PROFESSOR: Welcome to a new teaching, new lecturing of 8.421. 8.421 is an advanced course in atomic physics-- graduate level course. 8.421 is part of a new semester sequence in atomic physics. Actually, 8.421 is taken first in this sequence because we start with more basic things about light and atoms. But the cost is designed in such a way that you can start with 8.422 or 8.421.

So just to get an idea, who has already taken 8.422? Should be about half the class. OK, great. So yes, you're not repeating anything. And maybe for those of you it's a little bit anticlimactic because you had all the fun. You saw all the great things which can be done with two level systems.

And now in this course we sit down and I explain to you what are those two levels. What happens to those two levels in magnetic field and electric fields? How are what they modified by the lens shift and all of that? But you see how the two things are connected.

I talk about some course formalities in a few moments. But let me first point out that you're interested or you're doing research in atomic physics at a really exciting time. AMO science is booming and is rapidly advancing. And a lot of it is really do to, well, of course, new insight, new ideas, new breakthrough, but also combined with technology.

We have seen over the last couple of decades a major development in light sources. If I remember what lasers I have used in my PH.D. And what lasers you were using, well, there's a big difference. Big difference in performance but also big difference in reliability and convenience.

But just a few systems which didn't exist a few decades ago. The Ti:sapphire laser, which has really become the workhorse of generating lots and lots of power in the infrared domain. But then it can also be frequency doubled to the visible.

When I was a [INAUDIBLE] in the early '90s, people just starting to use diode lasers in atomic physics. Here you are 20 years later. We see you much more solid state lasers. And I would say even in the last 5 to 10 years there has been another, well, revolution is too strong a word but another major advance by having extremely high power fiber lasers, which are covering more and more of the spectral range.

So those advanced lasers empower in the spectral range. We have seen major advances in shaping short pulses. I remember when I was a student how femtosecond lasers were that the latest-- well, they're required.

The [INAUDIBLE] and femtosecond pulses could only be produced in a few laboratories in the world with a discovery of the Ti:sapphire laser in Kerr lens mode locking. This has now become standard and is even commercially available. But researchers have pushed on attosecond policies are now the frontier of the field.

Well, if you have very short pulses that also opens up the possibility to go to very high intensity, you don't need so much energy per pulse. You just, if the pulse is very short, you reach a very high intensity, which is the range of terawatt. And it is now pretty standard if you focus the short pulse laser.

In the focus of the short pulse laser, you create electric field strengths, which are stronger than the electric field in an atom. So therefore, the dominant electric field is the one of the laser. And then you may add [INAUDIBLE] on whatever scheme the field between the electons or the electron and the proton.

So this is the generational flight. But light also wants to be control. And this is done by using cavities. A single photon would just fly by. But If you want a photo to really intimately interact with a atom-- maybe get it absorbed, immediate absorbed, immediate.

If you really want to have the photon as a [INAUDIBLE] state and not just as something which flies by, you need cavities, resonators, and we have really seen peak advances in superconducting cavities as super codings in the optical regime. And cavity QED in the optical and the microwave domain have led to major advances in the series of spectacular experiment performed now with single photons.

So the single photon is no longer an idealized concept for the description of life atom interaction. It has been a reality. And single photon control has advances quickly. Well you can make major advances in terms of light. Find new lasers, shorter policies, higher intensity policies, and things like this.

But the other part of atomic physics-- one is light, the other one are the atoms-- we haven't invented new atoms yet. We still got stuck with the same periodic table. But we have modified the way how we can prepare and control atomic samples. A big revolution in the '90s or '80s has been the cooling of atoms that now microkelvin, nanokelvin, and with evaporative cooling, even picokelvin regime had become possible.

In terms of atomic samplers, this was an evolution which took place during my time as a researcher. Atoms always mean you're the sample of individual atoms. Sometimes you started interaction when two atoms are colliding. But atomic physics was really the physics of senior particles or two particles interacting, colliding, or forming a molecule.

