

Brijuni Conference 2004 Summary

Matter under Extreme Conditions

The Book of Nature

Its Ultimate Secrets Revealed!

The 1920s introduced two major revolutions;

The invention of Quantum Mechanics
and

The realization that the Universe is Expanding

Each raised new questions:

In 1935 Einstein, Podolsky and Rosen questioned the
completeness of quantum mechanics

A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777, 1935

In 1939, Paul Dirac asked whether the constants of
Nature could remain invariant in an expanding Cosmos

P.A.M. Dirac Proc. Roy. Soc., A 165, 199, 1938

Both questions have had an impact on this Conference

Mach's Principle

Toward the end of the 19th century, Ernst Mach postulated that processes on atomic scales should be determined by the large-scale structure of the Universe.

How else could one explain the identity of electrons everywhere?

Einstein, who later overlapped with Mach in his first professorial position in Prague, was strongly influenced by Mach's principle and thought it should find expression in general relativity - which it never did.

Why would we even expect the Constants of Nature to Change?

In 1939, Paul Dirac resurrected a variant of Mach's principle when he noted that many dimensionless numbers constructed using only the constants of nature, have a value close to 10^{39} or $(10^{39})^2$:

$$e^2/m_e m_p G \sim 10^{39}, \quad (3m_e c^2/e^2)^3 \sim 10^{39}, \quad M/m_p \sim (10^{39})^2,$$

where M is the mass of the Universe. Since Hubble had, ten years earlier, found that the Universe expands, Dirac took these coincidences to reflect a deep connection between Cosmos and atoms.

Measuring a gradual change in the constants over the age of the Cosmos, however, required reliable clocks.

Clocks are Fundamental to most Scientific Measurements

Nature has given us many different kinds of clocks:

1. The rotation of Earth about its axis each day,
2. The Earth's orbit about the Sun once a year,
3. An atomic clock that depends on the frequency emitted by a $^{133}\text{Cesium}$ atom that peaks every:

$$\frac{1}{9,192,631,770} \text{ seconds}$$

4. The half life of tritium ~ 12 years.

These clock rates depend on vastly different types of forces - gravitational, electromagnetic, and weak - each dependent on a different fundamental constant of Nature. What if these constants evolved along with the Cosmos, as Dirac was suggesting?

How would we know whether these Clocks all tell the same Time?

How do we compare clocks that emit their signals as visible light with those that emit radio waves?

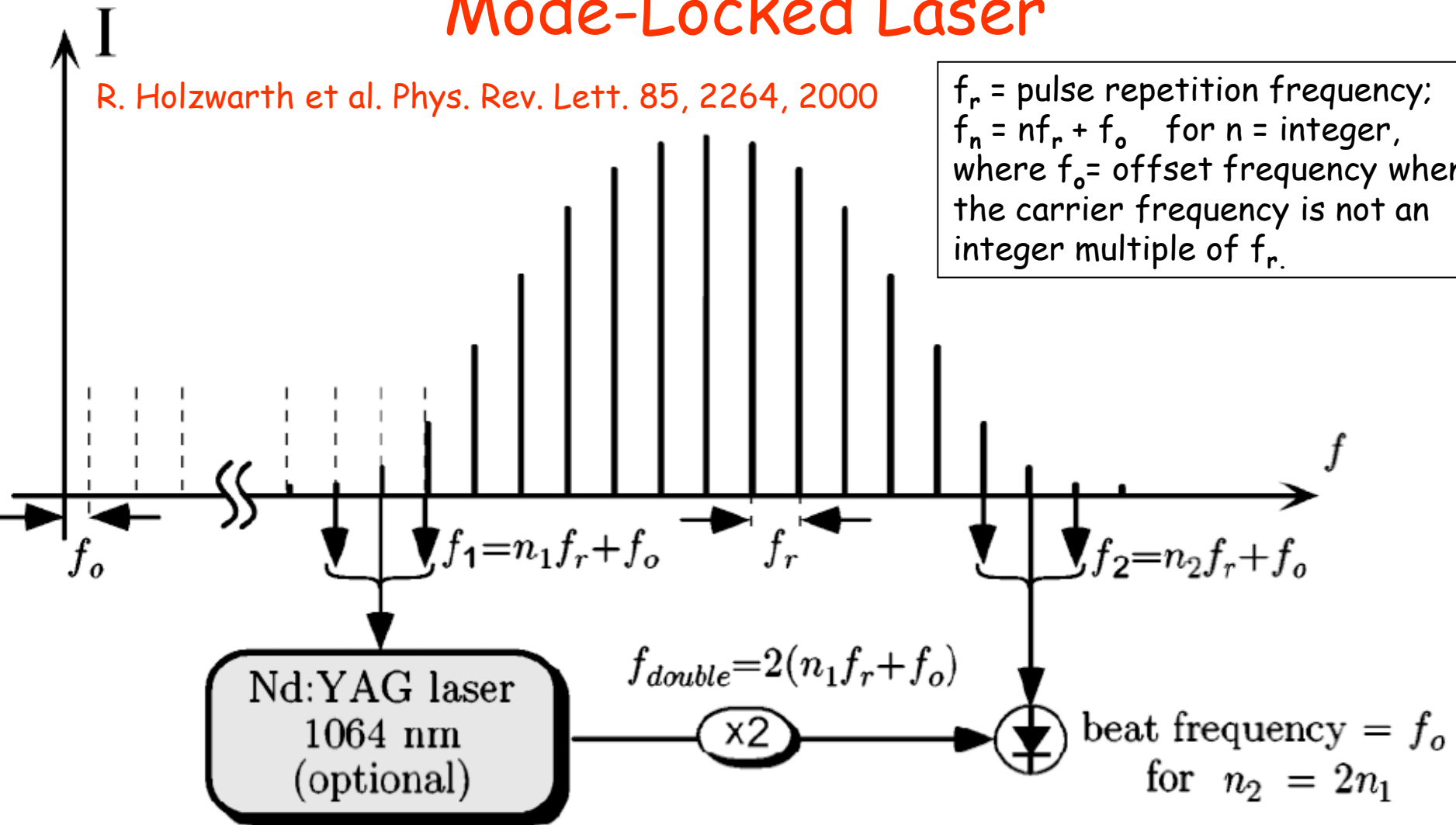
Theodor Haensch gave us an answer with the femtosecond laser frequency comb synthesizer:

With a mode-locked laser the frequencies of the individual modes are separated by identical intervals, their spectrum having the appearance of a comb. An optical laser frequency can, that way, be linked to the clock rate of an atom emitting radio waves.

The Optical Frequency Comb of a Mode-Locked Laser

R. Holzwarth et al. Phys. Rev. Lett. 85, 2264, 2000

f_r = pulse repetition frequency;
 $f_n = n f_r + f_o$ for $n = \text{integer}$,
 where f_o = offset frequency when
 the carrier frequency is not an
 integer multiple of f_r .



The frequency spectrum consists of several hundred thousand sharp lines equally spaced but with an offset f_o . Fractional uncertainties in frequency have recently been reduced to one part in $\sim 10^{19}$ by L.-S. Ma, et al. Science 303 2843, 2004.

Are the Constants of Nature Changing?

Laboratory measurements by Haensch and his collaborators have compared the absolute transition frequency of the ultraviolet 1S-2S transition of atomic hydrogen to that of the hyperfine splitting of ^{133}Cs . The experiment put an upper limit to the drift between these two electromagnetic frequencies of no more than 29 ± 57 Hz, from the year 1999 to 2003. This corresponds to a change of less than one part in $\sim 3 \times 10^{14}$ per year in the fine-structure constant α .

Have the Constants of Nature Changed over the Aeons?

Comparable astronomical observations on quasars that exhibit a number of different transitions in Mg^+ ions, respectively dependent in different ways on the fine-structure constant, put an upper limit on the change of α of one part in $\sim 8 \times 10^{15}$ per year over the past 5 billion years.

(R. Srianand et al. Phys. Rev. Lett. 92 121302, 2004)

But what about the other Constants of Nature ?

Both laboratory experiments and astronomical observations reassure us that none of the constants of Nature appear to have significantly changed over cosmological time.

This is fortunate, because otherwise we would have difficulty reconstructing the history of the Universe which, as Tanmay Vachaspati told us, can quantitatively account for the synthesis of deuterium, helium, lithium, boron and beryllium at the epoch when the Cosmos was only a few hundred seconds old.

Nor do the Constants of Nature appear to depend on local Temperature and Density

This too is important and follows from experiments at accelerators and at the fusion facilities on which Bruce Tarter and Karl Lackner reported. Were this not so, we would not know how to proceed with calculations on how stars evolve, how supernovae explode, or what produces the highest energy cosmic rays about which Peter Biermann spoke.

