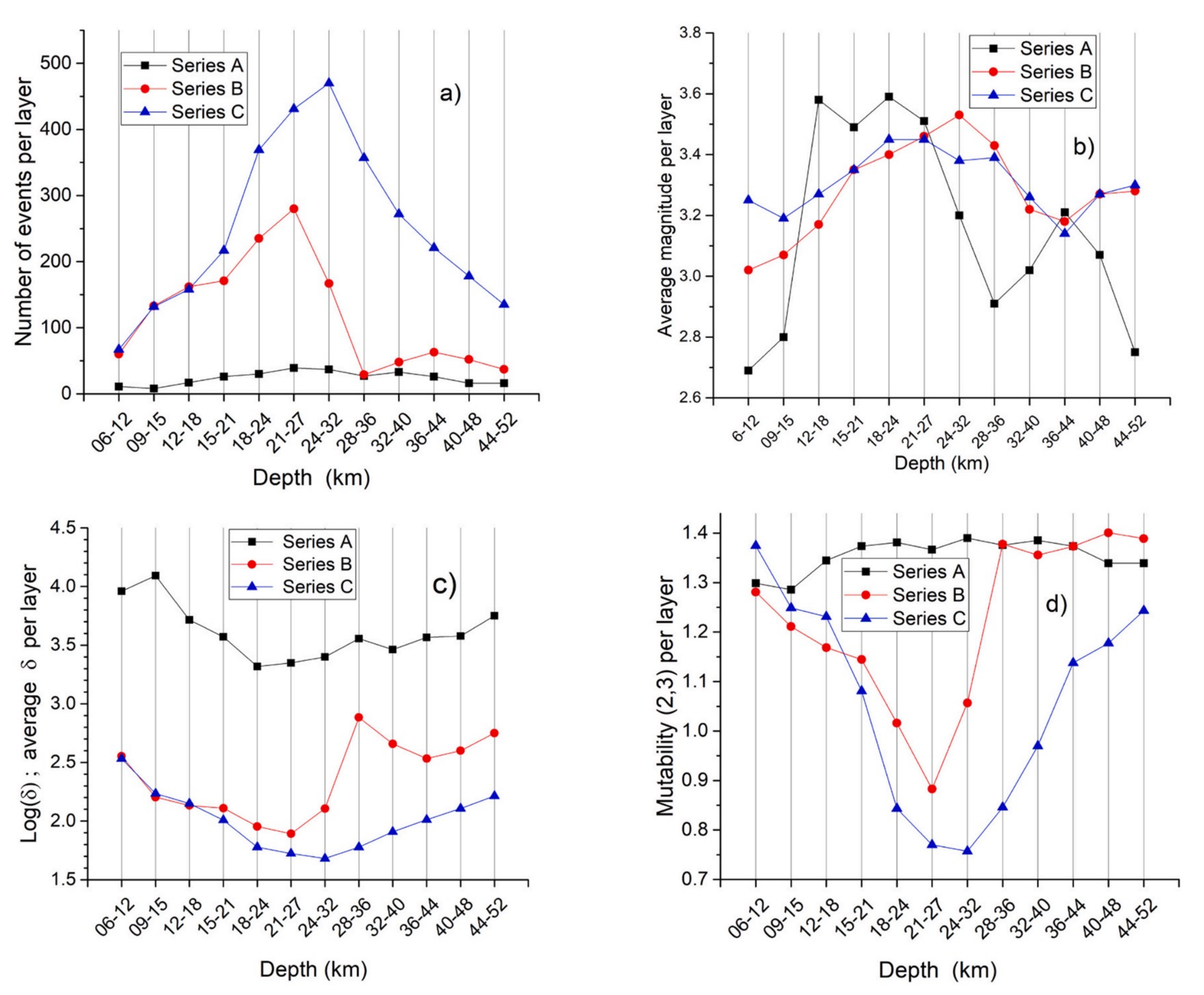




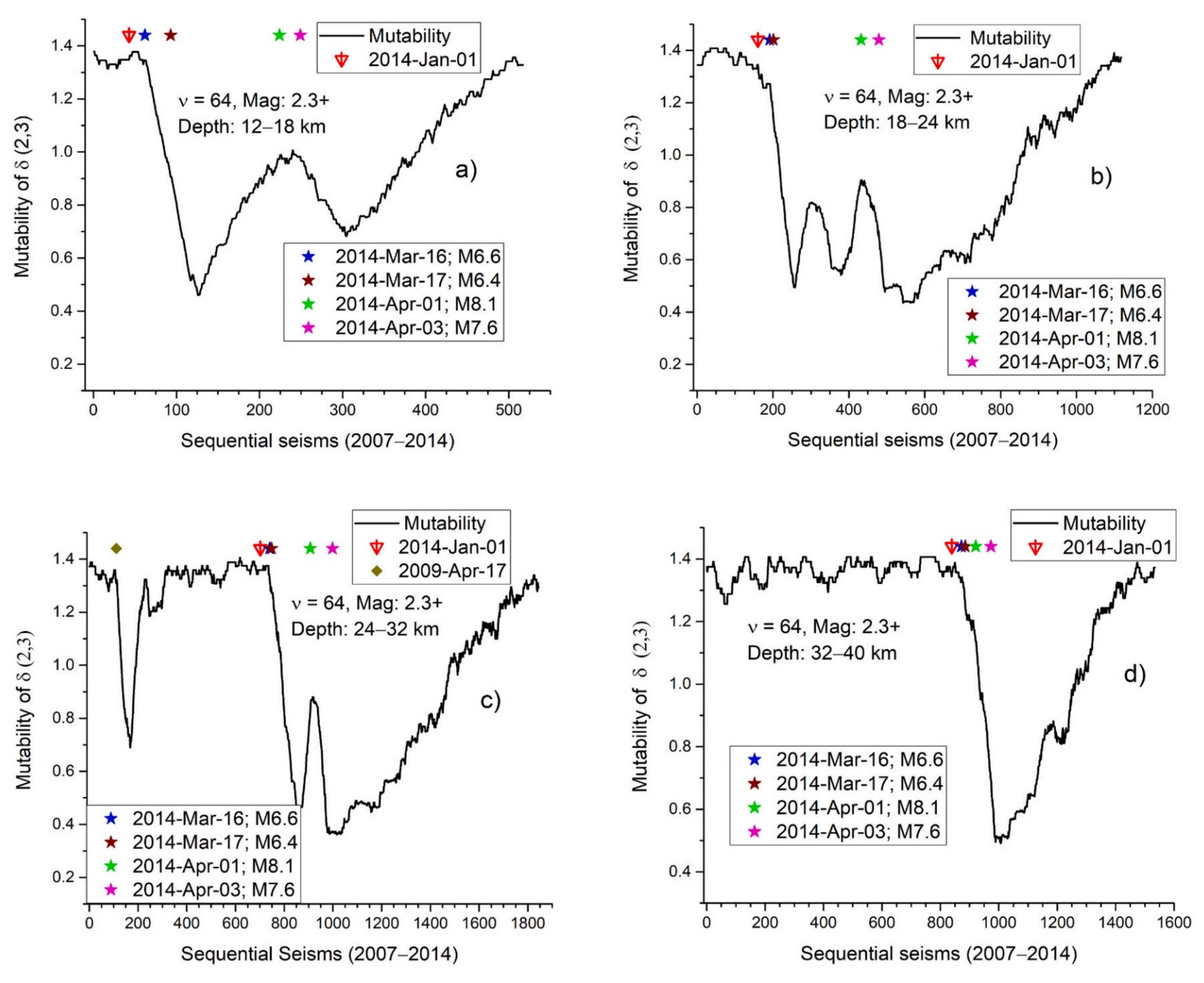
□□□ABI□□□□□ □AG□E□I□A□I□□ DA□A □=64: DIFFE□E□□□