But the moment we reach for cooling nanokelvin temperature, atoms move so slowly that they feel out each other. And that means suddenly we have a system to do many-body physics. So the event of quantum degenerate gases and many developments after that with optical lattices and lots of bells and whistles really meant that-- and this dramatic-- that atomic physics has made the transition from single and two particle physics to many body physics.

And for several research groups in this end of what are called atoms, this is, of course, an important point here. Well, somewhat related to that but more generally, the precision and preparation and manipulation which atomic physics has reached with quantum systems puts now atomic physics in a leading position at the forefront of exploring new aspects of Hilbert space.

One can say that Hilbert space is vast. But what is realized, this simple quantum system is only a tiny little corner of Hilbert space. And atomic physics, if I want to define it in the most abstract way, the goal is to master Hilbert space.

And that means we want to harness parts of Hilbert space, which are characterized by quantum entanglement. Maybe single forms between two particles but also between many particles. And of course, this is it to a whole new frontier in quantum computation and quantum information processing.

So this sort of should show you how technology, new ideas, control, and manipulation is suddenly opening up whole new scientific directions. And just to add something more recent to the list, we have now a major research direction in AMO physics dealing with cold molecules. And they're even prospects of rewritting chapters of chemistry. What happens when you do chemistry but not in the ordinary way but at nanokelvin temperature?

Or what happens when you do chemistry where you have coherent control in such a way that maybe the molecules before and after the reaction are in a cool and superposition state. So in that sense, the conclusion of that introduction is atomic physics has been successful because it continues to redefine itself.

And to prove the case, I can say when I predict, when I try to predict-- I didn't even try because I know it wouldn't work. But if I tried to predict 10 years ago what would be the hot topics of today, I would have failed. What happens is just breakthroughs and discoveries. And usually they happen in areas where they are not predicted.

As another angle, atomic physics has seen more than its usual share of Nobel prizes in the last two decades. Maybe the price in 1989 for ion trapping in Ramsey spectroscopy. Ramsey spectroscopy is used for the generation of atomic clock. Iron trapping is a basic building block.

This was sort of givenof some of the technology. But this was the only prize in the long list I'm writing down now which was given for something which was maybe invented a few decades ago. A lot of Nobel prizes are given decades after the discovery. But all the more recent Nobel Prize and this speaks for the vitality of the field, we awarded for developments which had just happened in the decade before the prize.

Whether it was laser cooling just invented in the '80s. Whether it was Bose Einstein condensation observed for six years before the 2005 prize on precision spectroscopy with lasers and frequency comb. This was also a development that happened just a few years ago.

And the most recent recognition for Serge Haroche and Dave Wineland is about the manipulation of individual quantum system. And this is where the highlights of this were accomplished just a few years, lets say, over the last five or 10 years.

OK. Just sort of to make a general case here, I continue to be amazed how interesting ad rich the physics of simple systems are. I actually expect that there maybe even two Nobel Prizes in the near future for, pretty much, understanding the Schrodinger equation.

You would say this has been done in the old days of quantum mechanics in the '20s and '30s. And of course, lots of people have been recognized. But there are two aspects of the Schrodinger equation, which hadn't been understood or which have been understood only recently.

One is the aspect of entanglement and error correction. Nobody until 10 or 20 years-- nobody until [INAUDIBLE] and collaborators introduced error correction would have thought that the quantum system can [INAUDIBLE] here, but you can reestablish coherence by what is called quantum error corrections.

[INAUDIBLE] properties of the simplest wording or equation for just a few-- well, [INAUDIBLE] it's for a few particles-- which we are not known or even the expert in the field would have fled and said, no, this is not possible. And another aspect of actually single particle quantum physics, which has been fully appreciated only recently is the question of [INAUDIBLE] phase and topological phase.

All the [INAUDIBLE] in quantum metaphysics, which is also spilling over to atomic physics of quantum [INAUDIBLE] topologically insulate as an [INAUDIBLE] means that there are non-trivial phases-- non-trivial symmetries in the single particle Schrodinger equation.

