

# IS COMPLEX STRUCTURE INEVITABLE IN THE UNIVERSE?

P.C.E. STAMP

7 Pines, May 14<sup>th</sup> 2016



**Physics & Astronomy**  
**UBC**  
**Vancouver**

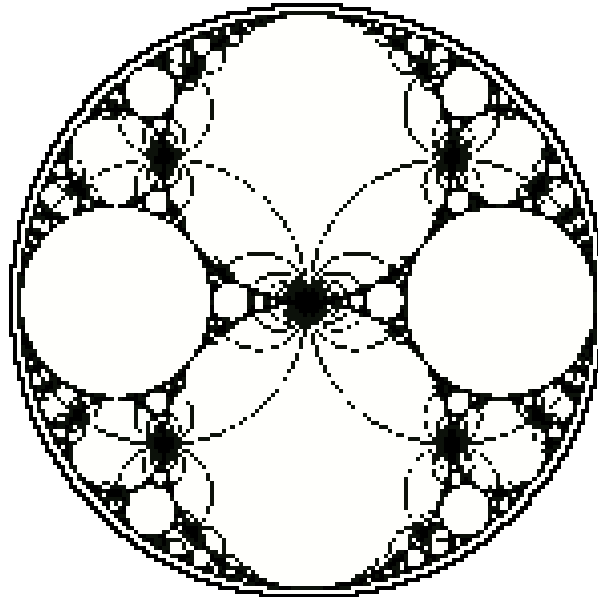


**Pacific Institute**  
**for**  
**Theoretical Physics**

Currently at the COLLEGE de FRANCE

The talk will address the following themes:

- (i) Distribution of entropy and order in the universe
- (ii) Mechanisms for development of complex systems in the universe
- (iii) Some remarks on evolution of complex systems on earth



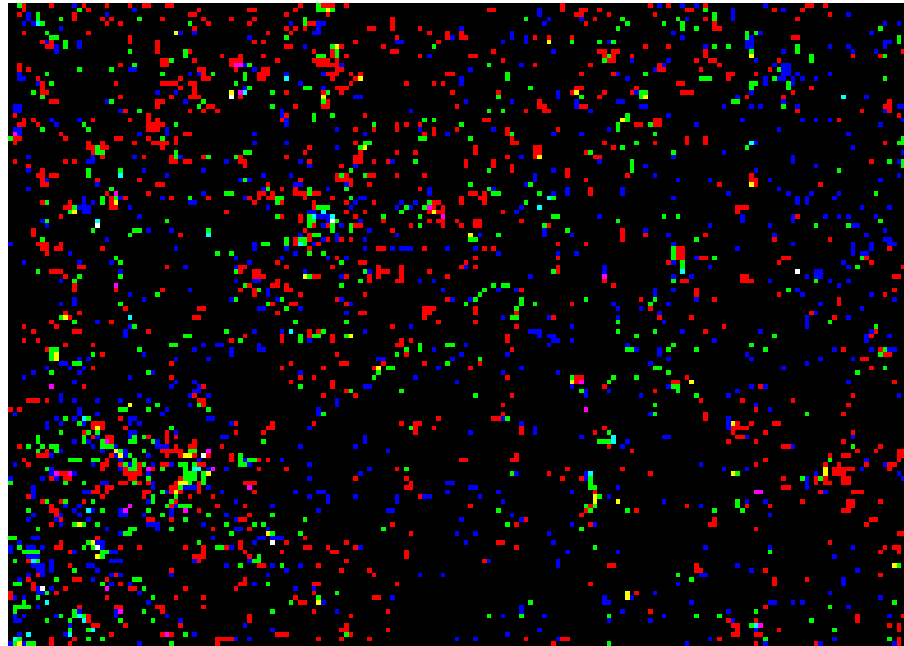
FURTHER INFORMATION:

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Energy/entropy/complexity are distinguished, at many different length scales, by incredible inhomogeneity in the universe. The questions at issue here are

- why & how has this happened?
- is it inevitable? And what possibilities are available?
- will it continue - and if so for how long?

Clearly I don't have the answers to these questions -- certainly not the 2<sup>nd</sup> and 3<sup>rd</sup> -- but they definitely are rather big questions (and our future may depend on them)

NB: The title/figure caption above could read in any one of the combinations:

Distribution of "energy/entropy/complexity" in the "universe/galaxy/biosphere..."

(it was originally an image of energy distribution in a low-temperature solid)

# INHOMOGENEITY on the LARGEST SCALES

Energy in the universe is concentrated in stars and stellar heated dust – that contained in CMB photons, neutrinos, and black holes is down on these by 2 orders of magnitude.

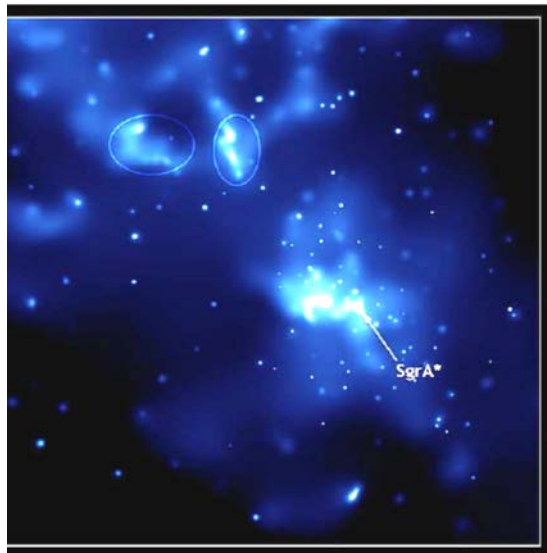
But the entropy is almost entirely in supermassive black holes, outweighing that in CMB photons & relic neutrinos by 14 orders of magnitude! Stars contain a tiny fraction ( $\sim 10^{-23}$ ) of the total entropy in the universe.

There are all sorts of questions here (not least of which: what are the mechanisms by which the entropy increases during stellar collapse to a black hole)? And – what happens to the info in the black hole?

| Objects                              | Entropy    | Energy                               |
|--------------------------------------|------------|--------------------------------------|
| $10^{22}$ stars                      | $10^{79}$  | $\Omega_{\text{stars}} \sim 10^{-3}$ |
| Relic neutrinos                      | $10^{88}$  | $\Omega_{\nu} \sim 10^{-5}$          |
| Stellar heated dust                  | $10^{86}$  | $\Omega_{\text{dust}} \sim 10^{-3}$  |
| CMB photons                          | $10^{88}$  | $\Omega_{\text{CMB}} \sim 10^{-5}$   |
| Relic gravitons                      | $10^{86}$  | $\Omega_{\text{grav}} \sim 10^{-6}$  |
| Stellar BHs                          | $10^{97}$  | $\Omega_{\text{SBH}} \sim 10^{-5}$   |
| Single supermassive BH               | $10^{91}$  | $10^7 M_{\odot}$                     |
| $10^{11} \times 10^7 M_{\odot}$ SMBH | $10^{102}$ | $\Omega_{\text{SMBH}} \sim 10^{-5}$  |
| Holographic upper bound              | $10^{123}$ | $\Omega = 1$                         |

## MASSES of some BLACK HOLES

|                        |                   |
|------------------------|-------------------|
| SDSS J102325.31+514251 | $33 \times 10^9$  |
| H1841+643              | $30 \times 10^9$  |
| ....                   | .....             |
| NGC 1600               | $17 \times 10^9$  |
| .....                  | .....             |
| M87                    | $6.3 \times 10^9$ |
| Cygnus A               | $10^9$            |
| .....                  | .....             |
| M31                    | $230 \times 10^6$ |
| Milky Way              | $4.3 \times 10^6$ |



TOP: Radio map of **Sgr A** complex – distance **26,000** light-yrs



RIGHT: The Monster galaxy **M87**, mass **3.5 trillion** suns, and its jet (length **100,000** lyrs)

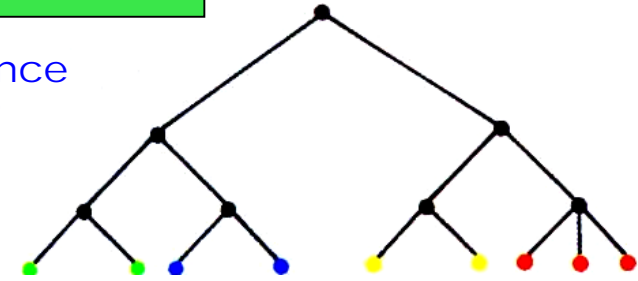
# COMPLEX SYSTEMS/STRUCTURES on EARTH

Imagine a spacefaring intelligence coming across the solar system, and looking for signs of complex structure. Here is what it might find on the moons of Jupiter and Saturn.

Knowing the enormous variety in the structure that exists in the universe, this intelligence would have a very refined & flexible means of defining it – far beyond what we presently understand.

On the moons of Jupiter & Saturn it will certainly find it – both in static structures like crystals (and with hidden order in glasses), or even hydrocarbon chains; and in dynamic structures like flowing liquids or gases.