Long-Range Behavior of Gravity

Since General Relativity has not been thoroughly tested on scales larger than the Solar System, $\sim 10^{13}$ cm, we cannot rule out that gravitational forces may exhibit deviations from an inverse square law on very large scales.

Nor, as Massimo Inguscio reminded us, do we know whether gravitational attraction might not deviate from an inverse square law on the smallest scales, as some brane theories predict.

How Does Gravity Behave
on the Largest Scales ?

A Group of Galaxies

Observed with the
Hubble Space Telescope





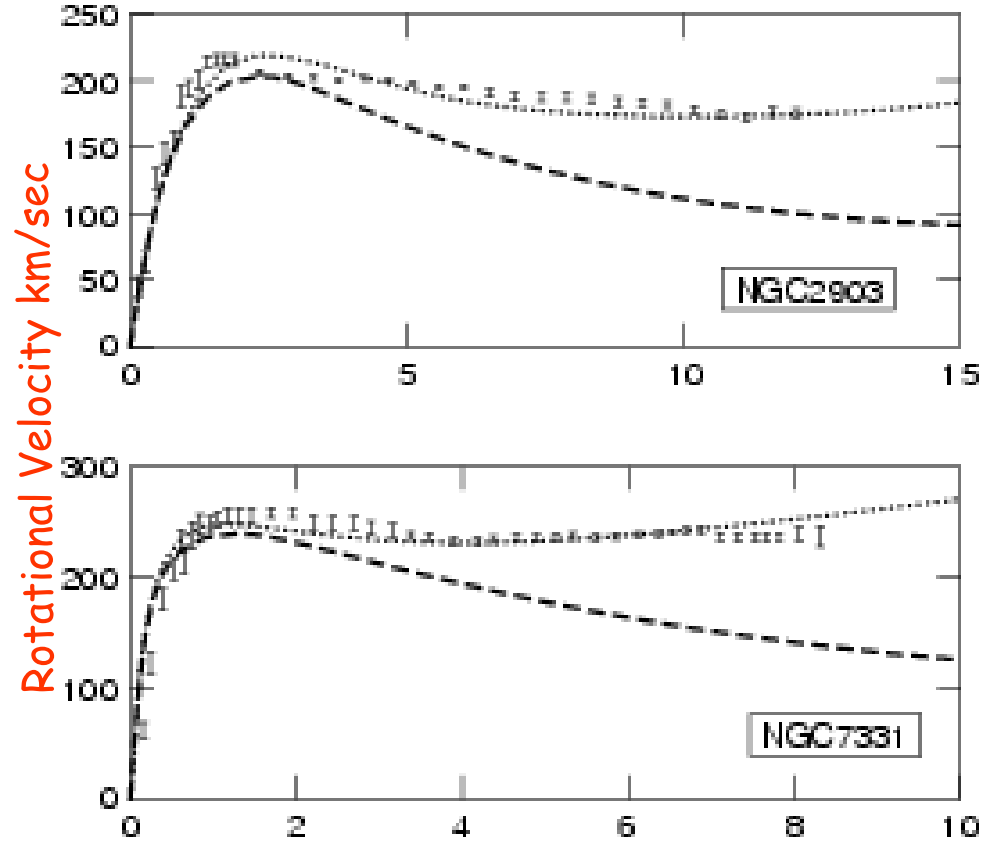
The
Spiral
Galaxy
NGC 4013

seen edge on

Hubble
Space Telescope

Dark Matter?

Dark matter makes itself evident through its gravitational attraction on stars and interstellar gases. It makes them rotate faster around the center of a galaxy. The data points show the orbital speed at of gases at different radial distances from the centers of the galaxies NGC 2903 and NGC 7331. The lower curves indicate the expected rotation rate if the only gravitational forces were exerted by the observed stars and gas. The higher rotation rate of the gas tells us that there may be unobserved Dark Matter exerting additional gravitational forces. **Does Dark Matter actually exist? Or does gravity strengthen at large distances?**

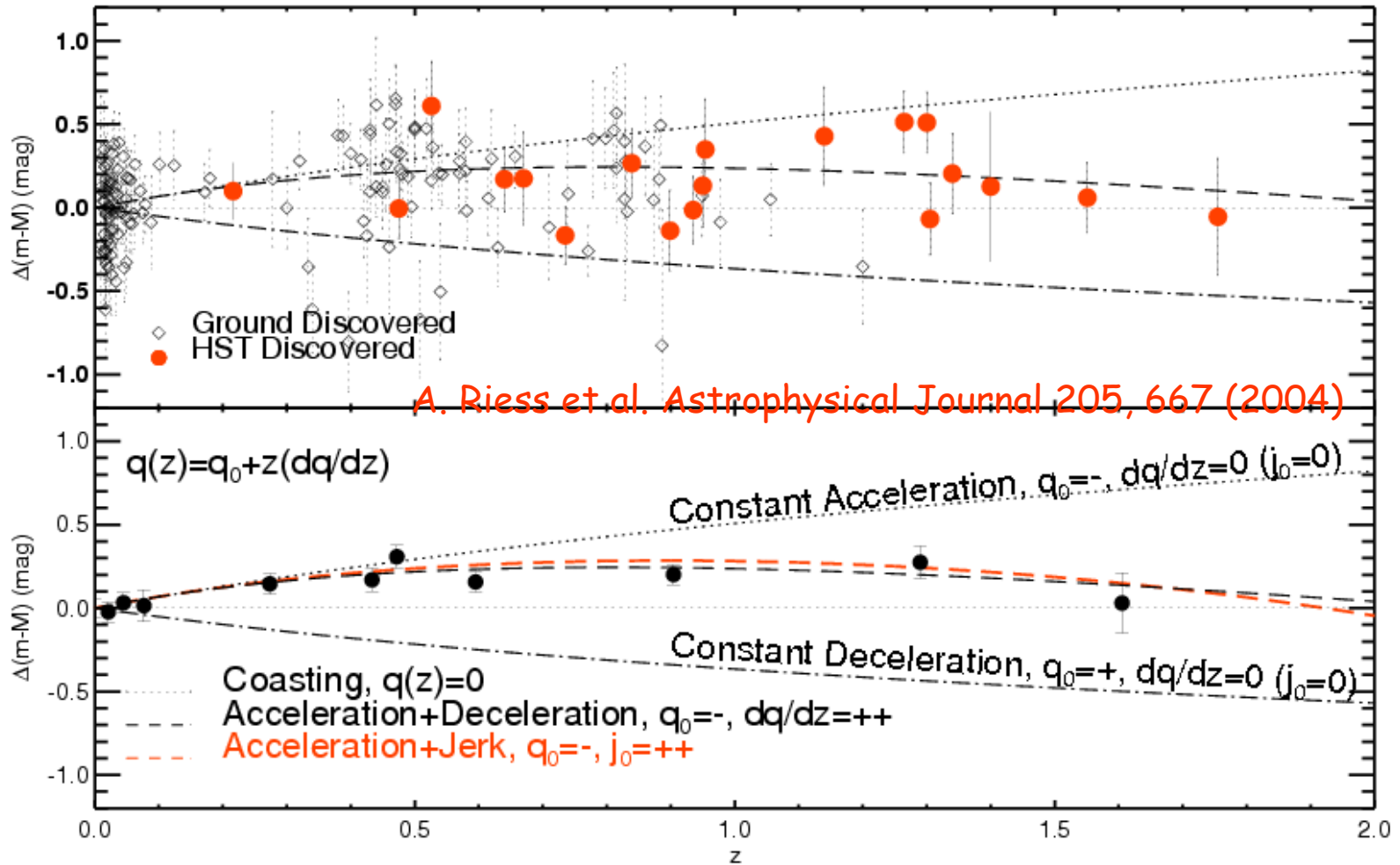


Multiples of the radius of the Optical Disk

Alternatives to Dark Matter

Although Dark Matter is currently favored by most astrophysicists a long-standing proposal by Mordehai Milgrom for a Modified Newtonian Dynamics, MONDS, which postulates a deviation from an inverse square law of gravitational attraction over long ranges, appears to fit observations equally well.

The Evidence for Dark Energy



As Edmund Copeland told us, the evidence for dark energy comes from the expansion of the Universe, which was rapidly decelerating a few billion years ago (red shift $z = 1$), but will nevertheless continue always expand, as far as we can now tell. The cosmic mass-energy earlier was declining, but now is nearly constant. **We do not know what source of energy is at work.**

How Far Out in Space can we Look and How Far Back in Time?