So it's just that as a case in point that the single particle Schrodinger equation a lot of people thought in the '40s and '50s. That's it. There is nothing else to do research. And now we when whole new fields emerging exploiting new aspects of the Schrodinger equation.

Will there be something else of the same caliber to be discovered? 20 years ago, people would've said no. And I just gave you two examples of major new insight, which is has really changed our understanding of quantum physics.

A few years ago, I served on a National Academy of Science committee trying to do the impossible to predict the future of the field. But sometimes the National Academy of Science is asked to give advice and try to provide the best [INAUDIBLE] impossible but is exciting.

Of course, we didn't predict the future. But at least to the extent possible, we summarized what are the frontier areas where we see rapid development and where it would be worth investing further. And you will actually see that a number of those frontier areas are where your research happens.

One is the traditional area of precision measurements. As long as atomic physics exists, one of the specialty of atomic physics is we can emphasize measurements, atomic locks, and precision measurements of fundamental concepts and all that. And that continues until the present day.

It was just two weeks ago that there was a new nature paper on the really major advance in atomic clocks. Strontium neutral atom clock has reached the precision of 6 times 10 to the minus 18. It's amazing. We'll talk more about it.

You really have to carefully understand and measure small changes in the black-body radiation because just the black-body radiation creates frequency shifts, which would interfere with their precision. An amazing accomplishment for the field. So precision measurements continue to be an important frontier.

Of course, is there's always the aspect of metrology, determine time frequency, and other things with higher and higher accuracy. But there are also applications. Just one example is making atomically. Atomic physics methods can be now used if you open at home in an environment you can measure the magnetic field.

So people are now talking by using atoms or artificial atoms in the form of AV senders to measure the magnetic field, biological sounds, and all that. So measurement is fundamental aspects but is also applied aspects.

Well, other frontiers are, of course, you can use support ultra cold. We've talked about high intensity lasers. Ultra intense. Ultra short. Atomic physics is more and more getting involved with nano materials.

Materials with blue properties. Maybe materials with negative index of the refrection, metamaterials or, in general or plus [INAUDIBLE] materials. Nano materials can help to shed light and explore new aspects of how light interacts with matter.

And of course, the major frontier is the frontier of quantum information. So given all this excitement, you have many reasons to want to learn more about it. And this course is definitely a good starting point. Let me maybe tell you a little bit what is the philosophy behind the cost and what you will get. That means, of course, at the same time what you will not get.

This course is meant as an systematic, basic introduction into AMO physics. It should really lead the basic foundation that when you talk about atoms to talk about light you are really an expert and you can talk about it at the most profound level. So it's important here, and this is the goal of this course, to provide enough knowledge and enough foundation for that.

So it's not a cause where I just try to sample highlights of the field and provide you with a semi understanding of all this wonderful phenomena. I rather try to focus on selective basic things but then also exciting things but rather explain them thoroughly and teach you by example than teaching you the big overview.

The course, if I want to characterize, is I would say it is a conservative course. It's also, r in this sense, traditional. One reason for that is MIT. The tradition we have at MIT. At MIT we have this several generations of atomic physicists who have shaped the field.

And I learned atomic physics as a postdoc from Dave Pritchard, who was a graduate student of Dan Kleppner. Dan Kleppner was a graduate student from Norman Ramsey. And Norman Ramsay was a postdoc with I Rabi. And Rabi resonance is this reciprocating of atomic physics. The resonance is sort of what we will also focus on today and in the first week.

This is, sort of, the most important concept in atomic physics to really understand the nature of resonances and all its implication. So I should say late in my life-- I was already passed 30-- when I took the first atomic physics class in my life, I took it from Dave Pritchard.

And I was really, sort of, amazed about the course, which had the traditional topics but provided a lot of insight. You can teach traditional physics from the perspective of somebody who does research today. So I want to give you all connections. But at the same time, I like a lot about the traditional approach. And some of it can be traced back to Norman Ramsey.

So eventually, over the last years, I was the main person who has shaped that on atomic physics course when I expanded it from one semester to two semesters. But when I created a lot of new topics, I always looked through Dan's and Dave's notes and made sure the best of what they taught, the best ideas they put the course, they still survive until the present day.