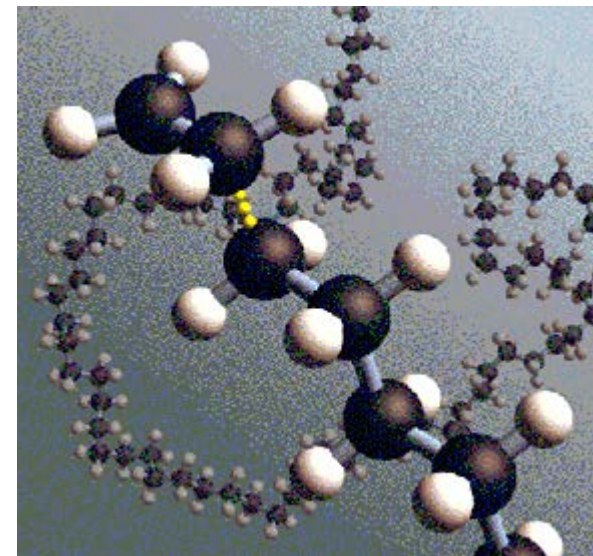
It would note the key role of gravity & the sun's radiation in generating all this.



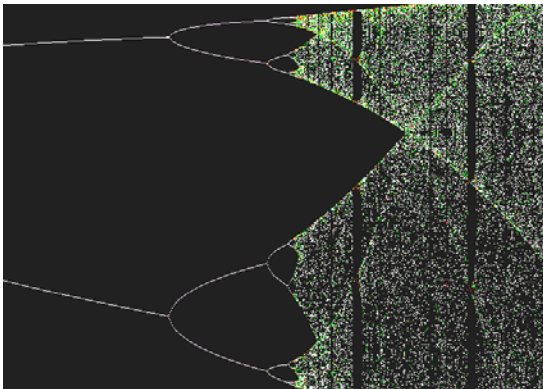
The hierarchical structure of 'glassy states' in a disordered solid



The surface of a lump of graphite, with its layered structure visible. Interstellar grains and dust look similar.

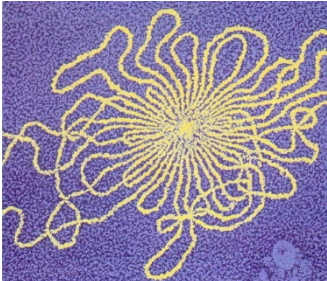


Chain of ethylene molecules (polythene)

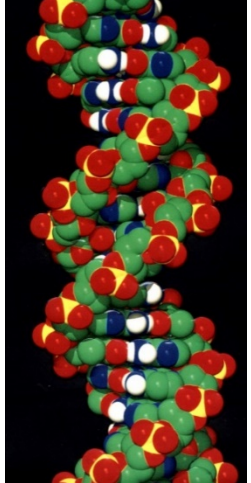


ABOVE: snowflakes & vortex streets

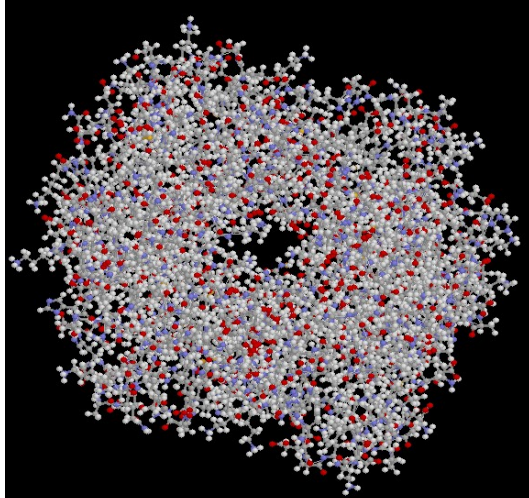
ABOVE: Period doubling to chaos, as an interaction is changed



ABOVE & BELOW:  
DNA molecule



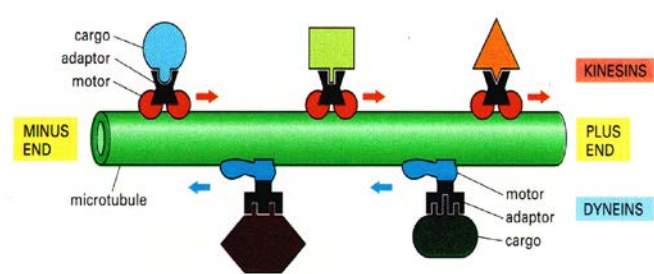
BELOW: Haemoglobin



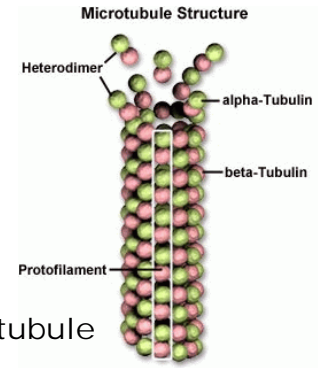
On earth it would note the existence of a complex hierarchy of structures, ranging in scale from molecular all the way to various extended ecologies and organizational networks traversing the whole planet.

way to various extended ecologies and organizational networks traversing the whole planet.

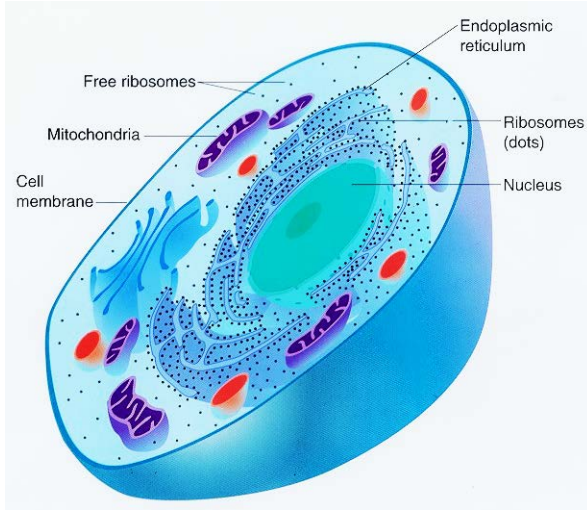
If it passed by in 2016, we would not notice anything - it would be far too advanced & strange for us to recognize.



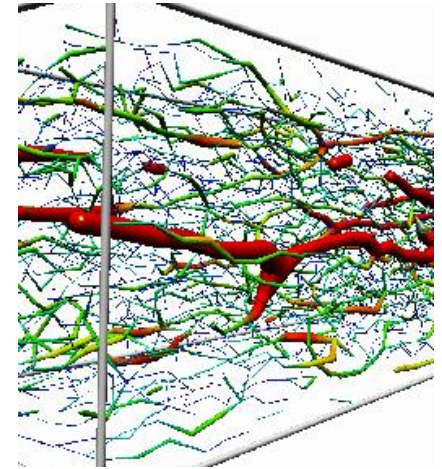
ABOVE: Molecular machine



Microtubule



ABOVE: eukaryotic cell  
BELOW: Cambrian sea



ABOVE: Vascular network  
BELOW: Amsterdam, 2016

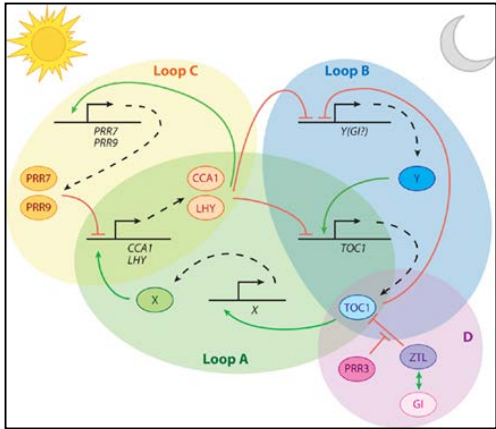


# STRUCTURE of the BIOSPHERE

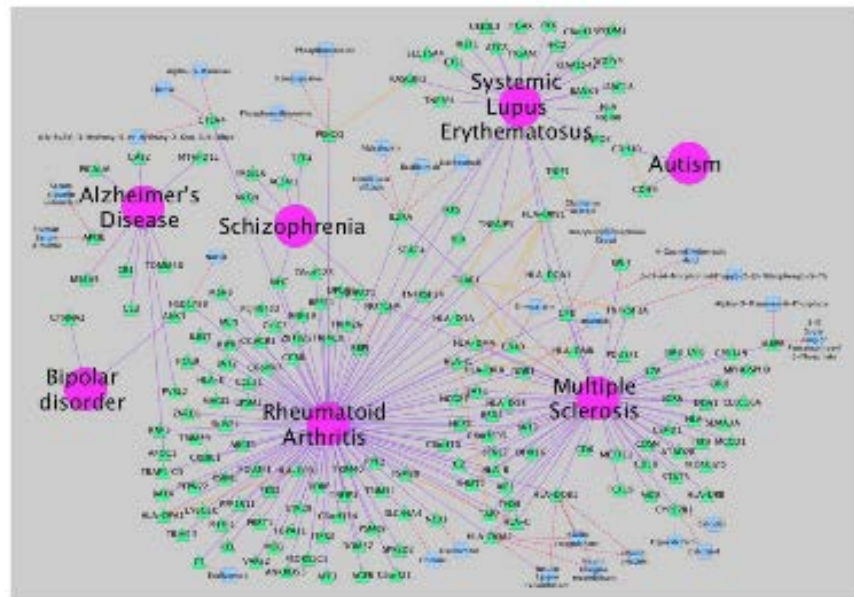
Our alien intelligence would note the role played by information and control networks in the biosphere. It would NOT make the mistake of ascribing a central role to DNA (the "central dogma"), although it would notice the almost

complete absence of epigenetic inheritance (ie., of acquired characteristics) in the germ cells of almost all organisms - in contrast to all other cells.