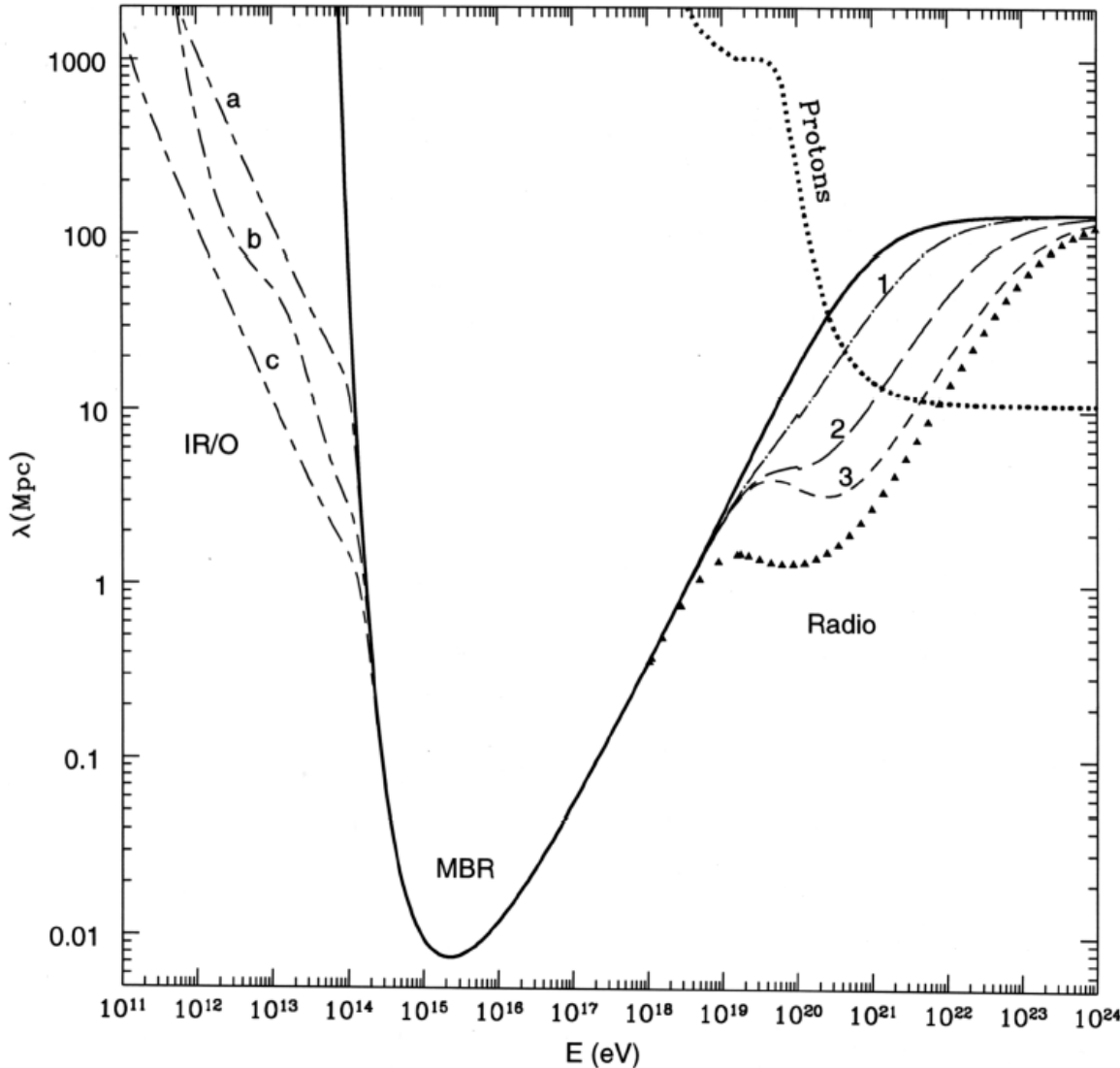
We heard that we can observe only out to a distance at which radiation decoupled from matter and gave us the Cosmic Microwave Background. Sydney Leach re-emphasized for us, how much the devil is in the details of all conclusions we hope to obtain from cosmic background radiation measurements.

The decoupling took place when the Universe was about 400,000 years old. Everything that preceded this, can only be inferred .

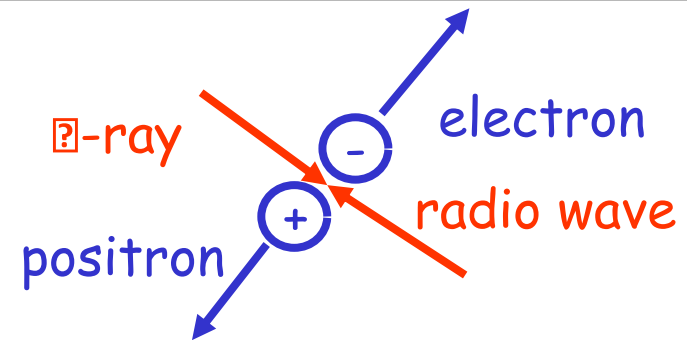
Does Energy Matter?

At very high energies our view is even more restricted. As Peter Biermann told us, photons and particles at high energies collide with microwave and infrared background photons and are destroyed, respectively, in the production of electron-positron pairs or pions over distances of 10^7 - 10^8 light years.

Energetic Gamma Rays and Protons Can't Travel Far Across the Universe



The most energetic gamma rays collide with low-energy photons of the Cosmic Microwave Background, or infrared radiation emitted by dust, and form electron-positron pairs. The positrons later annihilate against ambient electrons.



Protons also annihilate in collisions with radiation, as seen in the upper right.

Is Information also Lost When Objects Fall into a Black Hole?

This question raised in yesterday morning's discussions still has no definitive answer and involves currently evolving theories of quantum information and entanglement.

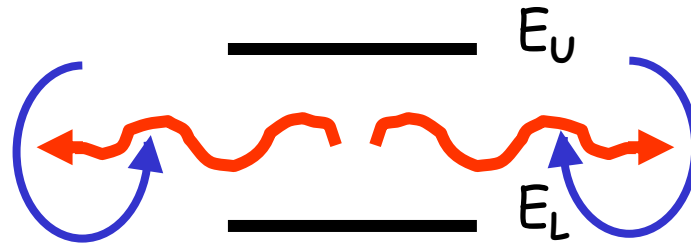
The Einstein, Podolsky, Rosen Paradox

In 1935, Einstein and Niels Bohr confronted each other on whether quantum mechanics could be considered a complete description of radiation and matter on atomic scales.

To understand their argument, one needs to introduce:

Entanglement

Entanglement



In 1935 lasers had not yet been invented. But one could envision a stationary atom devoid of angular momentum transiting from an upper energy state E_U to a lower state E_L by emitting two identical photons in opposite directions, the light quanta having equal energies and spins with opposite angular momenta. This process conserves both linear and angular momentum.

If we measure the spin -- or equivalently the polarization -- of one of the photons of this identical pair, we don't need to measure it for the other. We then already know what it is! Entanglement tells us that we can know the properties of one system by measuring another that may be far away.

This feature is called **non-locality**.

Entangled Photons may have Identical or Opposite Linear Polarizations

All photons in a laser beam have identical energies and directions of propagation within the Heisenberg uncertainty limitations. They also have identical states of polarization

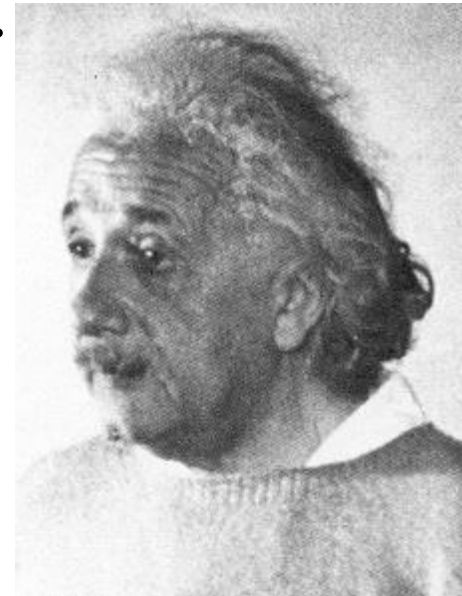


In contrast, the process of down conversion produces pairs of oppositely polarized photons of identical energy



Einstein, Podolsky, Rosen Paradox

In 1935, Albert Einstein and Niels Bohr debated the implications of Entanglement.



Einstein argued that if two photons with perpendicular linear polarizations were both incident at 45° to

the direction of a polarizing plate, they each would have a 50% probability for transmission. So, if one of the two photons was transmitted, the other could also pass through a correspondingly oriented polarizer, and we would not know whether the two were polarized along the same direction or oppositely.