So this course is a development and continuation of a longstanding tradition. I should say I have been immensely enjoyed to co-teach the course on a couple of occasion with Vladan Vuletic and Ike Chuang. And Ike has made major contribution to the second part of the course and Vladan especially to what we will be discussing in the next few weeks.

So what I think is unusual-- you won't find it in many textbooks is that we start out by discussing the phenomenon of resonance of the harmonic oscillator. And we will emphasize for a while the classical part but then also, of course, go to the quantum mechanical aspects of resonance. Now I have to say this balance between classical and quantum mechanics is something I will emphasize again and again in the course.

I can guarantee you in this course I will sometimes ask you interesting question, which challenge your intuition. And you will most likely recognize that often when your intuition goes completely wrong it happens because you believe too much or you over-interpret one aspect of quantum physics.

If I then tell you, but wait a moment, now think classically. Push the classical concept further. Regard the electron and the atom as an harmonic oscillator. Regard light scattering as the effect not of a quantum mechanical atom but of a driven harmonic oscillator.

Suddenly, a lot of things which come out of quantum mechanics make much more sense. So I've often seen when I had a conflict in my understanding. And it's a semi-classical and quantum mechanical explanation, I've learned to trust much more the semi-classical explanation.

So that's why I feel it's important to understand the classical aspects. And usually I would also say understand the means to really understand it's limits. And often I feel you can understand the phenomenon only when you have a quantum aspect, a classical aspect, and we know exactly where they overlap and where they differ.

So to see even quantum mechanical objects occasionally from the classical perspective provides additional insight. So therefore, I would emphasize classical aspects. And for instance, it may come for many of who as a surprise and you will see that next week that some aspects like the generalized Rabi frequency, which you all or many of you have seen for a two level system.

We find it in classical resonance. Just the classic equation of motion of a gyroscope has a generalized Rabi frequency. And I do feel that it is absolutely important for the understanding of concepts that you know where do the concepts emerge? Where are they? Are they already there in classical physics and survive in quantum physics? Or is it something new, which is genuinely quantum.

So yes, I will teach a little bit more classical physics than in the standard [INAUDIBLE] course. But because I've seen within my own research experience that it's healthy to shape the intuition for the fuller understanding of the systems we're dealing with.

So residence is an overarching theme here. But then we have to introduce our main players. The atoms come to stage. And we want to understand the electronic structure, the fine structure, the hyperfine structure, you're going to understand what happens in magnetic, electric, and electromagnetic light fields.

We want to understand in a deep way how do atoms interact with radiation. This also leads us. There's a big difference. You would say, well, what's the difference when atoms interact with microwave and atoms interact with light.

Well light or at high frequency spontaneous emission becomes important. And then you have an open quantum system. You have an [INAUDIBLE], which couples automatically to many, many states. So that's why radiation is different from just electric and magnetic fields because of the presence of all the vacuum modes, and we'll talk a lot about it.

There's one special aspect about the cost, which I don't think I've seen in textbooks in the same way. We are singling out in a rather long unit the aspect of line shape. OK, we talk a lot about an atom as a resonance. But when you measure the resonance, there is a line shape.

And I found it extremely insightful when I first saw Dave Pritchard doing it in his atomic physics course to just talk about all aspects which modify a resonance from a data function from a stick diagram into a real shape. It can be doppled up water. It can be finite lifetime broadening. It can be inhomogenous field.

But there are lots of interesting effects. And By discussing them all together you gain major insight. So we discuss how photon recoil, how the velocity of atoms effect the line shape. And if you think you've understood everything, I will talk to you about in a very counter intunitive aspect of line shapes named Dicke narrowing.

If you put atoms in the environment, you would say they collide. This should lead to collision and broadening. But there is one aspect where collisions lead to narrowing. And that's sort of a highlight of this chapter which really sort of shows you how actually all of those broadening mechanisms are somehow connected.