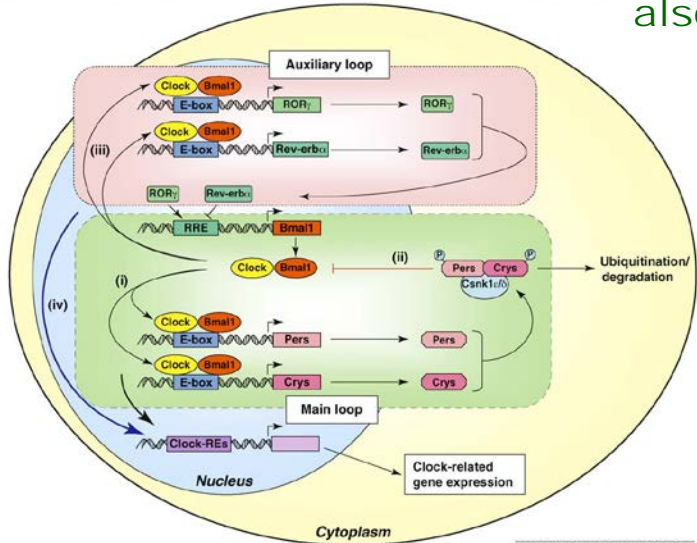
BELOW: various aspects of the Circadian network



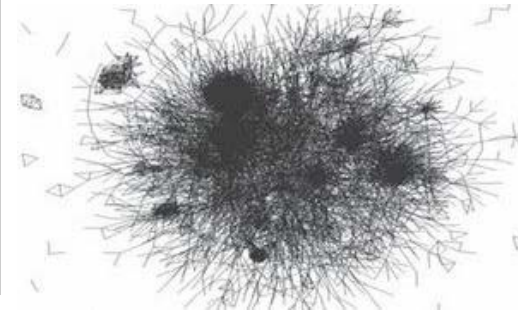
It would note the way in which information flowed in all directions throughout these networks (and if the notion of causation was meaningful to it, that causation & control mechanisms operated in the same cooperative way). It would also notice, in 2016, the existence of other networks involving elementary properties of QED and solid-state physics, extending across the biosphere.



ABOVE: Small part of a "disease network"



BELOW: map of a gene-protein network



BELOW: map of the internet



# MECHANISMS: CATALYSIS & AUTOCATALYSIS

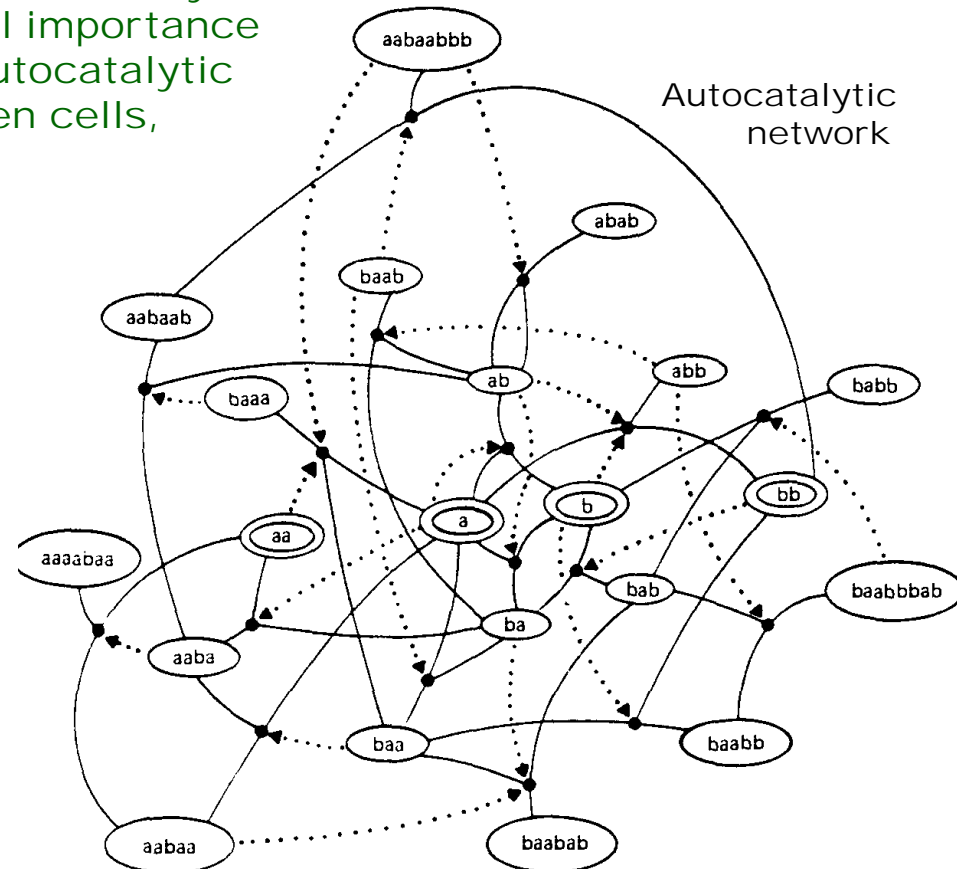
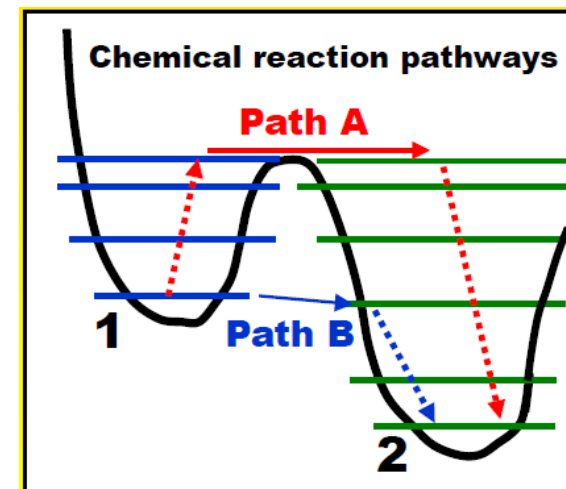
Catalysis is very common in Nature: certain chemical reactions and reaction chains are accelerated, via the intervention of a “3<sup>rd</sup> party” substrate, which lowers the relevant energy barrier. It is utterly crucial in biochemistry.

In the quantum tunneling regime one can still have catalysis – but the final state needs to be “de-excited” (Q relaxation). It plays little role in earth-based biology.

If one or more catalytic products are the same as one of the original reactants, we can set up “autocatalytic networks”. These are also of fundamental importance in earth-based biology, which has huge autocatalytic networks, extending through cells, between cells, even between organisms & species.

Autocatalytic networks are highly non-linear, and generate more and more complex structures → local regions of ‘negentropy’ + large amounts of entropy generated on a more global scale.

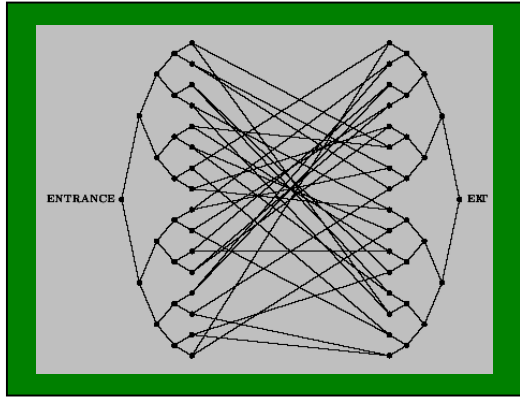
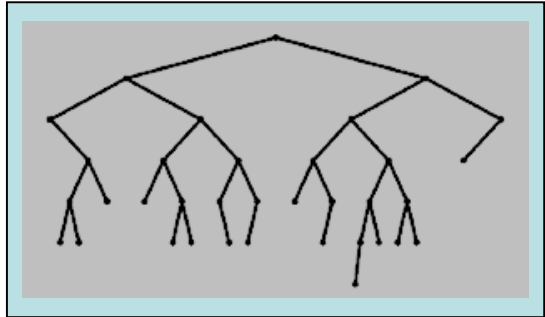
We thus have one (but not the only) way of generating ever more complex structures. They exist on planets, interstellar grains, & certainly elsewhere.



M Hordijk, *BioSci* 63, 877 (2013)  
D Penny, *Biology Direct* 9, 26 (2014)  
PG Higgs, N Lehman, *Nature Rev Genetics*  
doi:10.1038/nrg3841



# QUANTUM NETWORKS and QUANTUM WALKS



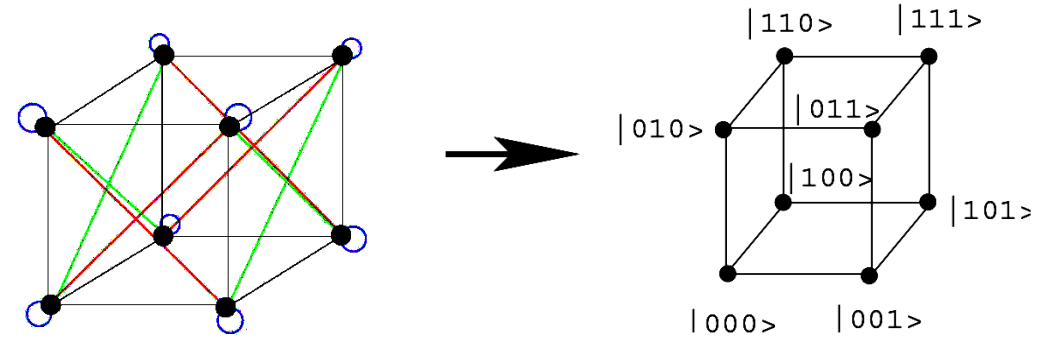
We define the dynamics of a particle on a graph, with nodes representing different states in some Hilbert space. The Hamiltonian is

$$\hat{H}_s = - \sum_{ij} \Delta_{ij}(t) (\hat{c}_i^\dagger \hat{c}_j + \hat{c}_i \hat{c}_j^\dagger) + \sum_j \epsilon_j(t) \hat{c}_j^\dagger \hat{c}_j$$

where hopping and node energies can be functions of time. A special case of this is a gate quantum computer; another is a quantum memory. A simple example is shown below – a quantum information processor involving 3 qubits.