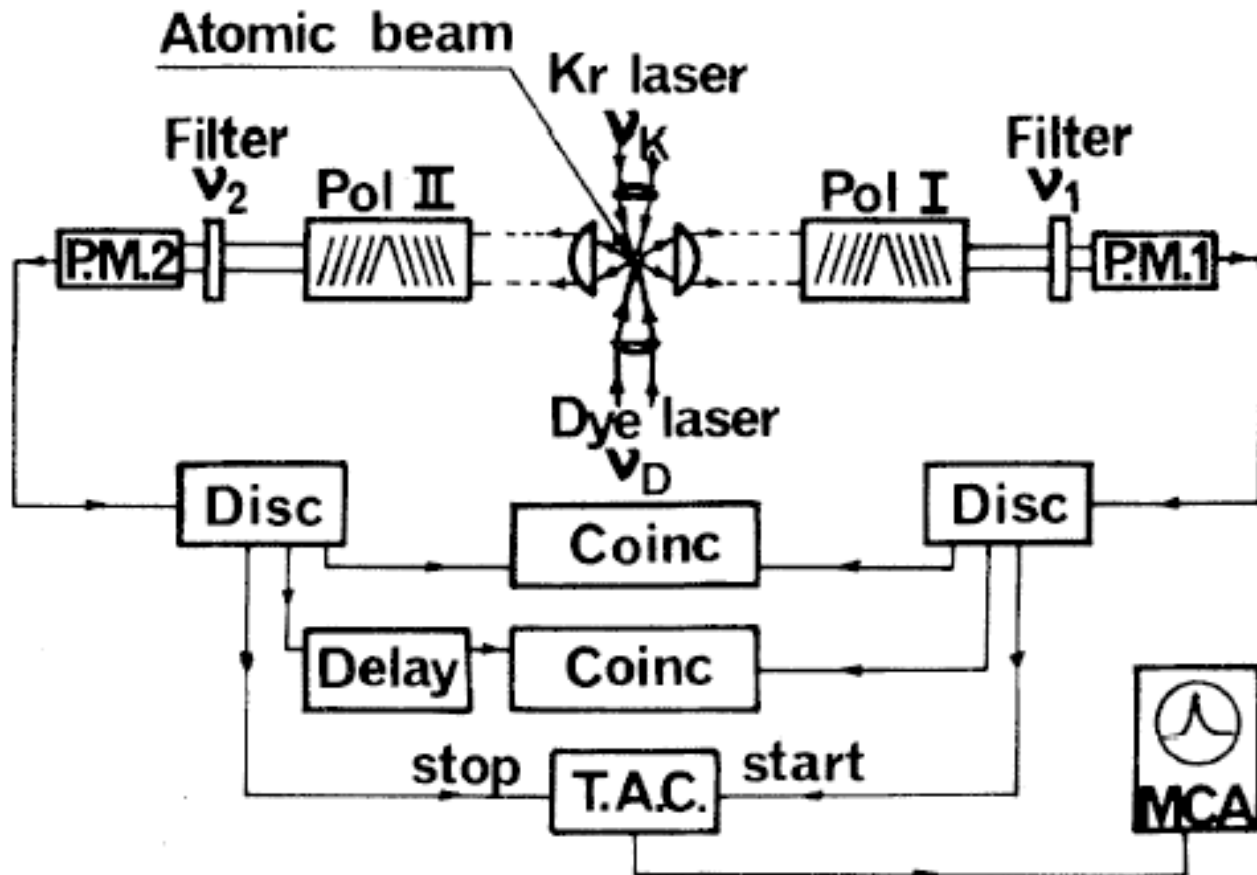
The Alternatives for Einstein and Bohr

If this was not so, the alternative, for Einstein, was that there would have to be communication between the two photons at a speed exceeding that of light, which he considered impossible.

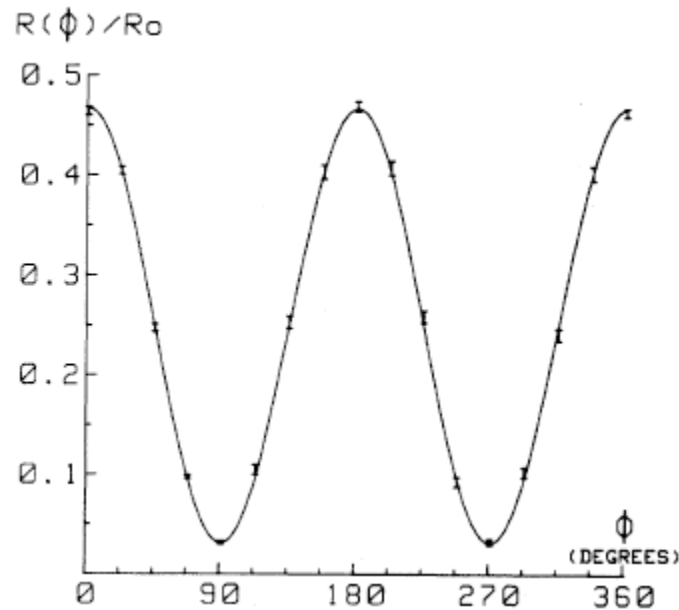
Bohr was adamant, perhaps even dogmatic, insisting that quantum mechanics would permit only one of the two photons to pass through such polarizers.

Not until 1981 was Alain Aspect in his PhD thesis finally able to show that when one photon of the pair transits a polarizer, the other never does. Einstein had been provocative. Bohr had been right!

The Experiment of Aspect, Grangier & Roger



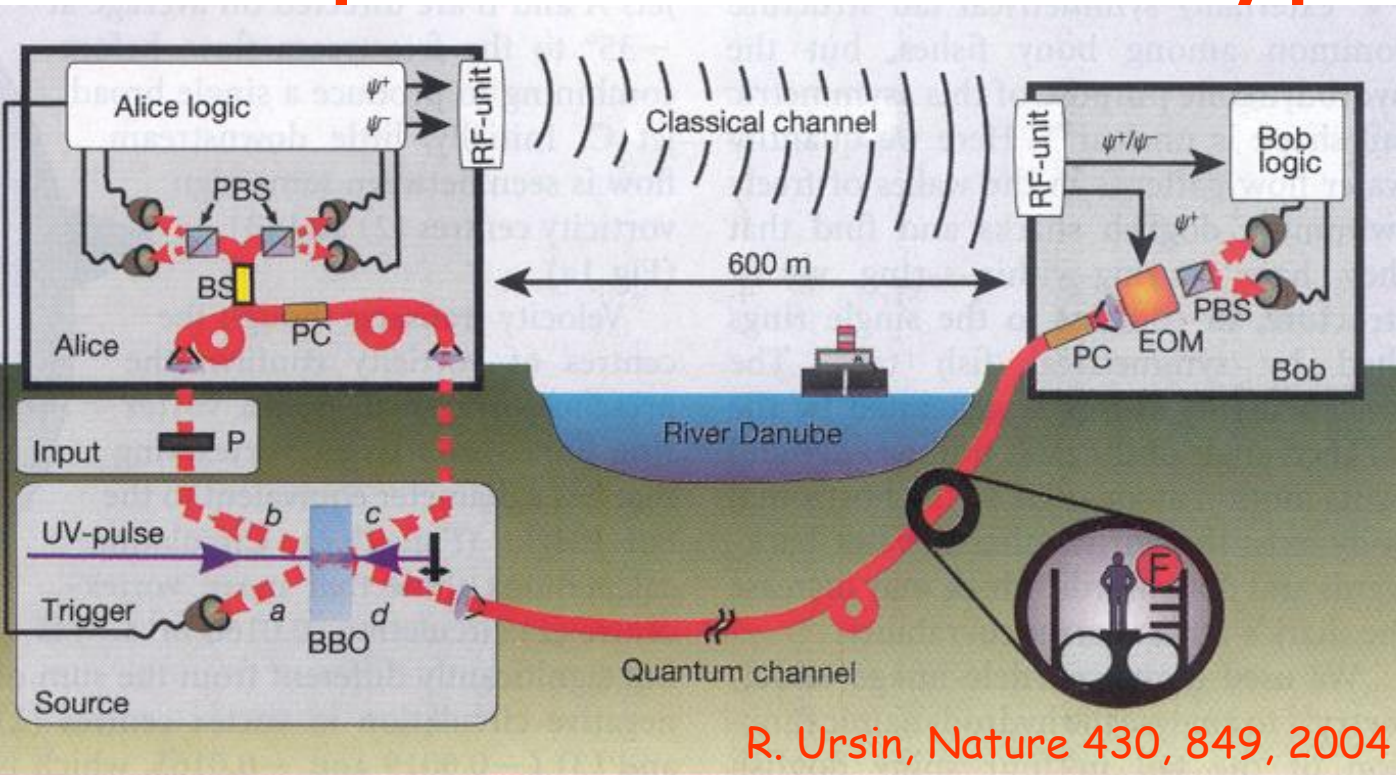
Results of Aspect's Experiment



A. Aspect, P. Grangier & G. Roger, Phys.Rev. Lett. 46, 407

As the polarizers through which the two photons have to pass are turned from parallel positions to perpendicular, the coincidences in the counters - i.e. the fractions of photons passed by one polarizer when a photon is transmitted through the other declines and becomes nearly zero. In a perfect experiment the coincidences would actually decline to zero.

