Following real-time processes in live.

What Infra-Red luminescence spectroscopy can tell us about living cells and quantum systems?

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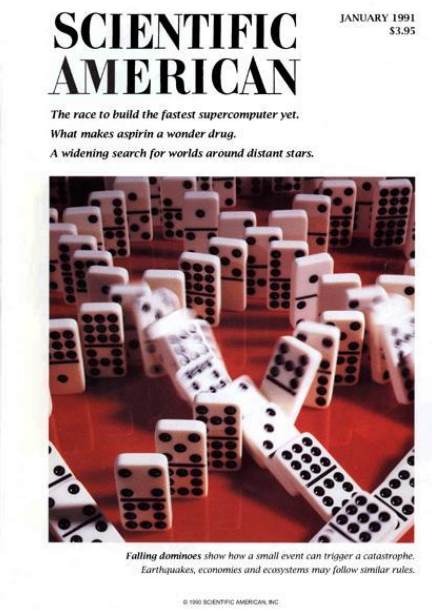
Systems with energy flow
Self-Organized Criticality

Ilya Prigogine (left)
Noble Price 1977

Emerging phenomena in In systems under energy flow

- Formation of dissipative structures
- Emerging of order out of chaos
- Emerging of complexity

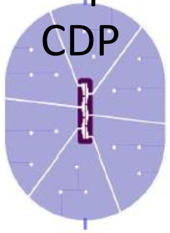
Per Back, Chao Tang and Kurt Wiesenfeld   (1991 paper)
Self-Organized Criticality
Another avenue for **complexity**
1/f noise explained



Prigogine's nonequilibrium thermodynamics ideas are important for understanding of the origin of life and live system functioning, but they are applicable to many complex systems

Energy accumulation and releases in materials: Internal interactions lead to new emerging phenomena

Super-SDMS-CDP



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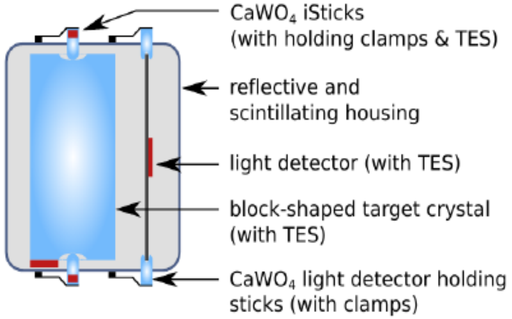
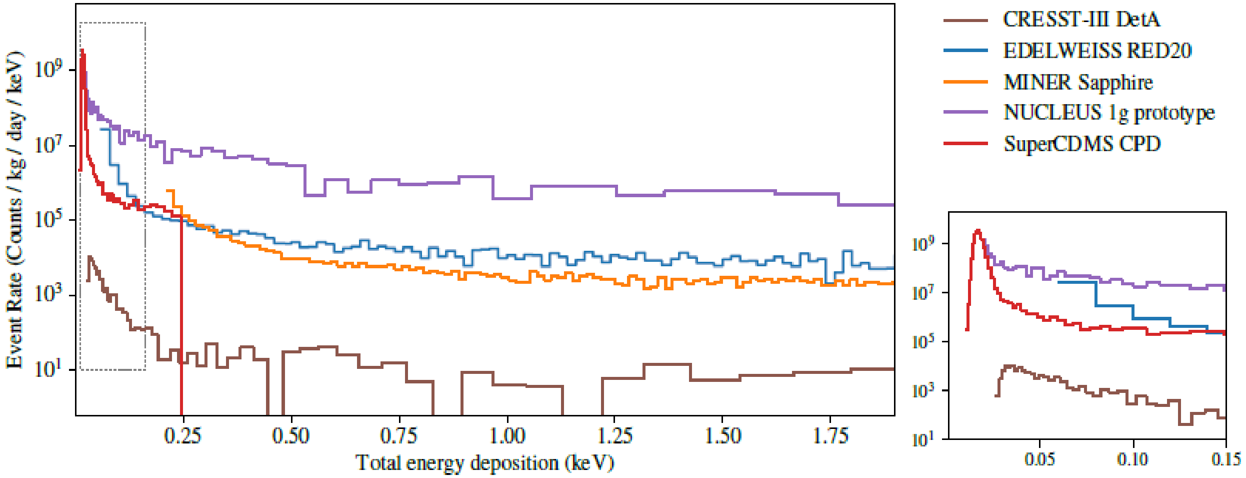
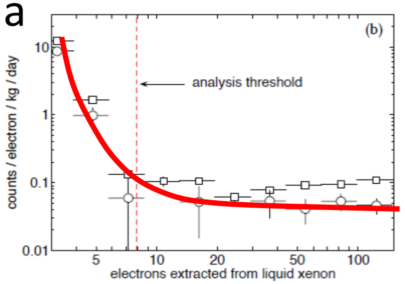