AP Hines, PCE Stamp, Phys Rev A75, 062321 (2007)

ABOVE: 2 different graphs for quantum walks



ABOVE: Mapping between 3d hypercube Q Walk & 3-qubit system

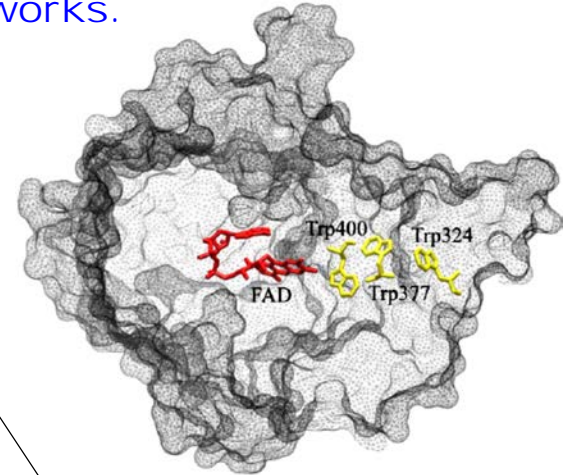
One difficulty in applying this to autocatalytic networks, or other similar networks in which complex systems evolve, is that we need “open networks” in which more and more complex systems evolve. Nevertheless there are certain useful things that can be learned.

# QUANTUM RELAXATION in BIOLOGICAL NETWORKS

A key question - of great current interest - is the role of large-scale quantum superpositions and entanglement in biological processes/networks.

**EXAMPLE 1:** EPR-style entanglement between 2 separate spins in cryptochrome molecules (avian navigation); the Hamiltonian is:

$$H = \sum_{k=1,2} H_k = -\gamma_e \vec{B} \cdot \sum_k \vec{S}_k + \sum_{k,j} \vec{S}_k \cdot \hat{\lambda}_{k_j} \cdot \vec{I}_{k_j}$$

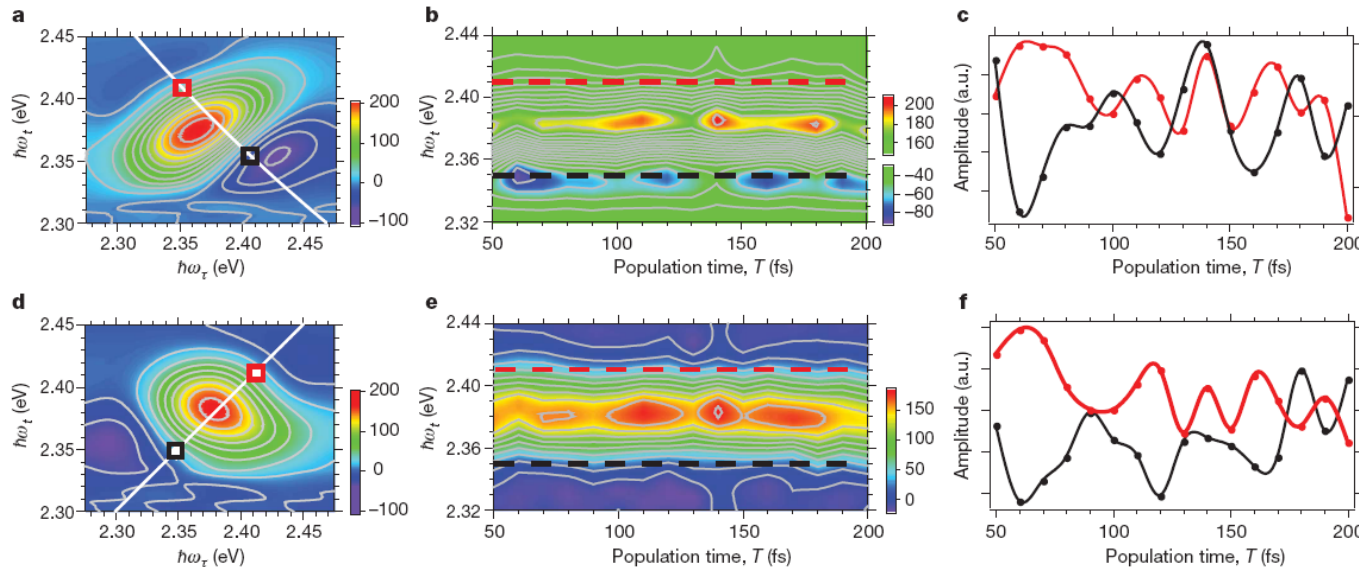
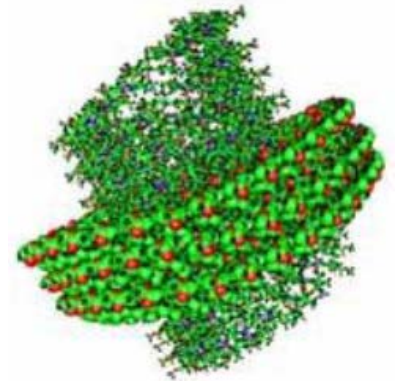


*Arabidopsis Thaliana*  
cryptochrome-1

**EXAMPLE 2:** Coherent motion of excitons delocalized amongst chromophores in Light Harvesting molecules, With Hamiltonian:

$$H_o = \sum_{ij} [t_{ij} c_i^\dagger c_j e^{iA_{ij}^o} + H.c.] + \sum_j \epsilon_j c_j^\dagger c_j$$

*chlorosome (green sulfur bacteria)*



E Collini et al.,  
Nature 463, 644 (2010)

# DYNAMICS of QUANTUM RELAXATION

Given the colossal number of possible ways in which complexity can develop, it is worth asking whether there is some mechanism for selecting out certain evolution paths at the quantum level. Two ideas often discussed, in the biophysics literature & elsewhere, are (i) non-eqlbm dissipative structures, and (ii) quantum decoherence/relaxation.

P Trebst et al New J Phys 11, 033003 (2009)  
M Plenio, SF Huelga New J Phys 10, 113019 (2008)

The devil here is in the details:  
toy models are often a poor guide.

(i) One needs a realistic model for the quantum environment (eg., spin bath or oscillator bath model)

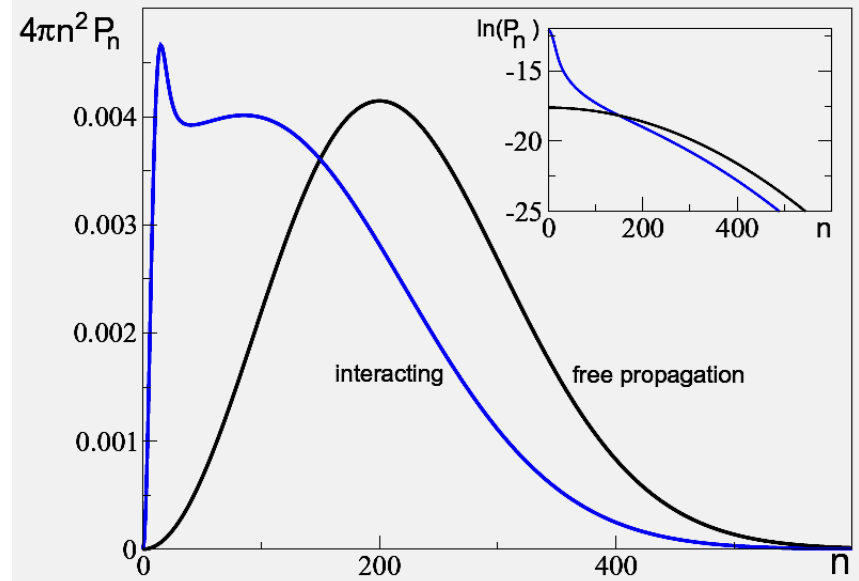
(ii) The simple-minded 'pointer basis' idea of how this works is often wrong. Thus, the quantum environment can often delocalize a system that would have been classically localized; & even strong decoherence can still give 'mixed' behaviour. There is still much to learn.