Finally, and this puts us more towards the end of the course, we want to understand what happens when atoms interact not just with one photon but several photons. And then we talk about multiple photon processes.

I should actually say that I'm also emphasizing the multi photon process a lot. I mean, often we just simply do a transition between two levels. And there is a operator that can be single photon or two photon operator, yes. But to understand the multi photon aspect is important.

And maybe to just give you one aspect of it, when you think you do one photon physics, often, you do two photon physics. A lot of people think atoms can absorb the photon. I've never seen in my life an atom which has absorbed a photon. The photon is immediately readmitted. It's a scattering event. An atom cannot absorb the photon for good because the lifetime of the excited state is short.

So when you think absorption is a single photon event, there is a limitation where, yes, you're allowed to think about it. But if you get confused and it will confuse you, then you need the fact that every absorption process is actually a two photon process. Photon in and photon out.

And sometimes by remembering that it's not single photons, there are always two photons involved, it helps you to avoid some pitfalls of the similar photon picture. So therefore, multi photon, yes. It's not just high intensity to photo transitions and atomic and such. It's also about the deeper understanding. How does the single photon interact with atoms?

And finally, there is something which has fascinated many physicists. The question about coherence. And coherence is as fascinating as it is diverse because coherence can have as many aspects and has many implications. And I also like a lot in this traditional MIT cause that coherence is sort of singled out as a chapter.

And now I'll tell you about all the different phases of coherence in this chapter and not scattered throughout the whole course. We have coherence in single atoms. The simplest one is the coherent superposition of two level, which is so simple that it's almost boring. But there is an enormous richness when we put in a third letter.

About 20 years ago, an understanding of three level physics has really created a new frontier in the field. Let me just tell you buzz words. Lasing without inversion. Electromagnetically induced resonance. Those concepts happen due to coherence between three levels. And we'll talk about that towards the end of the course.

Well we have coherence within an atom between two different or three different energy levels. But we can have also coherence between the atoms. And at that point, the atoms interact not individually. They act collectively.

And of course, coherence between atoms can be the coherence of many atoms in a Bose-Einstein condensate where they form one big matter wage. But it can also be the coherence. The atoms are not coherent because they've formed the Bose-Einstein condensate. But they interact in a coherent way with light.

So there's only one aspect where the atoms act coherently. They may be in different quantum states. But the interaction with the light is absolutely identical.

And when it then comes to optical properties of the system, the light doesn't care if the atoms are different. The light only cares if whether the atoms interact with the light in an absolute identical way. And then you have certain symmetries of the light atomic reaction.

And these coherence between many atoms in the interaction with light needs to-- I just give you the passwords. It's responsible for the process of phase matching when you have a crystal and frequency-doubled laser light you want all the atoms to interact coherently. And it is also important for the phenomenon of super radiance.

I found this subject of coherence particularly fascinating. I should say it was the subject of coherence where some maybe 10 years ago, I was in a long lasting controversy with some colleagues in my field. You know, they're people like Phillips. When I met him, he's one of the smartest [INAUDIBLE] atomic physicist and one of the fastest ones. And ideas just fly back and forth.

And there was only one example where we disagreed over a long period of time where he had good, intuitive arguments, I had good intuitive arguments, and we couldn't agree. And this was related to the question when it came to warm atom amplification.

You know, some coherent process, whether it is really necessary to a Bose-Einstein condensate or whether you can get away with less, which is more the simple radiant way where the atoms are different on different states but they have an identical way to interact with light.

And in the end, I could prove that certain aspect which all people thought in the field were due to the coherent nature of atoms where sort of they were due to the fact that these atoms can be regarded as an atom laser. It was just some form of super radiance in disguise. So anyway, you will notice some of my own interest in the chapter of coherence when I teach it.

So it's something which is this phase matching and super radiance is the physics of the '50s. But a deeper understanding of it really developed when we had Bose-Einstein condensate and could put some of those ideas to the test. So lets what you expect. Let's an overview over the topics.