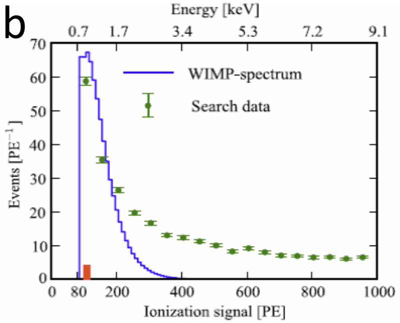


EXCESS workshops

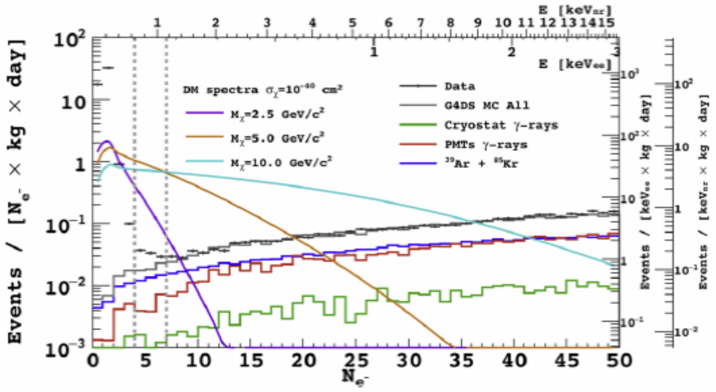
a



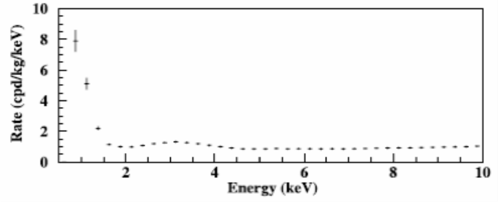
b



c



d



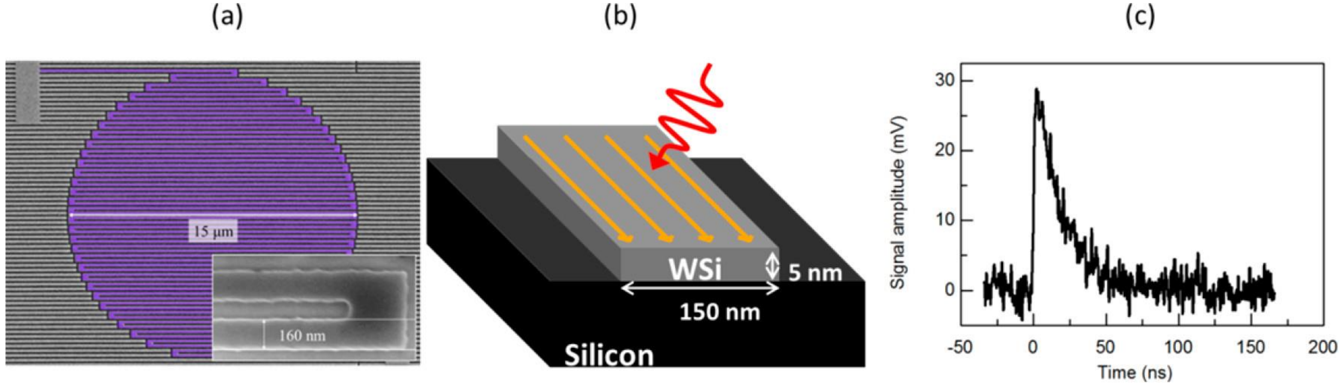
a: Xenon 10 experiment, b: Xenon 100,

c: Dark Side 50 experiment, 50 kg liquid Ar TPC;

d: DAMA-LIBRA experiment, NAI(Tl) scintillator, energy deposition of 1 keV results here in registration 5.5-7.5 photons (Nygren paper0