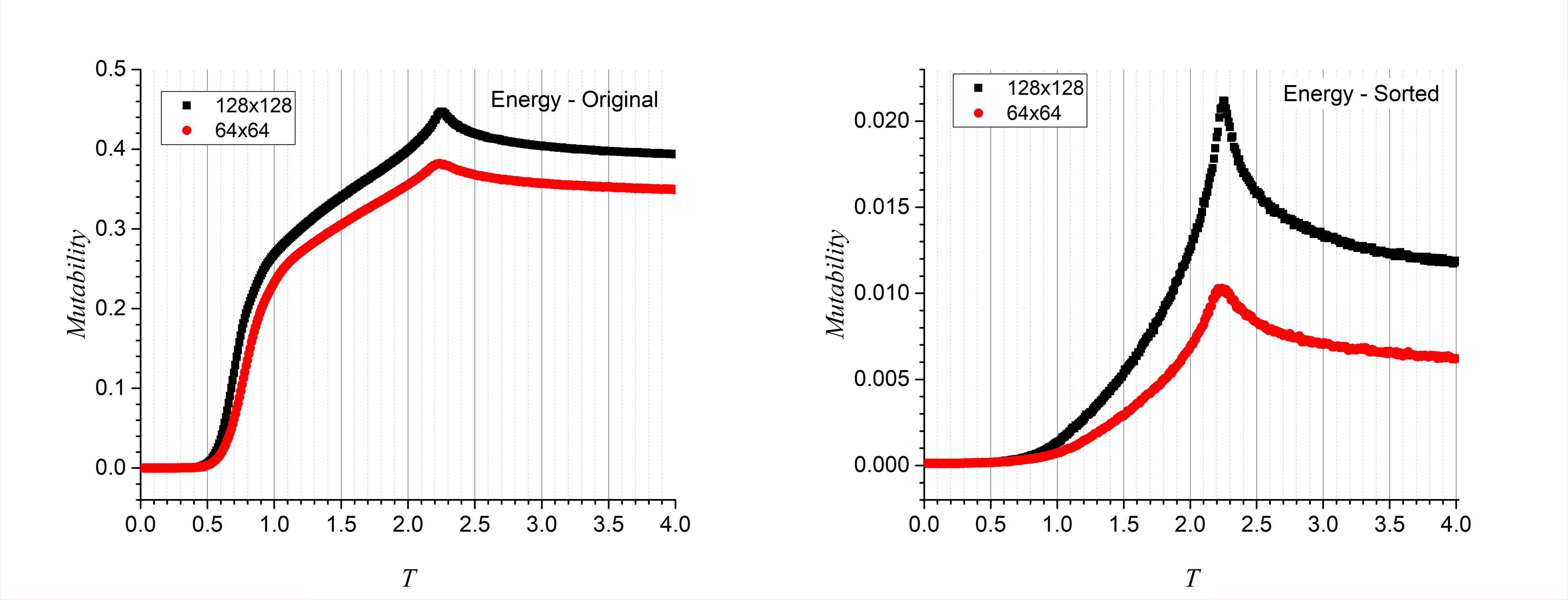

A) W=256
8.1
7.6
6.6
Mutability
Natural time (n)
B) W=512
8.1
7.6
6.6
Mutability
Natural time (n)
C) W=1024
8.1
7.6
6.6
Mutability
Natural time (n)
D) W=2048
8.1
7.6
6.6
Mutability
Natural time (n)