The course will have 26 lectures. And these are the topics we cover. Do you have any questions about the two levels in the structure of the course? There is something I'm going to say about homework. This semester Ike Chuang has teamed up with me. And as many of you know, Ike is one of the real drivers of MITx, edX, and digital learning at MIT.

So he is now teaming up with me and trying to put some of the pieces online that you can have conceptional questions where you can work on. And you will et immediate feedback whether you're on the right track or not. So this is a new element, which we ant to introduce to the course.

I still think there are certain problems you have to just sit down with a white piece of paper not knowing what to write and start scribbling some creations. So we'll have conventional problems. But you also want to experiment to what degree is it possible to use elements of new technology of digital learning for a course like that.

I actually have to say I regard it as a really very interesting and Paul promising experiment to have some aspects of teaching and learning in a graduate course. When MIT does MITx and, you know, broadcasting education to the whole world, it's much easier to think about what to do when you have a basic introduction to classical physics into circuit design.

There is, sort of, a standard curriculum. A lot of questions are simple. It's pretty straightforward how you can have simple questions as multiple choice questions. But this is different. This is really a graduate course in atomic physics. It's about deep and profound understanding of complicated and complex physics.

I'm not sure to what extent those complexity can be broken into smaller elements, which can be put up as multiple choice questions. Probably not. But on the other hand, since MIT will never reach millions of people with a graduate course in atomic physics, the whole interest of going to the whole world and reaching the whole world is absent.

And for me, I just want to introduce this technology to increase the residential experience for you students. So for instance, videotaping, I'm not sure if these videotapes will ever be shown to a worldwide audience before we make them available. But the primary audience maybe people like you who have a conflict in attending a class and you want to check what was presenting in class.

I also have the idea that this would be in the future. Once we have the videotapes, maybe I can tell you look at the video recording of the class. And instead of having a lecture, we'll just have a classroom discussion. So these are aspects I want to experiment.

But it's sort of exciting to see how can new technology be used for a course, which is very, very different from all the other courses, which have been put online at MIT. Well then, as expected, we have some 20 minutes to start with our first topic, which is resonance.

And resonance is what describes what is relevant for two level systems. And also, and we will touch upon this, resonances are the way hope precision measurements are made. So what is a resonance? Well, we can first look at the classical resonance.

Well a resonance is something where we have some variable and it varies periodically. So in other words, yes, there is a variable, which an be anything. It can be the population of quantum state. It can be an electric field.

It can be the position of an atom. It can be anything you can think about and anything you can measure. And if this variable the varies periodically, you have a resonance. Of course, the periodic variation usually requires that you drive the system.

So you first drive it. And then the system oscillates. And this means now that when you drive the system-- so this maybe a free oscillation. But now you drive the system with a variable frequency.

And what you then observe is you observe a peak. So the phenomenon of resonance is that you have something which can periodically vary. And when you drive it, you see peaked response when driven with a variable frequency.

Yep, this is pretty basic. And I don't want to dwell much more about it. But I can tell you we are interested in atomic physics in every single possible aspect of this resonance.

The shape of the curve. How we can modify it. What happens when we tie it strongly? When we tie it weakly? I mean, resonance is really the language we talk atoms with. So but here I just want to give a lighthearted introduction. The first thing we want to add to the phenomenon that there is a resonance at a certain frequency is finite damping that would mean, after the system is driven, the oscillation does not last for an infinite amount of time.

And that implies that when we drive the system and look at the response as a function of frequency, it's there is a finite [INAUDIBLE] delta f for the driven system. And as we will see in many ways, the damping time in delta f are related by Fourier transform.

And we usually characterize oscillators by the sharpness of the resonance. And the sharpness of the resonance is a ratio of the beats of the resonance and the frequency or the inverse of it. So if you have an oscillator, the kilohertz and the resonance is one hertz wide.

We see the resonance has a Q-- a quality factor of 1,000-- and that means you can observe a thousand oscillations before the oscillation decays away. So what is special about atomic physics here? Why do I emphasize it in the introduction of an atomic physics course?