We cannot yet build first-principles models and finding new phenomenology in in noise and backgrounds production

Superconducting Nanowire Single-Photon Detectors are already good for studies SOC, nonequilibrium thermodynamics



Detection of a single 5 µm photon with
Superconducting Nano-Wire Photon Detector (SNSPD).
(a) SEM image of an SNSPD with false color for clarity;
(b) (b) Absorption of a photon
produces a hotspot in a superconducting nanowire.
Thermal time constant = ~30 ns; Working temperature = ~250 mK-1.5 K

Li Chen et al., Accounts of Chemical Research, V. 50 pp1400-1409 (2017)
Detection of IR luminescence t photon level is demonstrated in this paper

nanowire detectors outperform other superconducting photon detectors and PMTs
in response time and quantum efficiency, low dark counts; large arrays available
have macroscopic sensor (pixel) areas, require cooling to 250- 300 mK, (1.5 K for Near-IR) ;

in superconducting /quantum sensors and processes in live cells

Discussion

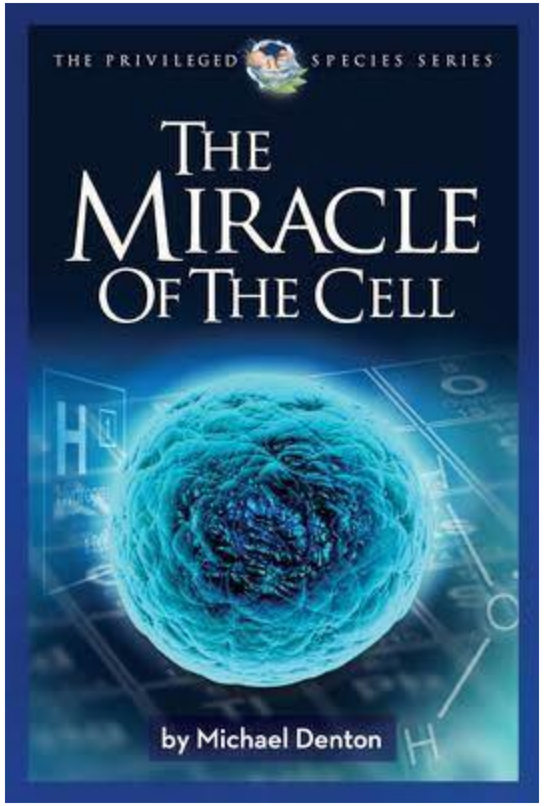
- Interactions of excitations and defects bearing excess energy in materials can lead to the production of backgrounds and noise in dark matter and CEvNS searches, photon detectors, quantum sensors &qubits.

- Non-equilibrium thermodynamics effects are “harmful” to low-energy threshold detectors, sensors, and qubits.

On the other hand,

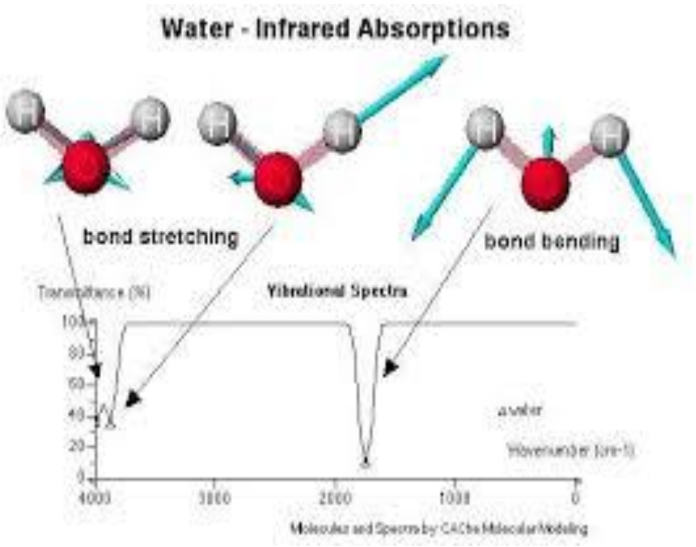
- Non-equilibrium thermodynamics/effects in systems with energy flow are important for the understanding of life origin and functioning of live systems.