Teleportation and Cryptography



R. Ursin, Nature 430, 849, 2004

If $a = -$, $b = +$

If $c = -$, $d = +$

If $b \neq c$, $b = d$

Photons can be polarized either $+$ or $-$. Alice wants to send a $+$ photon to Bob. She sends an ultraviolet pulse to a barium borate crystal, to produce photon pairs, a/b and c/d , each with one $+$ and one $-$ photon. By setting a $-$ polarizer ahead of a trigger, a is made $-$, and triggers that b and c go directly to Alice and d is sent to Bob along a slow fiber optic channel. Alice at once compares the polarization of b and c . If it matches, she alerts Bob to insert a polarization switch before d reaches him. If b and c differ, she notifies Bob that d matches b . **Only Alice and Bob know what she sent him.**

Atoms and Photons as Qubits

With known states of polarization, atoms, just like photons, can be used to store and transmit information.

In contrast to classical bits encoding either a **1** or **0**, quantum bits - **qubits** - may also be in a superposition of these two states, a flexibility with considerable advantage in quantum computing.

Eugene Polzik and Peter Zoller spoke of preferring atoms as qubits, since they may have greater stability. The possibility of bringing light to a virtual standstill may, however, give photons some of the same advantages.

BEC & BCS

For bosons degeneracy is natural and resembles that of photons emitted by a laser. An individual boson is indistinguishable from others in a "Bose Einstein Condensate", BEC.

Fermions circumvent the Pauli principle by pairing through long-range interactions and acting as though each of these "Cooper" pairs is a boson.

Cooper pairing underlies

Bardeen Cooper Schrieffer superconductivity. Hence the name "BCS condensates".

Boson & Fermion Condensation

Massimo Ignuscio told us about the condensation of ultracold atoms and molecules. The particles occupy a small volume of dimension

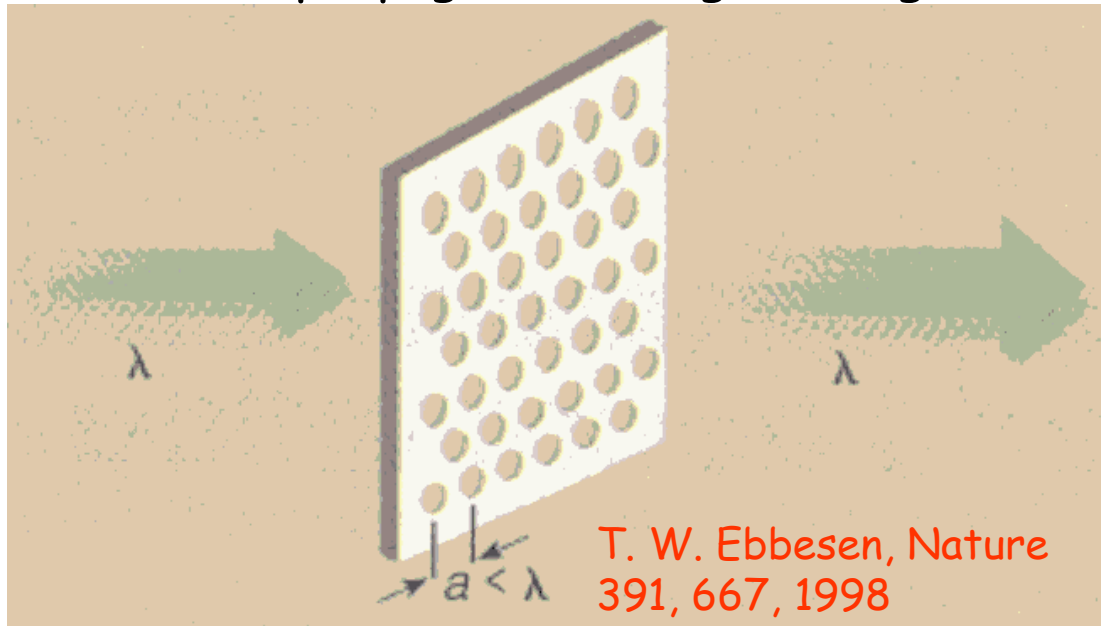
$$\Delta r \sim \Delta / \Delta p,$$

where Δp is the uncertainty in momentum. If the particle temperatures T are sufficiently low that their random momenta are $\Delta p \sim (mkT)^{1/2}$, then many particles can condense indistinguishably into a volume with dimensions $\sim \Delta / (mkT)^{1/2}$.

To fit into a volume of roughly a cubic centimeter, temperatures of $T \sim 10^{-7}K$ are required for most atoms and small molecules.

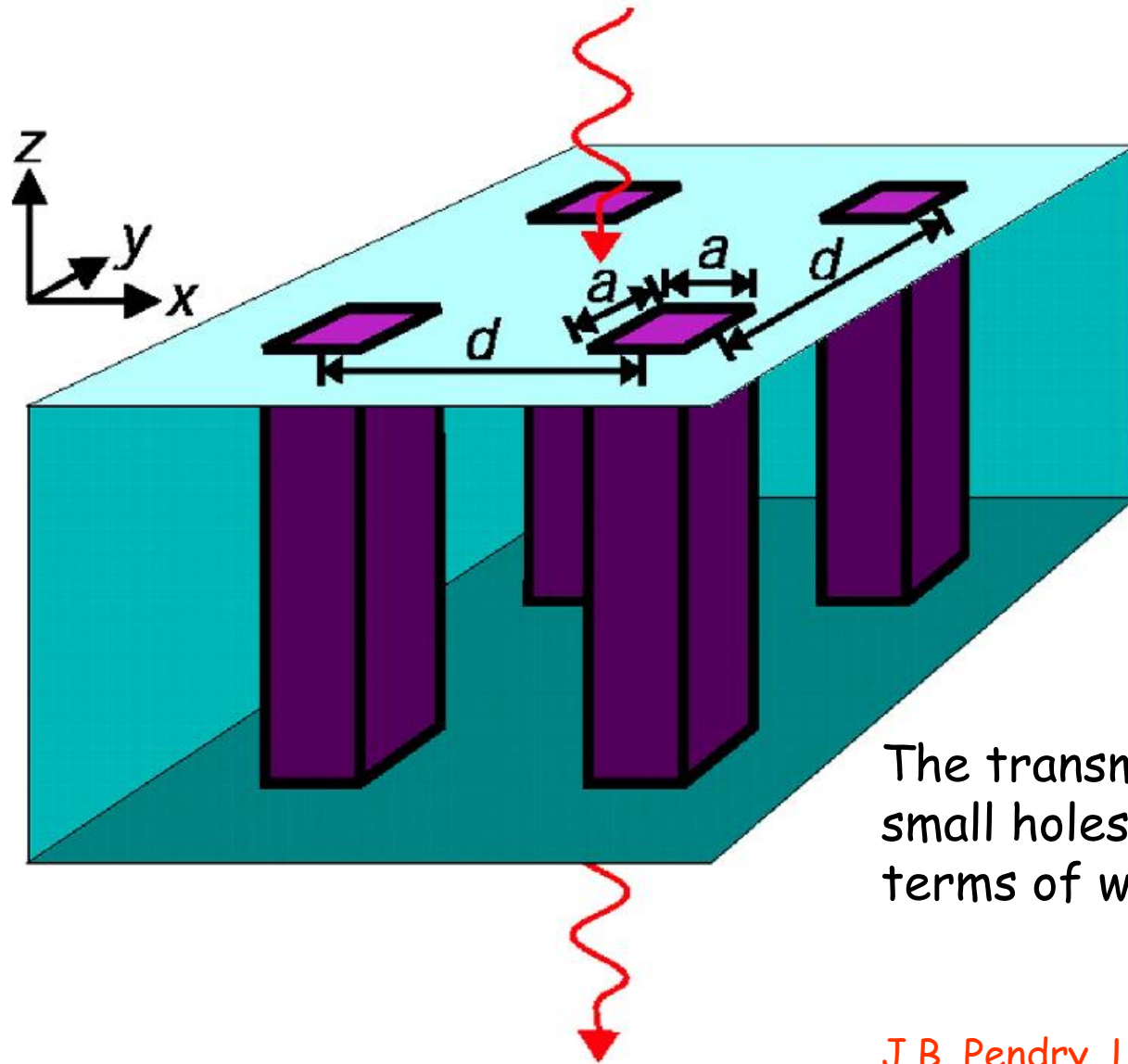
Thomas Ebbesen's Magic Screens

Thomas Ebbesen showed us how light incident on a metal screen in which holes much smaller than the wavelength of light have been drilled at a spacing also less than the wavelength of light, produces **surface plasmons**. These plasmons are oscillating electromagnetic fields collectively propelling electrons in the surface layers of the metal. The plasmons tunnel through the small holes and give rise to electromagnetic waves on the other side of the screen and the further propagation of light along the initial direction of propagation.