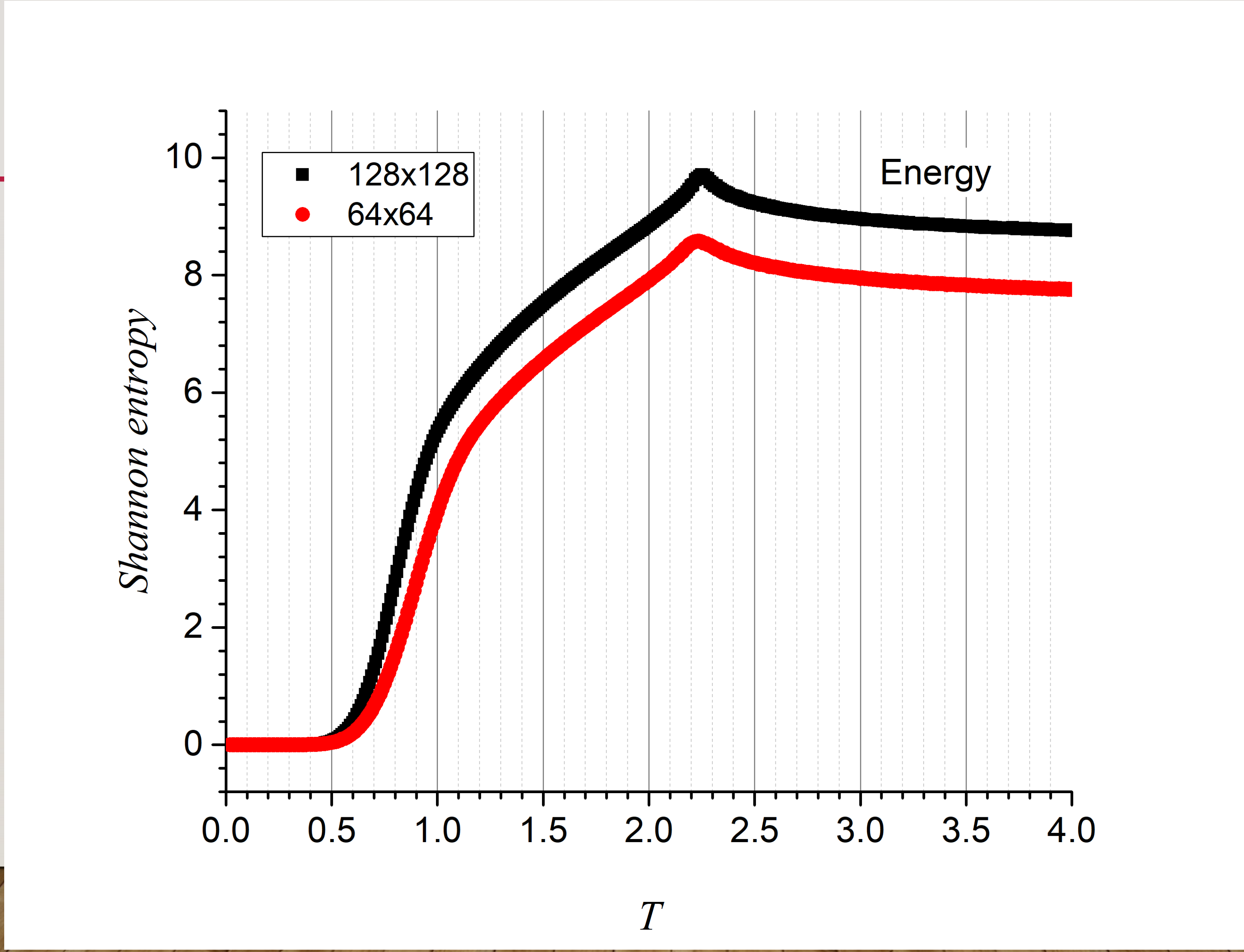
a)
Series A
Series B
Series C
Number of events per layer
0
100
200
300
400
500
06-12
09-15
12-18
15-21
18-24
21-27
24-32
28-36
32-40
36-44
40-48
44-52
Depth (km)
b)
Average magnitude per layer
2.6
2.8
3.0
3.2
3.4
3.6
3.8
6-12
Depth (km)
c)
Log(δ) ; average δ per layer
1.5
2.0
2.5
3.0
3.5
4.0
4.5
d)
Mutability (2,3) per layer
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4


Mutability
2014-Jan-01
ν = 64, Mag: 2.3+
Depth: 12–18 km
a)
2014-Mar-16; M6.6
2014-Mar-17; M6.4
2014-Apr-01; M8.1
2014-Apr-03; M7.6
Mutability of δ (2,3)
Sequential seisms (2007–2014)
Mutability
2014-Jan-01
ν = 64, Mag: 2.3+
Depth: 18–24 km
b)
2014-Mar-16; M6.6
2014-Mar-17; M6.4
2014-Apr-01; M8.1
2014-Apr-03; M7.6
Mutability of δ (2,3)
Sequential seisms (2007–2014)
Mutability
2014-Jan-01
2009-Apr-17
ν = 64, Mag: 2.3+
Depth: 24–32 km
c)
2014-Mar-16; M6.6
2014-Mar-17; M6.4
2014-Apr-01; M8.1
2014-Apr-03; M7.6
Mutability of δ (2,3)
Sequential Seisms (2007–2014)
Mutability
2014-Jan-01
ν = 64, Mag: 2.3+
Depth: 32–40 km
d)
2014-Mar-16; M6.6
2014-Mar-17; M6.4
2014-Apr-01; M8.1
2014-Apr-03; M7.6
Mutability of δ (2,3)
Sequential seisms (2007–2014)

MUTABILITY OF ENERGY DATA: L=128 AND L=64



□HA□□□□E□□□□□□□E□E□G□



128x128
64x64
Energy
Shannon entropy
T
0
2
4
6
8
10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0