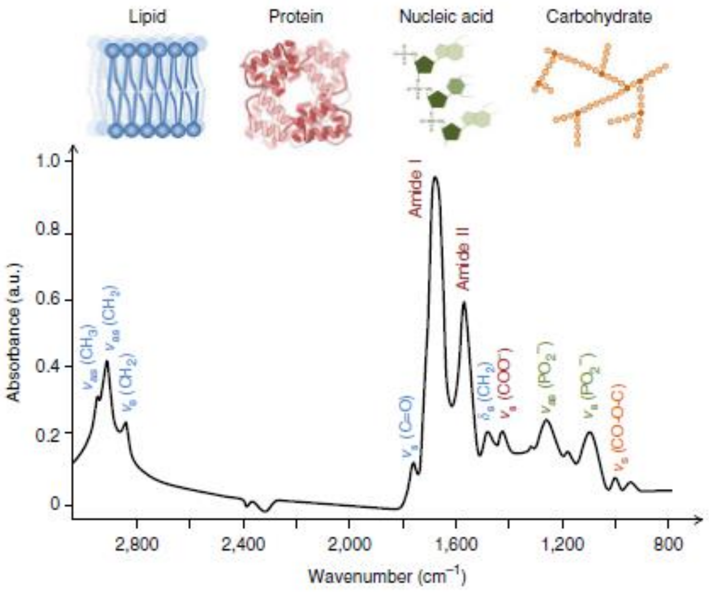
- **Can one detect energy flows and processes in a single live cell with “quantum” detectors?**



Is detection of IR self-luminescence or induced luminescence of live cells possible with SNSPD?

IR spectroscopy-probe-free cell chemical imaging





3.57 4.17 5.00 12.5 6.25 12.5 **mm**

Sensitivity at cell size is limited by thermal background

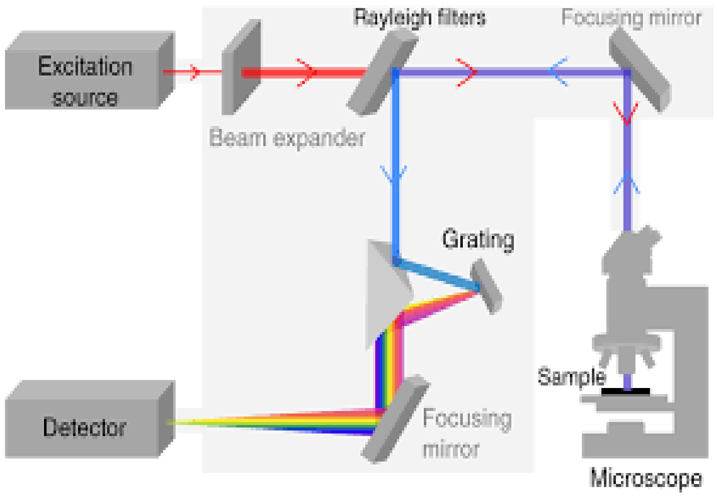
Nature protocols V.9 n8, p.1772 (2014) “Using Fourier transform spectroscopy to analyze biological samples”

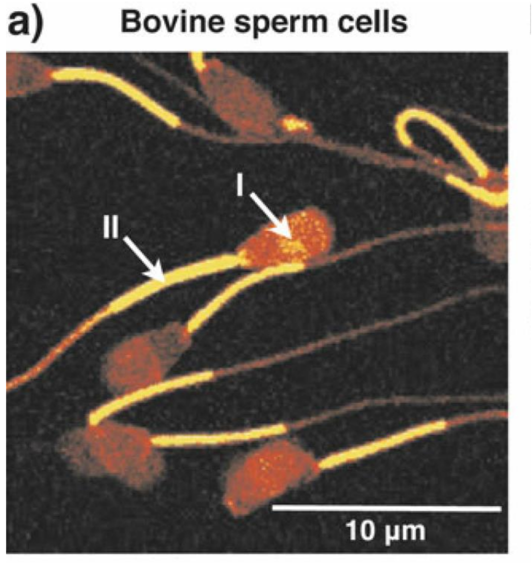
N.B. *resonance vibration modes should be excited by molecule deformations, electron transitions, charge transfer- i.e. specific IR radiation should be emitted in specific cellular molecular processes.*