Surprisingly, more light can be transmitted than would be expected if the holes were only transmitting radiation directly incident on the cross sectional area of the holes.

Making Light Pass through Holes Smaller than the Wavelength



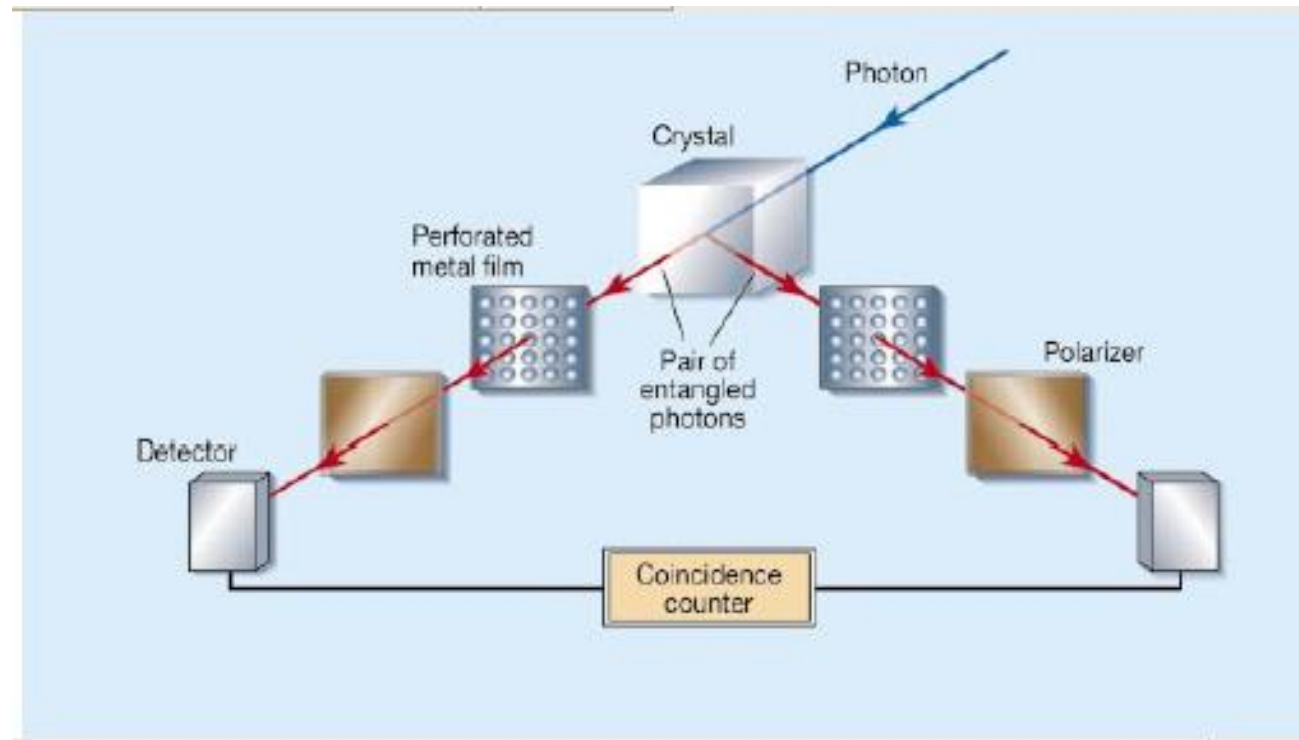
The transmission of light through small holes can also be understood in terms of waveguide theory.

J.B. Pendry, L. Martino-Moreno & J. Garcia-Vidal *Science* 305 847, 2004

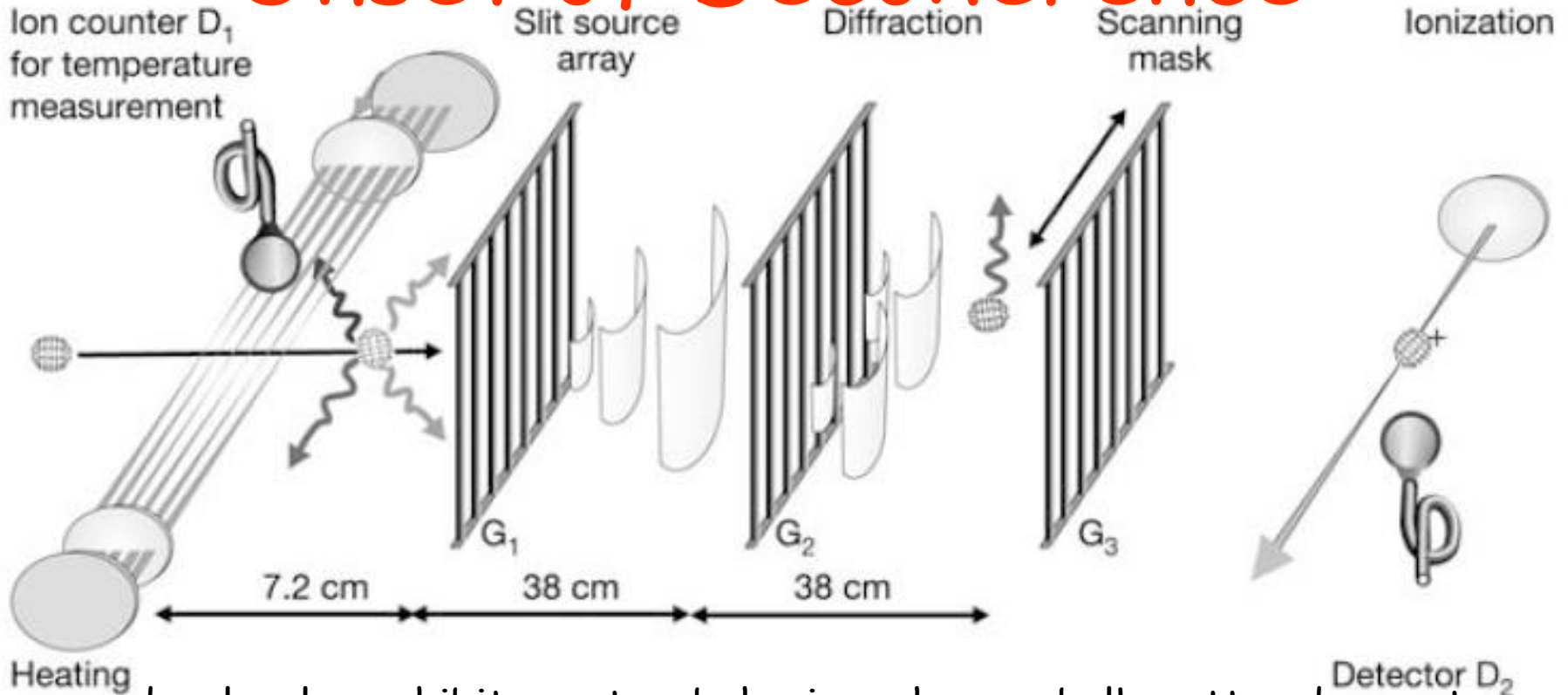
Perforated Screens and Entanglement

An experiment by Altewischer and colleagues examined what happens when entangled photons are incident on these screens. They showed that, although the propagated beam is much weaker than the incident beam, the light remains entangled.

Light is downconverted in a crystal to produce two identical photons with opposite spins. These are passed through an Ebbesen screen and a polarizer before hitting detectors joined by coincidence counters.