NV Prokof'ev, PCE Stamp, PR A74, 020102 (2006)  
Z Zhu et al, PR A81, 062127 (2010)

RIGHT: Density matrix after time  $t$  such that  $z=2\Delta t \gg R^2$ , with  $z = 2000$  and  $R=10$ . Long-range part is ballistic, short-range part is sub-diffusive.

$$H_{sp} = \sum_k^{N_s} \mathbf{h}_k \cdot \boldsymbol{\sigma}_k + \sum_{k,k'}^{N_s} V_{kk'}^{\alpha\beta} \sigma_k^\alpha \sigma_{k'}^\beta$$

$$V_{int} = \sum_k^{N_s} \left[ \sum_{ij} (\mathbf{F}_j(k) \hat{c}_i^\dagger \hat{c}_j + H.c.) + \sum_j \mathbf{G}_j(k) \hat{c}_j^\dagger \hat{c}_j \right] \cdot \boldsymbol{\sigma}_k$$



# CAPRICIOUS VOTER MODEL

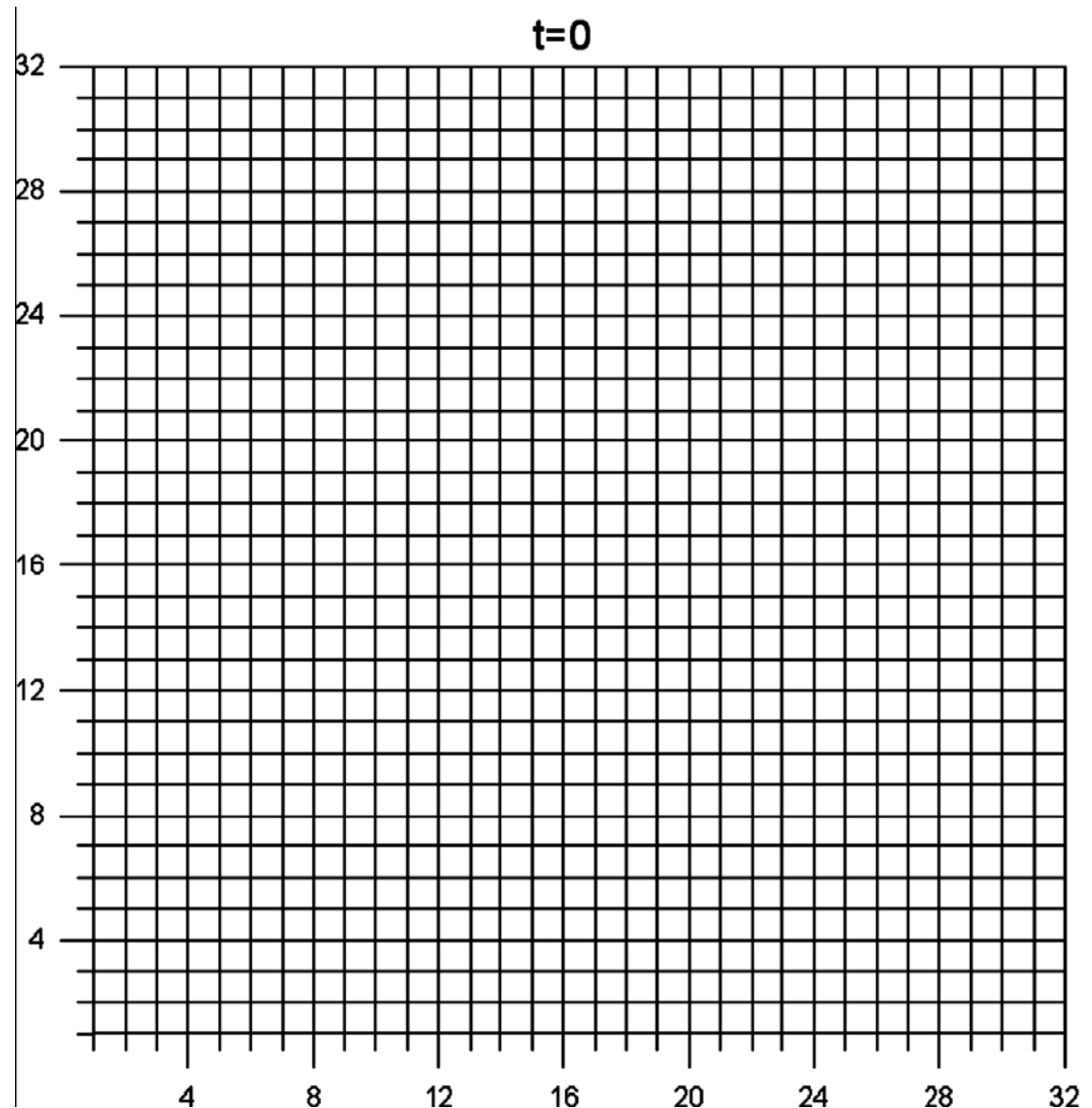
$$\mathcal{H} = \sum_j \Delta_o \hat{\tau}_j^x + \sum_{ij} V_{ij} \hat{\tau}_i^z \hat{\tau}_j^z + H_{int}^{env}$$

This is actually a Quantum Ising model with coupling to an environment; here we will look at the case of long-range interactions.

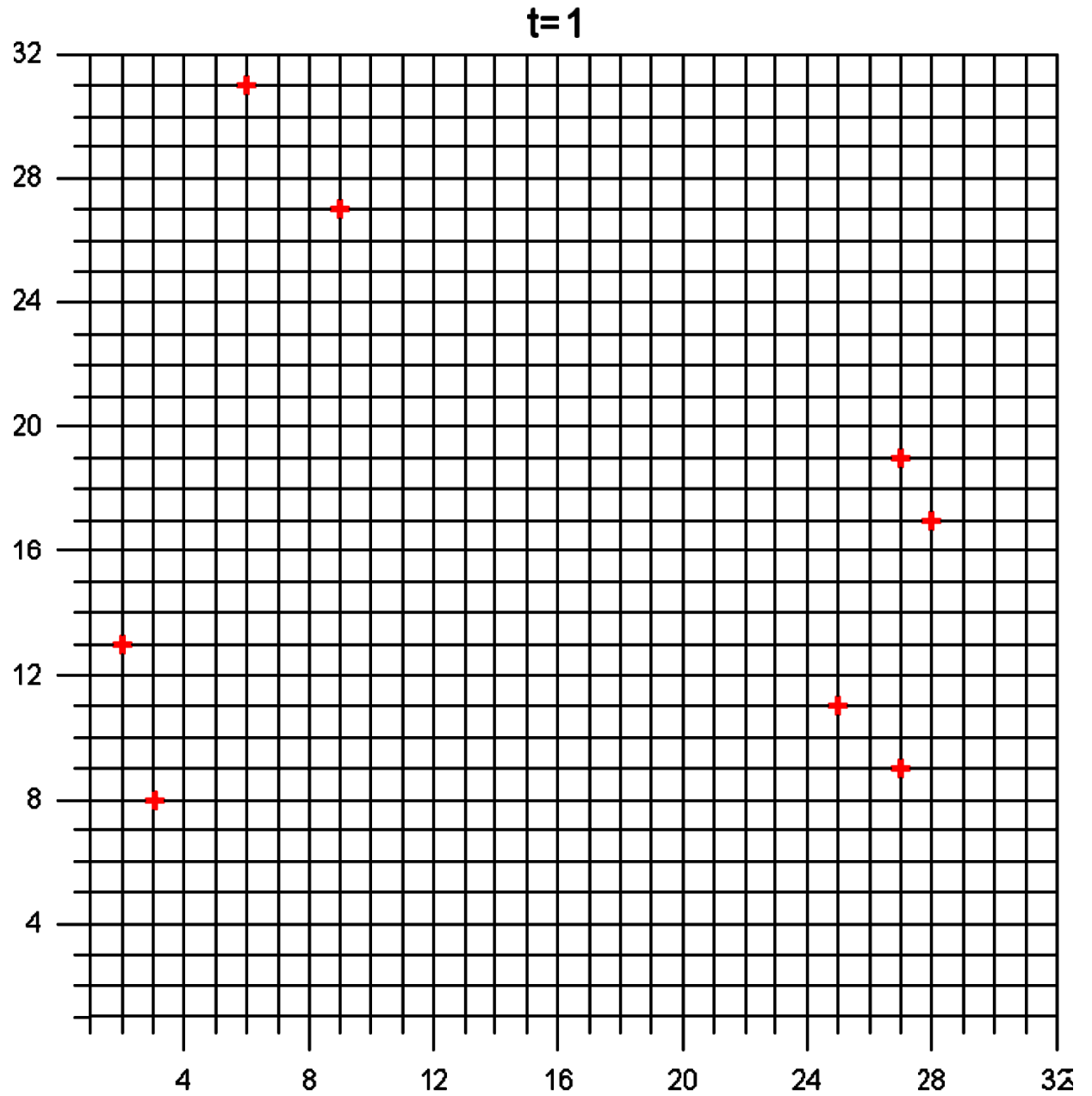
At  $t=0$ , start with an unpolarized array of spins (qubits) with random orientations (half up, half down).