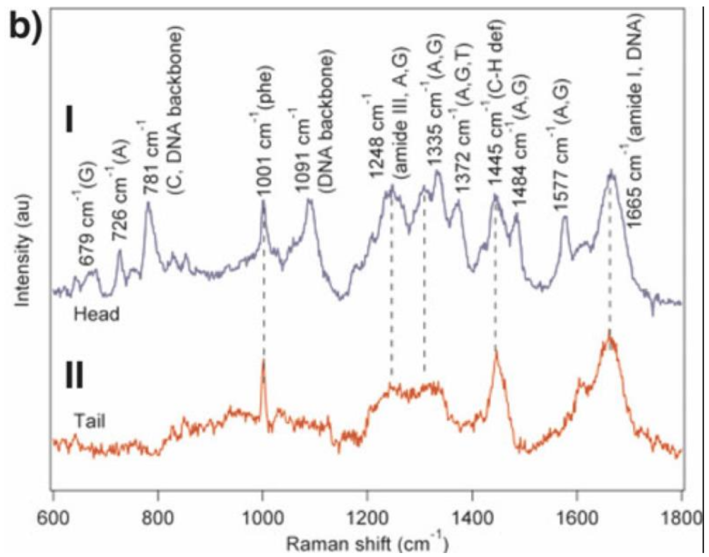
Raman Micro-spectroscopy
workhorse of cell chemical imaging

IR spectrum shifted to visible light (combinational scattering)

No background, but cross-section for the process 6-10 orders smaller than for IR





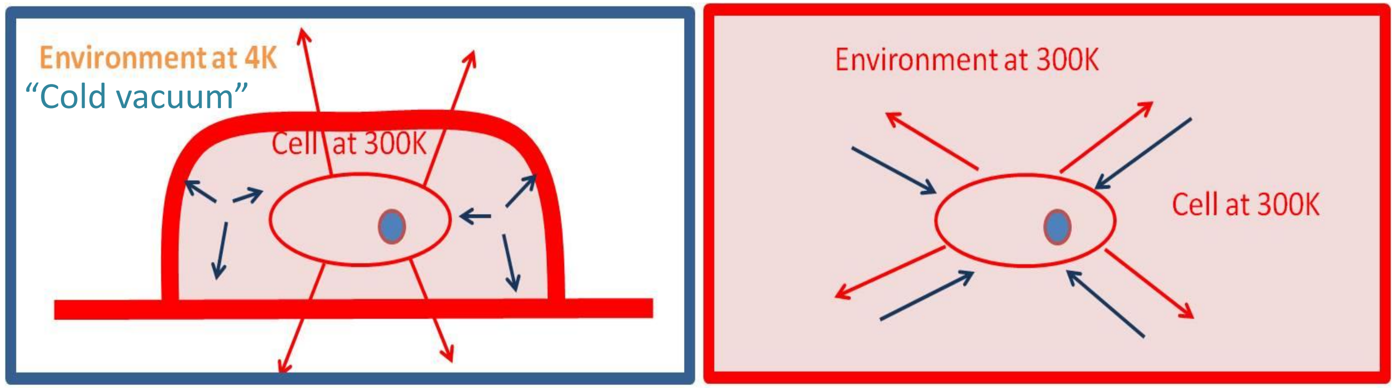


Chapter Biomedical Applications of Biophysics
Volume 3 of the series Handbook of Modern Biophysics pp 185-210
Humana Press. , 2010

Limited by intensity of excitation light (phototoxicity)

IR luminescence spectroscopy can faster and more sensitive

Problem of of the thermal radiation background



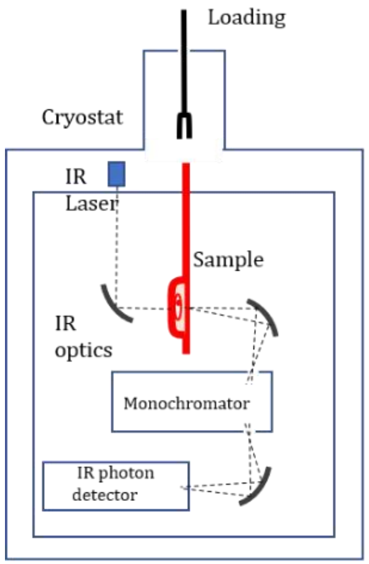
Radiation in liquid is out of equilibrium with temperature-
size is below equilibration (absorption) length-

cell is deprived from the thermal radiation background –

… and IR detectors too!