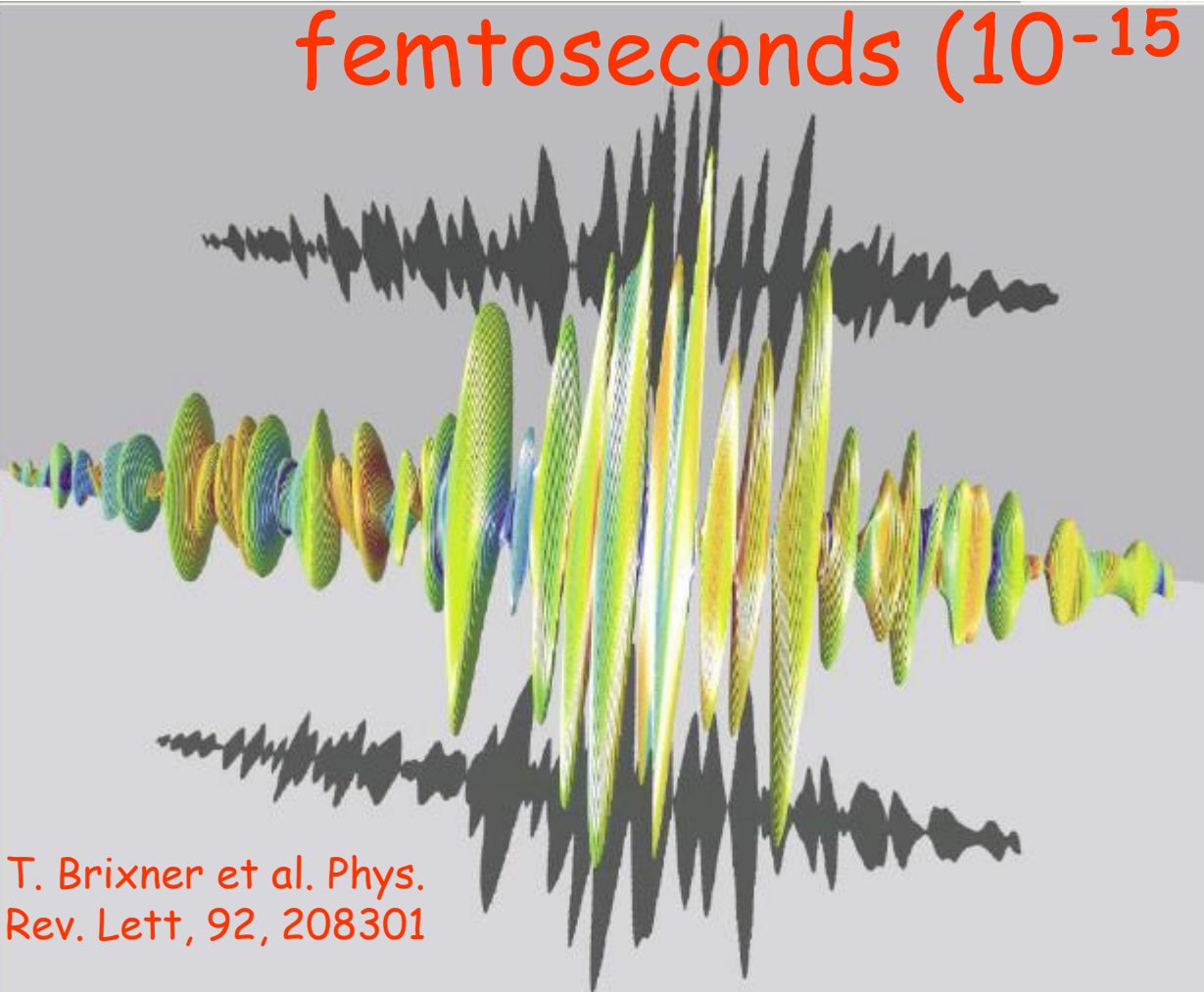


Onset of Decoherence



Atoms and molecules exhibit quantum behavior, whereas bulk matter does not. Gerard Meier showed us one technique for producing slow beams of cold molecules and passing them through or reflecting them off grids. Anton Zeilinger's group in Austria has used related techniques to produce cold beams of C₇₀ fullerene molecules to pass through multiple slits to obtain interference fringes. At vibrational temperatures < 1000 K the molecules exhibited quantum interference on passing through the slits. At internal temperatures > 3000 K, they did not, as they radiated vibrational energy away. This affected the molecules' center of mass and led to decoherence - loss of quantum interference.

Manipulation with Laser Pulses whose Polarization can be switched in femtoseconds (10^{-15} seconds)

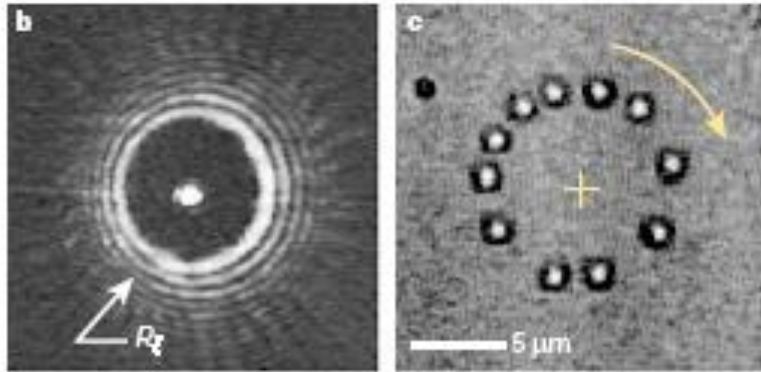
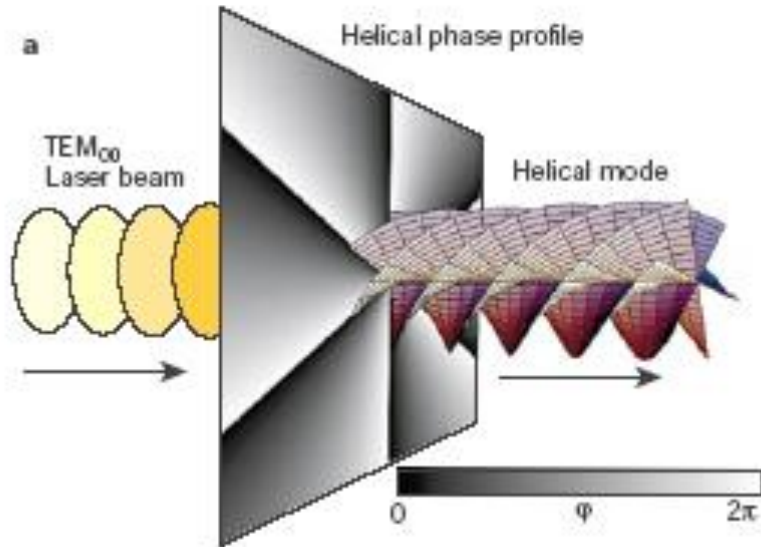


T. Brixner et al. Phys.
Rev. Lett, 92, 208301

The pulse shown here is only 3×10^{-12} seconds long. Colors represent the frequency of the light, and shadows show its orthogonal polarization components.

Gustav Gerber has optimized the rates at which alternative chemical reactions proceed. Computer based learning algorithms maximize these rates to ionize a supersonic beam of K_2 molecules by selecting favored ionization pathways.

Twisted Light Manipulates Atoms and Nanoparticles



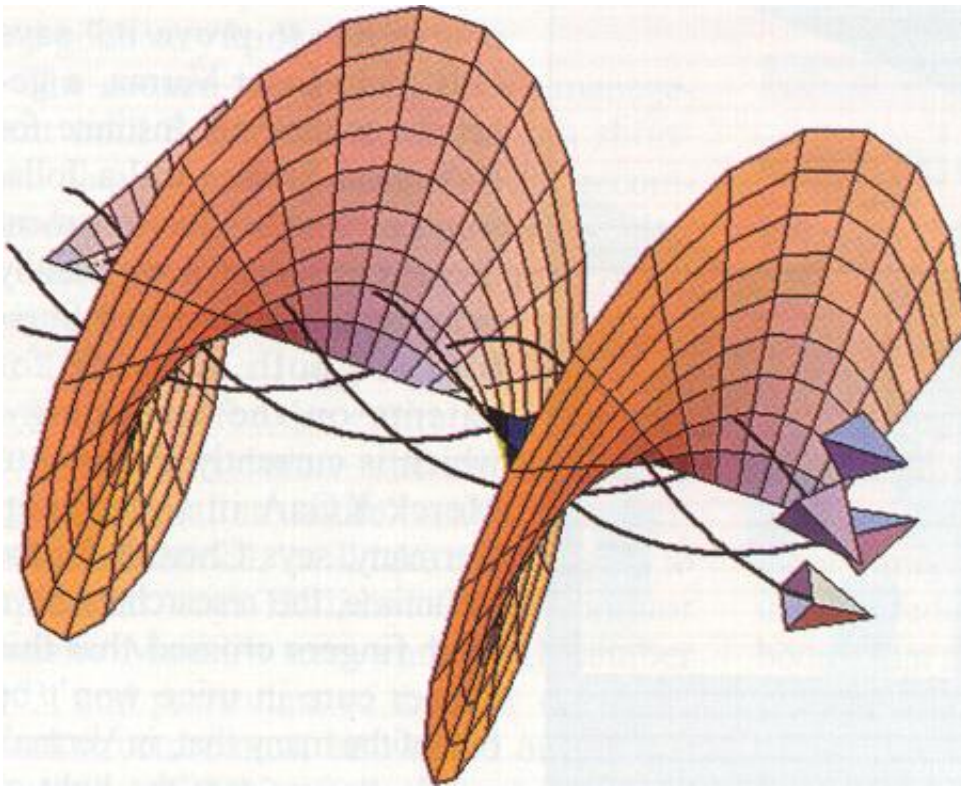
- (a) Light from a laser can be given a twist by passing it through a specially designed phase plate that produces a set of m nested spiral waves wound around each other with a repeat pattern every m wavelengths. m is called the winding number. It is easy to make $m > 200$.
- (b) An ordinary laser beam can be focused to a point. If all its quanta carry the same spin, the focused beam can set a dust grain spinning about its center.
- (c) A beam of twisted light can only be focused onto a ring. A dust grain placed there, will be set orbiting along this ring, showing that twisted light carries orbital angular momentum.