In what follows we show which spins have flipped after a time  $t$

Thus, at  $t=0$ , no spins have yet flipped

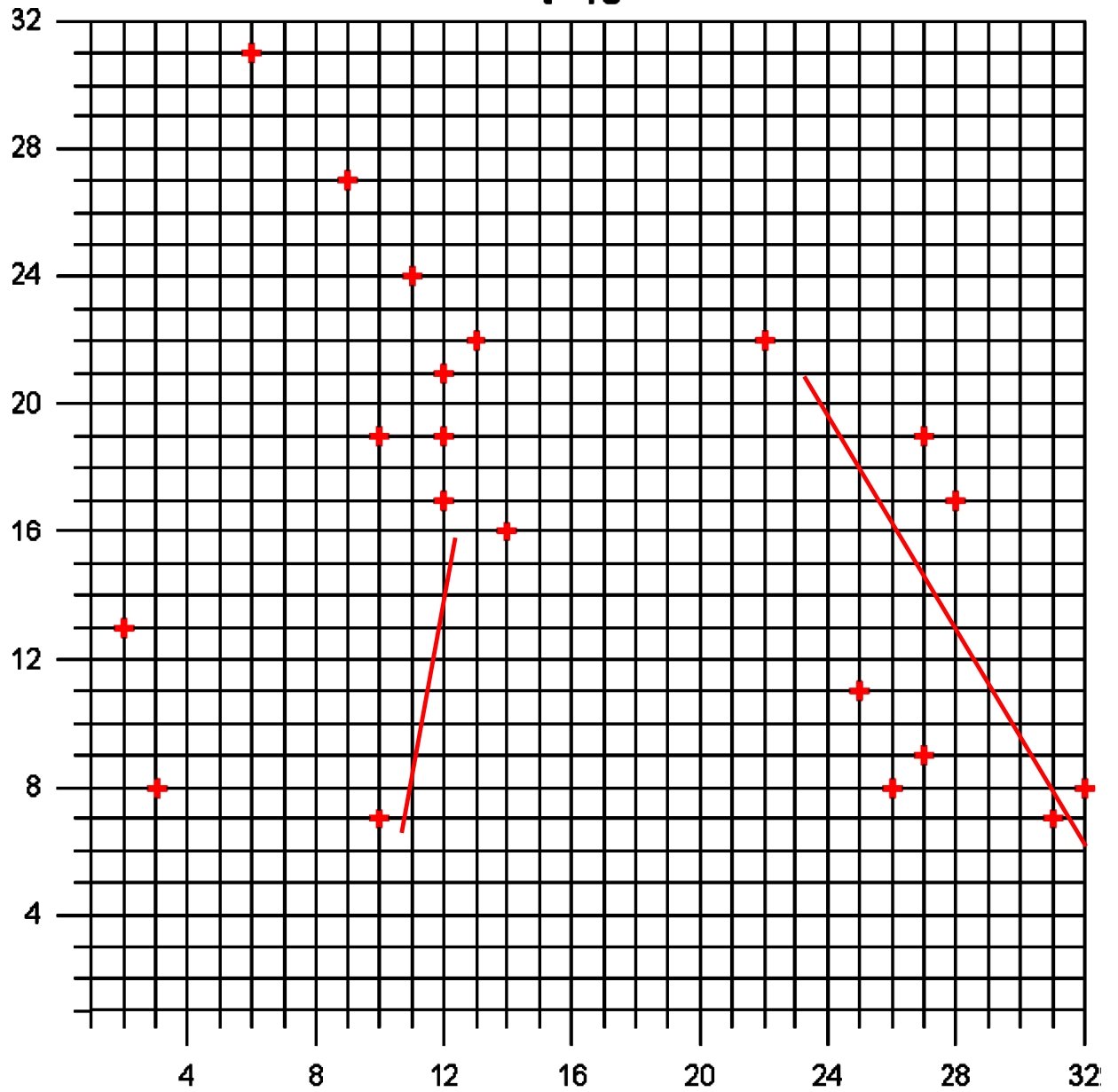


The spins flip in pairs. At  $t=1$ , 4 pairs of spins have flipped (8 flipped spins)

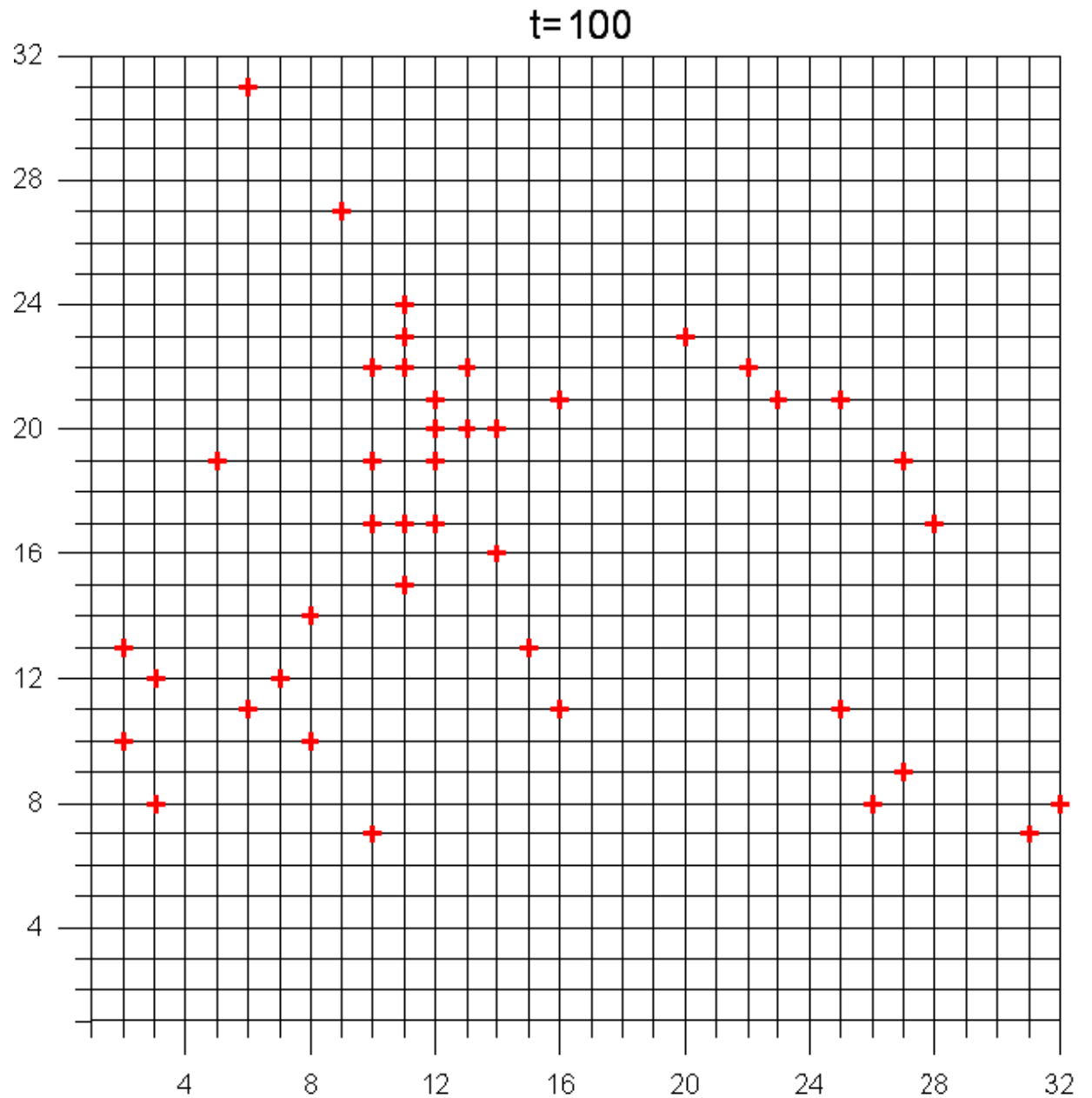


t=10

At t=10, 10 pairs of spins have flipped.  
(20 flipped spins)  
Note that a few of these are 'outliers',  
far from the others.