Detection of weak IR cell bio-luminescence could be possible

Combining small sample size, cryogenic environment, and multi-pixel IR SNSPD with high photon counting rate

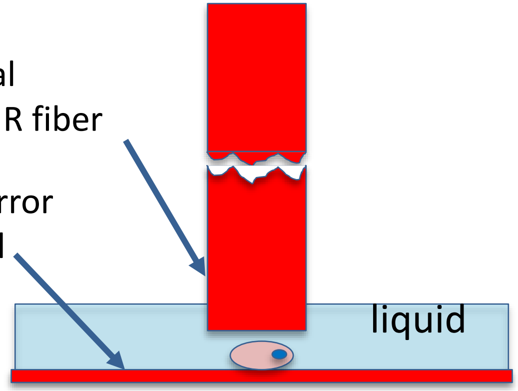


a

b

- 100-1000 parallel channels allow timestamp with 10 ps resolution all photon –thermal radiation background and IR luminescence- arriving to the detector
- Coupling cryogenic to live sample with IR fiber
- High data acquisition speed

c



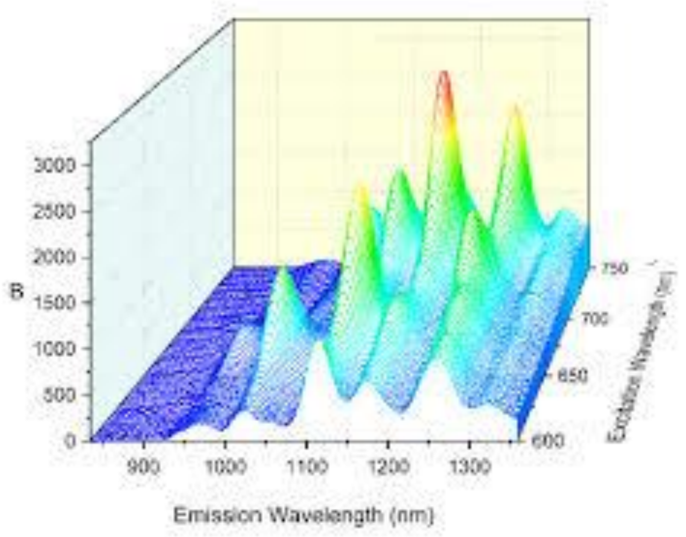
More simple way to suppress background – based on high IR reflectivity

a. US patent N 9366574. Cells can be frozen or alive (S. Pereverzev)
*b. spectrometer with grating and focal-plane **detector array***
c. Simplified coupling to live samples

We can build table-top cryogenic system for IR cell luminescence spectroscopy which can measure light-induced and self-luminescence of live cells

Non-destructive, non-perturbative, the fastest detection of chemical changes and biochemical reactions in a single cell

Fast multi-dimensional data acquisition



- Spatial resolution in IR ~cell size
- For each cell: record photon signals in many spectral channels
- As function of time with 50-100 ps resolution (self-luminescence)
- As function of excitation wavelength (photo-luminescence)
- Extract spectral &time patterns (multi-dimensional analysis)

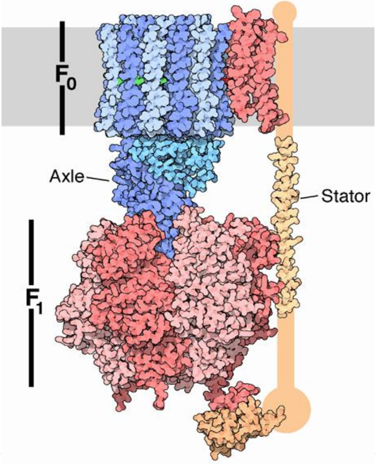
Bonuses:

- **Cell processes in real time**
- **Cell signaling**

Outperform cell Raman imaging and synchrotron-based Cell IR absorption specrocopy

- No phototoxicity for IR excitation light
- Cross-section for direct IR process (absorption) is much larger
- Synchrotron as IR light source not required (table-top set-up)

Cell machinery operation in real tome?
Cell IR signaling?
Controlling cell by IR light?