David Grier, Nature 424, 810
www.u.arizona.edu/~grovers/SO/so.html

These new Tools are called Optical Vortices and Spanners.

Molecules and Photons with Extreme Angular Momenta.

Phil Bunker and Per Jensen spoke about molecules spun up to angular momenta $J \sim 300 \hbar$. Twisted light can convey comparable orbital angular momenta to excite molecules. For laser communication, such photons also increase channel capacity. Each photon carries $\log_2 m$ bits of information.



Arrows show the Poynting Vector $S = E \times H / 4\pi$ twisting about the angular momentum axis J_z .

Complex Structures

Bill Klemperer explained that there is still a great deal that we cannot predict in chemistry. Here, as in many problems of disordered structures and turbulence, a problems involving information - entropy - that we do not yet master, may often be at play, as Stephen Berry's talk so nicely showed.

Damien Jouvenot showed us how to construct new molecular structures with complex topologies and getting these to form controllable machines exhibiting piston motion or rotation.

The impressive successes, to date, suggest that in a few decades artificial molecular motors will be used for energy conversion, information storage and computing. Medical motors may also be envisaged. Biological motors taken out of their natural environment have already been demonstrated to operate in vitro. Reverse engineering will presumably enable us to synthesize similar motors relatively soon.

Novel Synthesized Molecules



Courtesy Damien Jouvenot, Institut Le Bel, Université Louis Pasteur, Strasbourg

Nanostructures and microbes

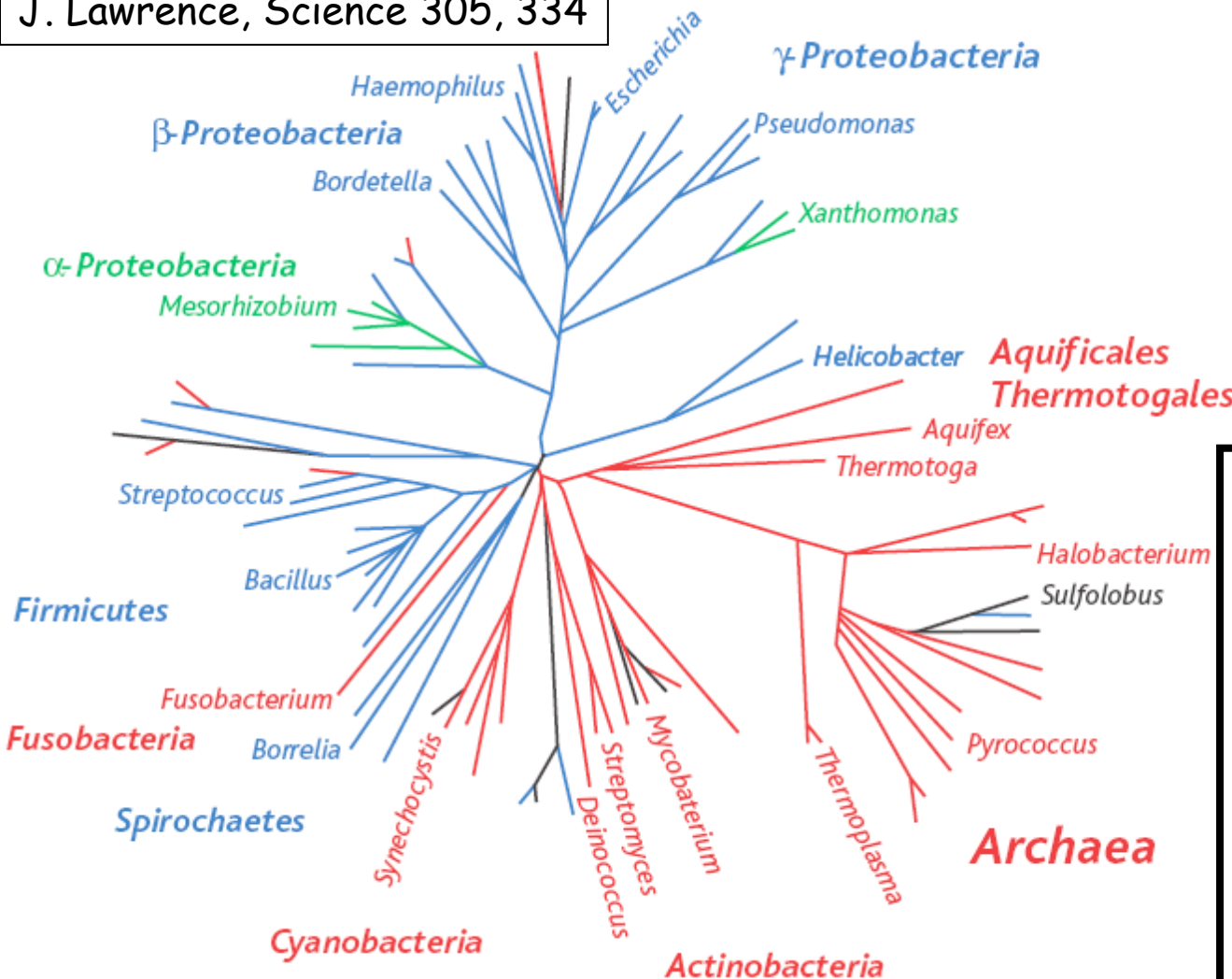
Nanostructures, jets, droplets, and catalysts, are being computer designed and fabricated, almost at will, as Uzi Landsman showed; but what about Stephen Berry's disordered states and voids?

Enormous pressures produce new structural phases, as Russell Hemley demonstrated. But as he also showed, shewanella strains can be subjected to pressures up to 1.6 GPa and still thrive.

This confirms, as Ken Nealson told us in his beautiful lecture, the ability of microorganisms to survive under extreme hardships -- acidities, temperatures, pressures, and deprivation of nutrients -- and to adapt to such conditions.

Many Microbial Organisms Appear to have been Swapping Genes

J. Lawrence, Science 305, 334



Ken told us of gene swapping between species. This suggests that swapping may be a means to adapt to new environs.

Is interstellar travel likely to remain lethal even for microbes? And is panspermia totally ruled out, as cosmic ray laboratory studies now suggest?

Gene transfer as well as common ancestries may account for similarities indicated by distinct colors

Horizontal Transfer (Swapping) of Genes



Bacteria can exchange genes by mutually extending threads. Eugene Madsen mixed bacteria having a gene that degrades naphthalene with bacteria lacking it, and placed both on media containing naphthalene. Within 24 hours bacteria lacking the gene acquired it and were thriving in this hostile environment.

Transitions from Nonliving to Living Matter

Two approaches have been taken to synthesizing artificial cells:

One is by simplifying and genetically reconstituting existing cells with a new genome.

The other aims to produce artificial cells entirely from nonliving organic and inorganic materials.

To be considered alive a localized molecular assembly should be capable of continually regenerating itself and replicating itself with evolution. Regeneration and replication involve transforming energy and environmental matter into cellular aggregates, Evolution requires heritable variation.

Research to create artificial life is highly active.

Man-made Energetic Particles

Innovations continue unabated

While accelerators can now produce highly energetic particles, these come nowhere near the energies of the highest energy cosmic rays.

However, as Bruce Tarter and Karl Lackner told us, laboratory experiments are beginning to approach sustainable fusion -- the process that permits stars to shine. Two rival approaches are pursued. The first is the compression of plasmas -- ionized gases -- by magnetic fields, the second is confinement by intense laser beams.

In energetic collisions of gold atoms, we may by now have created quark gluon plasmas of the kind believed to have existed before the Universe was a second old. Soon we also hope to create small black holes at CERN, as well as primordial Higgs particles.

Increasingly we are building a Universe of our very own!

Science used to be Devoted to
the Study of Nature

This Meeting has largely Exhibited

The Transformed
Nature of Science

Our study of

The Study of Matter Under Extreme Conditions
is showing us how to transcend Nature's extremes.
We are beginning to create our own, entirely new
Cosmos populated with novel forms of matter --
animate, inanimate but intelligent, and other states
quite foreign to Nature.

Our most powerful tool is Science

But

We have no map to tell us how this journey will

END