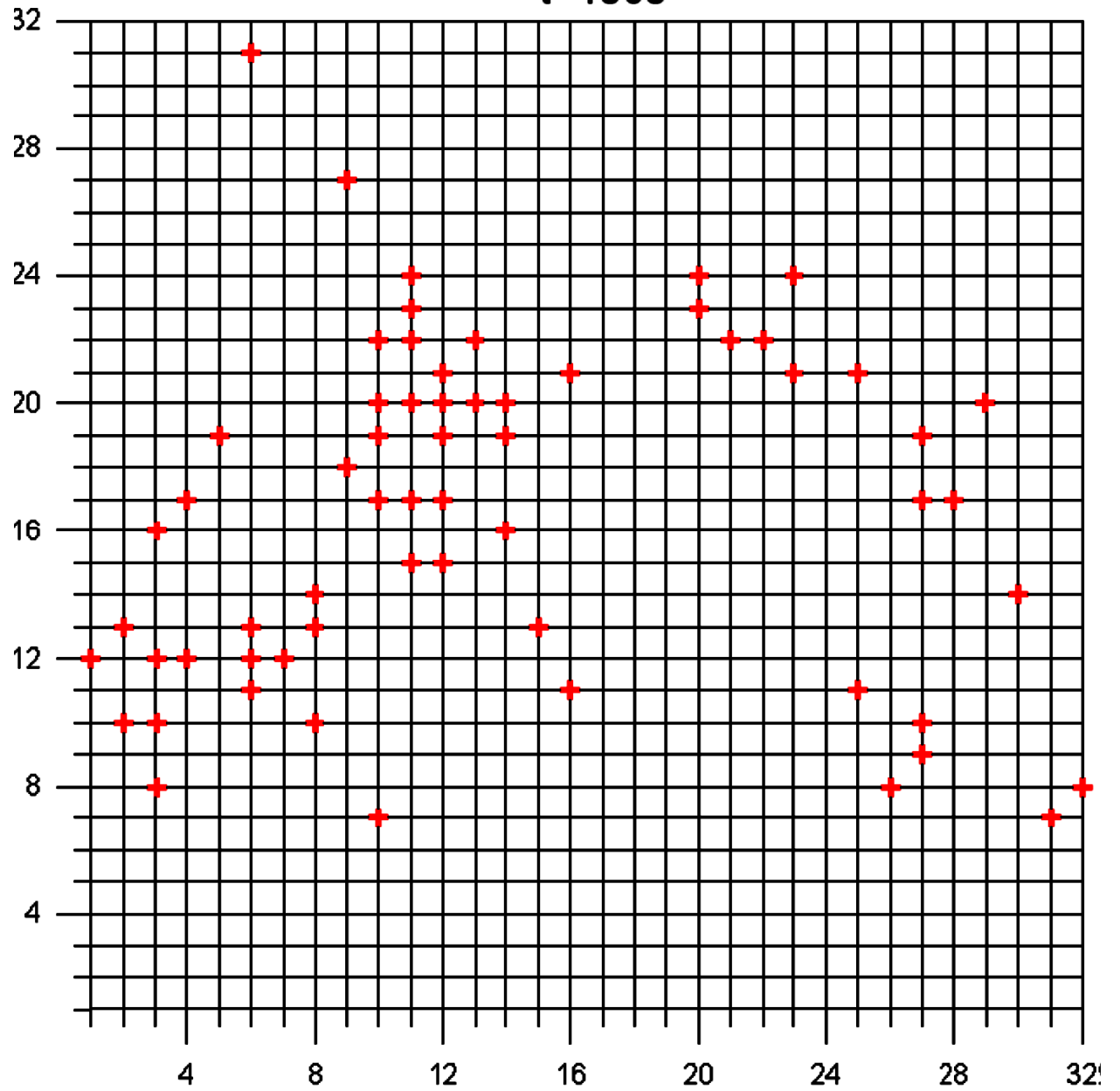


At  $t=100$ , 42 spins have flipped. Although it is hard to see, a complex pattern is building up, both in real space and in energy space.



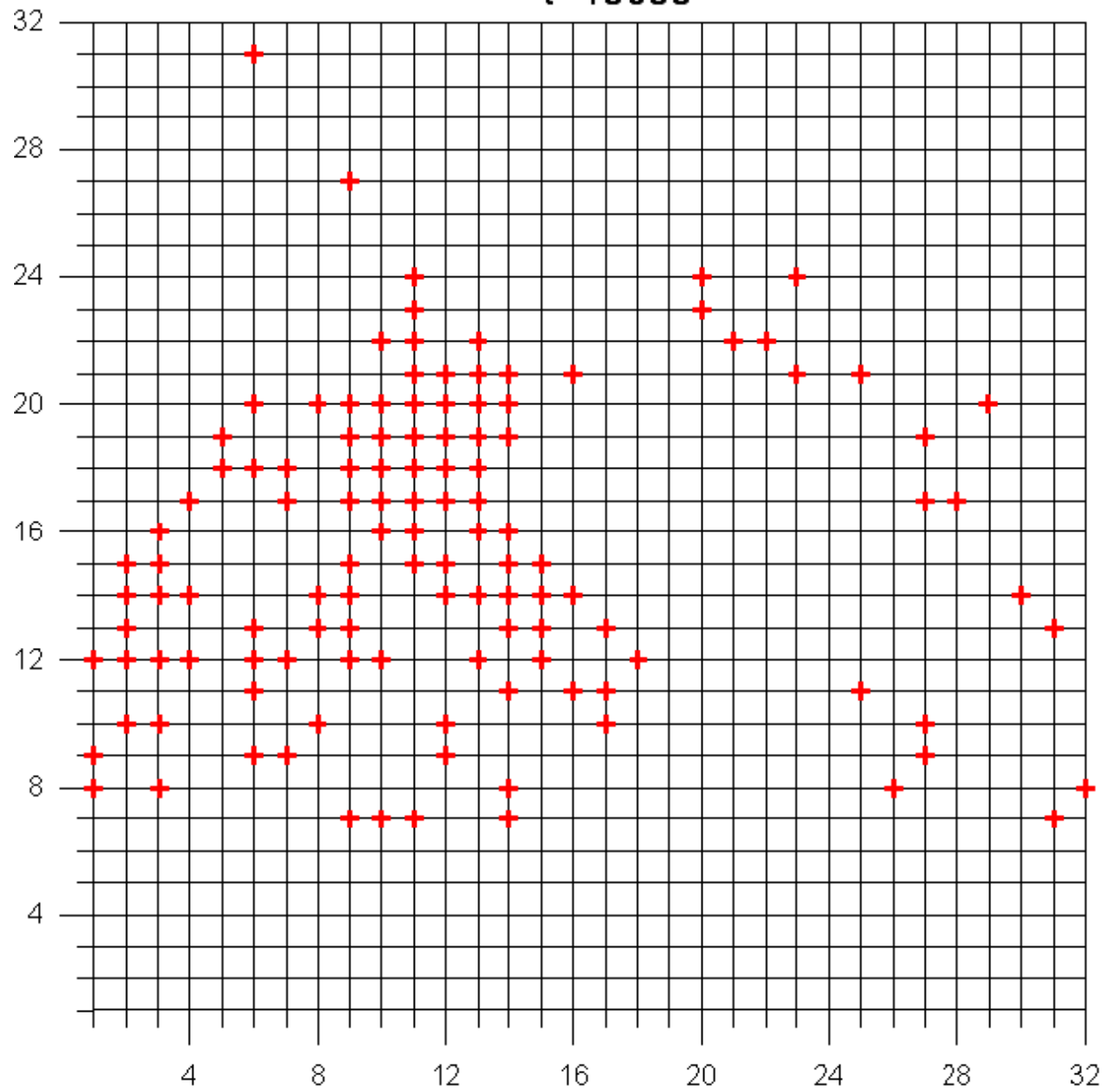
t=1000

At t=1000, we  
now have 62  
flipped spins.



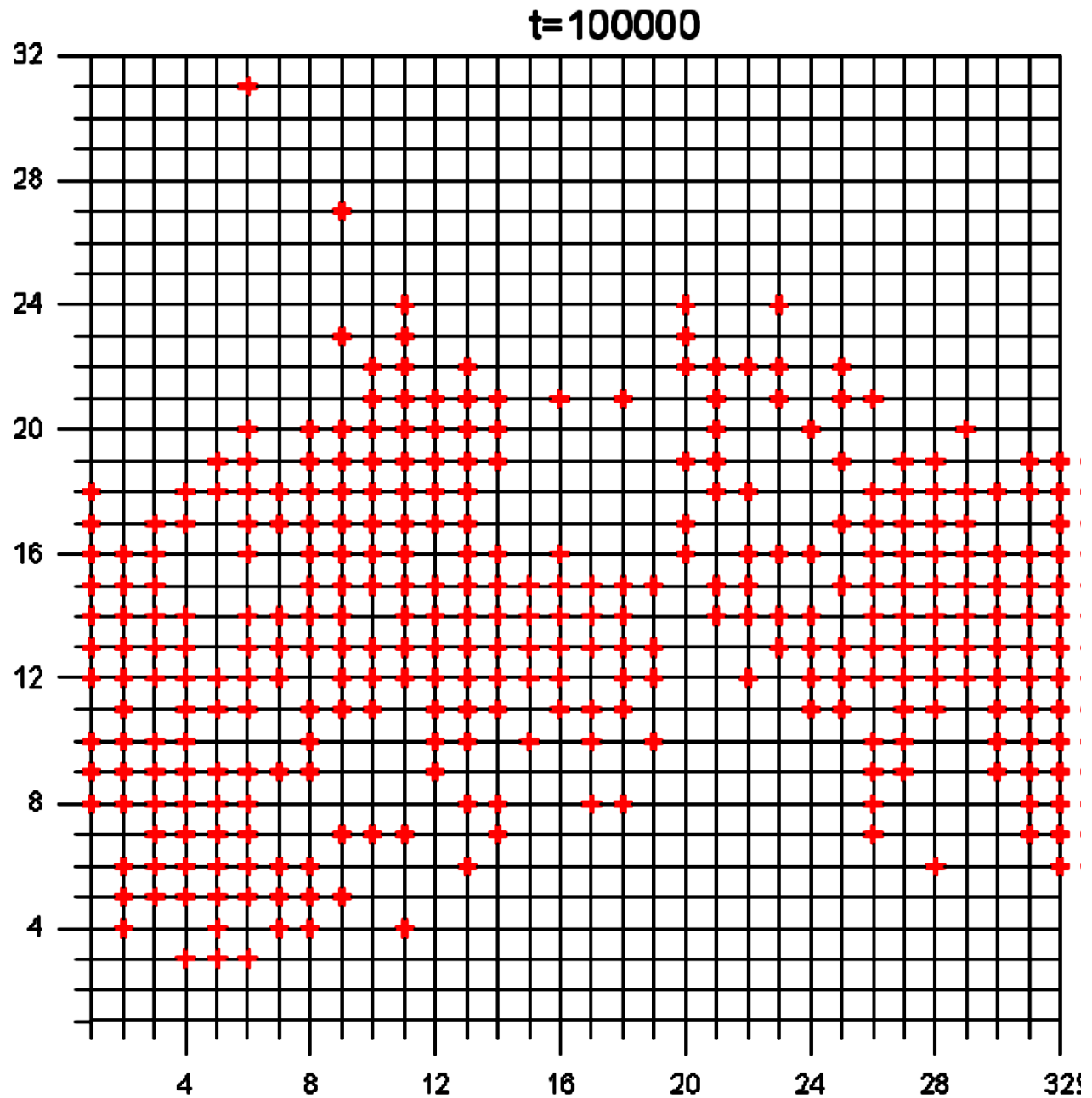


t=10000



At t=10,000, there are now 132 flipped spins

At  $t=100,000$ , we have 320 flipped spins. A spatial pattern is somewhat discernible.