Energy accumulation and releases in material: history of the problem and possible trends

No theoretical models yet
Physics is experimental science!

?

Tunneling,
Entanglement
Squeezing
In non-equilibrium thermodynamics
& quantum biology

Phenomenology
Experimental studies
Physics of complex systems

?

HEP detectors
Quantum sensors
Condensed Matter

2022: Excess Background and glass-like relaxation everywhere?

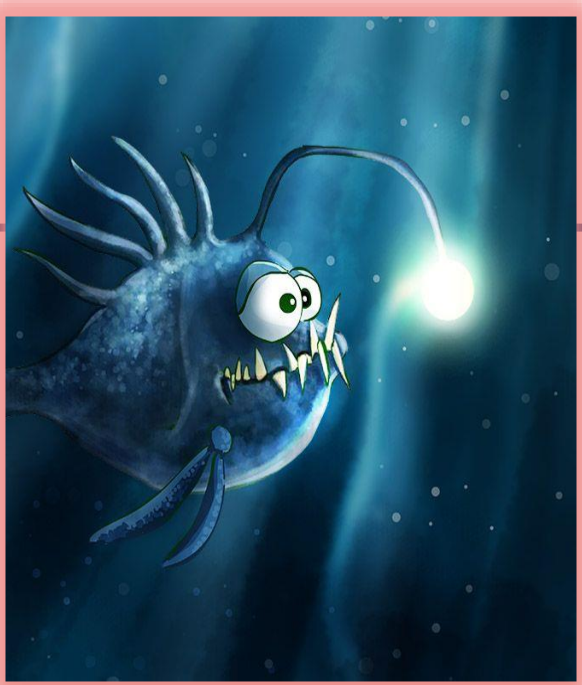
Chemical physics
Cell biology

~2010 Interacting TLS in Quantum devises
1987 W.A. Phillips
1972 P.W. Anderson et al., Non-interacting tunneling two-level systems

Glasses
stored energy
energy flow

1988 Self-Organized Criticality
1977 Prigogine (Noble prize)
Complex internal interactions

Why we need IR bio-photonics (conclusions)



Cell Biology:
Processes in cell are not random , but correlated;
Likely electromagnetic interactions are involved in inter- and intra-cellular regulations
We have chance to see these correlations in real time

Physics:
quantum entanglement and squeezing was discussed for biophotons.
Visible and UV light emission by live cells is extreamlyweak.
Much more photons are emitted in IR.
Will we see unusual quantum properties of the IR light emitted by system of interacting molecular machines (quantum machines)?

Quantum computers are not yet operational. Live cells are working, and likely are quantum micromachines. We can get new tools to see these machines in operation

Lawrence Livermore National Laboratory

SOC-like dynamics and superconducting detectors & qubits

- SNSPD outperforms other types of superconducting IR photon detectors – best time resolution (10-15 ps) , high counting rate (10 MHz and more), energy sensitivity (up to 15 mm wavelengths photons at present), lowest dark count rate while operating at a higher temperature.
- Our hypothesis: no dissipation in nanowire or substrate while waiting for photon, i.e. no energy pumping into material, so SOC-type noise production mechanism is suppressed.

Example: CMB and IR photon detectors:

<<< AC and DC heating <<< Noise equivalent power "energy sensitivity">>>

MKIDs	TES with SQUID array readout	Superconducting nanowire
Sensors are a parts of microwave resonant circuits	Sensors separated from array of SQUIDs; SQUIDS included in resonators	DC current in sensors while waiting for "click" RSFQ -compatible*

Microwave and RF signals (applied and leaking from the environment), changes in electric and magnetic fields, and thermomechanical stress are pumping energy into glass-like sub-systems in materials at low temperatures. Interactions of energy-bearing states (defects, charges, magnetic moments, spins, etc., can lead to SOC-like dynamics in sensors and qubits