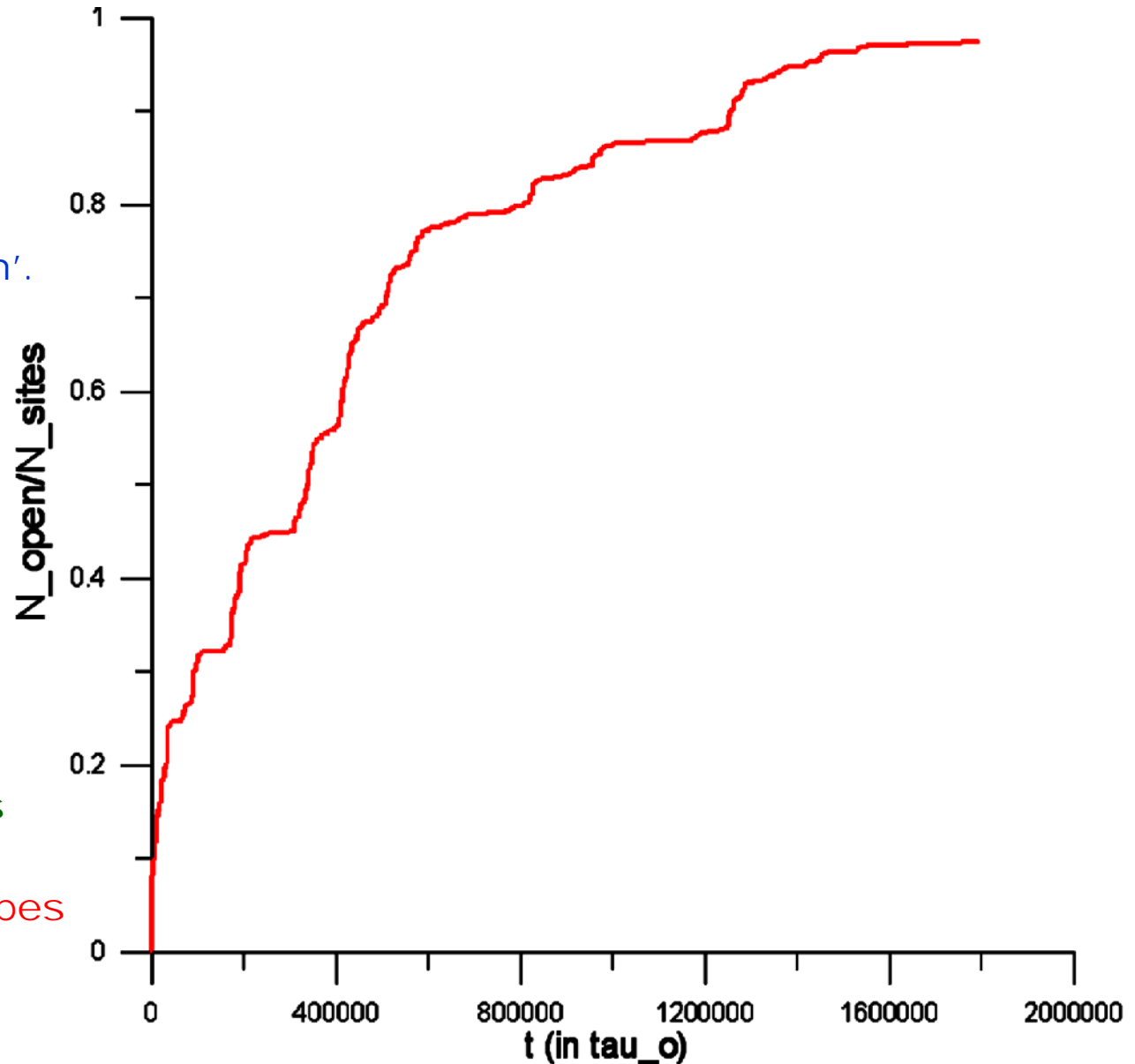


The growth of regions of flipped spins is in fits and starts – physicists call this ‘anomalous diffusion’, characterized by Levy flights. Biologists now call this pattern ‘punctuated equilibrium’.

### CONCLUSIONS:

- (1) No localization
- (2) Pattern formation in energy space (and it turns out, in real space), even for long-range interactions

This model also describes voting patterns (eg., in the good old USA)



# COMPLEXITY on EARTH: a summary, & the FUTURE

We have no reason whatsoever (except for antiquated religious arguments) to avoid/deny the following:

- (1) what happened on earth is not special – complex organized systems have certainly formed in a huge variety of places in the universe.
- (2) the organization appearing on earth is in no way special. It arose from a specific set of conditions (specific chemistry & geology, size of earth & distance from sun, particular characteristics of sun, etc).
- (3) It is likely that highly advanced organized systems elsewhere would be unrecognizable as life to us – or if the term 'life' as we use it would even be meaningful.
- (4) humans as a species are nowhere near the most sophisticated forms of organized system – we're likely very primitive compared to some of what is out there.

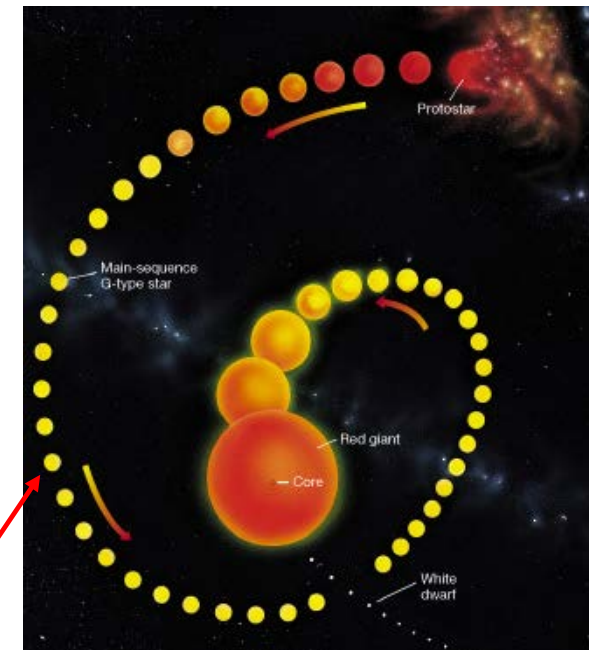
In the short term, humans will likely ruin the earth. The causes: human overpopulation, resource depletion, species destruction, modern science & technology. Escape to other planets is not an option. The next 100 yrs will be crucial. However life on earth has survived far worse disasters.

In the very long term, the sun will slowly heat up – in 2 billion yrs the oceans will boil on earth; in 6 billion yrs the sun will go to its red giant stage (and then to a white dwarf). The earth will then vaporize.



ABOVE: One possible near-term scenario for the development of the earth – dominated by environmental pollution

BELOW: The evolution of the sun over a 12 Gya time period



Where we are now

# The FUTURE of COMPLEX STRUCTURES in the UNIVERSE



If our alien intelligence was a film buff, it would notice the influence of narrative & fiction in guiding intellectual discourse & plans for future activity amongst humans. Emphasis on disaster scenarios like the "Terminator scenario", with the possibility of conscious (read: "self-aware") machine networks

taking over the world, would be noted. So would talk about "singularities" or "advanced general intelligences" (typically without citation of the original science fiction sources), and the extraordinarily anthropocentric discussion of all these issues by humans.

[http://www.huffingtonpost.com/stephen-hawking/artificial-intelligence\\_b\\_5174265.html](http://www.huffingtonpost.com/stephen-hawking/artificial-intelligence_b_5174265.html)

However, this alien intelligence would have more important things to do & worry about. It would doubtless be thinking a lot about the long-term future of the universe, and whether it was possible for intelligences like itself to avert an eventual collapse of local organized complexity, brought about by fundamental processes.

Decay timescales in the universe (cf Dyson)

|  |                   |
|--|-------------------|
| Low-mass stars cool off  | $10^{14}$ yr      |
| Planets detached from stars  | $10^{15}$ yr      |
| Stars detached from galaxies   | $10^{19}$ yr      |
| Decay of orbits by gravitational radiation                           | $10^{20}$ yr      |
| Decay of black holes by Hawking process                              | $10^{64}$ yr      |
| Matter liquid at zero temperature                                    | $10^{65}$ yr      |
| All matter decays to iron  | $10^{1500}$ yr    |
| Collapse of ordinary matter to black hole [alternative (ii)]         | $10^{10^{26}}$ yr |
| Collapse of stars to neutron stars or black holes [alternative (iv)] | $10^{10^{76}}$ yr |

According to estimates made using current understanding of physics, it will have plenty of time to think about this (see left).

MJ Rees, Observatory 89, 193 (1969)  
FJ Dyson, Rev Mod Phys 51, 47 (1979)



THANK YOU TO:

Lee & Carlota Gohlike, & everyone else @ 7 Pines