Well, the system is that in atomic physics we often have exquisitely isolated system. An atom [INAUDIBLE] vacuum chamber or systems, which are prepared with all of the tools and the precision, which we have developed over decades in atomic physics. And therefore, the result is that in atomic physics our oscillators are characterized by an extremely high quality factor Q.

And let me give you an example. If we look at an optical excitation, the-- maybe let me point out it's something you all should try when you take a class in atomic physics and even more so when you do research in atomic physics that you have a few numbers in your mind which match.

So you know, every single person in this room should know what is the frequency of light. How many hertz is-- what is the frequency of a laser? The number I usually use for those estimates is 10 to 15 hertz. Who knows what wavelengths this laser-- 10 to the 15 hertz-- is?

Well I view some visible light. But the speed of light is 3 times 10 to the 10. So therefore, if I just use the power 10 to the 15 hertz, it has to be 300 [INAUDIBLE]. OK, so never forget that for the rest of your life. 300 nanometer is 10 to the 15 hertz.

That means that most of us who are working with rubidium, lithium, and sodium, which is 600 nanometer or 800 nanometer, the frequency is more 5 times 10 to the 14 or 3 times 10 to the 14. But just as a ballpark number, 10 to the 15 hertz is 300 nanometer. OK, so if we have an optical excitation and many atoms have that, what is the Q? What is the quality factor of this resonance?

Well when you stabilize you laser to a vapor cell and you look at the resonance, then you observe in a vapor cell that you have room temperature Doppler broadening-- we'll talk about Doppler broadening later in this course-- that usually corresponds to a frequency on the order of a gigahertz.

And that means that your quality factor is on the order of 10 to the 6-- a million. That's pretty good. A million oscillation. That's a very pure oscillator. But of course, you can do much better if you do Doppler free spectroscopy. Either by having the atomic beam, which is intersected at the right angle. Or even better, put the atoms in an optical lattice.

And this is what people are now doing with the optical lattice clocks that they put an atom in optical lattice where the Doppler broadening is completely eliminated. If you take a metastable level, the lifetime of the exciting state is, maybe, one second.

And strontium and other atoms have those metastable labels. Then you can actually get aligned with, which is one hertz. And the Q factor is on the order of 10 to the 15. I will show you a graphic example of such an experiment in one hertz line widths of an optical transition for an optical clock experiment in the next class on Monday when I want to discuss other aspects of it.

But this is one of the worlds best oscillator you can imagine. 10 to the 15. It's a mind boggling number. Well it's clear why clocks have gone atomic. Mechanical systems are actually not bad but, of course, not nearly as good.

If you take quartz oscillator, well you can build pretty good clocks out of quartz oscillators. You have quality factors which vary between a few thousands and a million. The best values are reached at low temperature. And actually, even in the event of atomic clocks, quartz oscillators or sapphire oscillators still play a roll because you need, sort of, fly wheels.

In atomic clock you may interrogate only every Ramsey spectroscopy. You know, every tens of seconds you get a signal. And in between you need a fly wheel. And then clocks, which have a very high signal to noise ratio but not the [INAUDIBLE] help you to interpolate between measurements.

We see actually a renaissance of mechanical systems in the form of micro-mechanical oscillators. It was only achieved in the last 2 or 3 years that micro mechanical oscillators could be cool to the actual ground state.

And there's a lot of interest of coupling the emotion of the mechanical oscillator to an atomic oscillator because they have different properties and for parental computation and other explorations of Hilbert space you want to have different oscillators. And, you know, combine the best of the properties.

So therefore, there is a real renaissance in mechanical oscillators. And those micro-mechanical mechanical oscillators have often quality factors of 10 to the 5. Here, I want to show you a picture of a fairly nice one.

Yeah, this is a micro fabricated device. It looks like a little mushroom. And what happens is this mushroom type structure can confine light, which travels around the parameter as a so-called whispering gallery mode. It's similar to an acoustic mode, which can travel in the dome of a big cathedral. That's how it was discovered.

It's an amazing effect. I wish somebody would demonstrate it to me. But if you go to one of the ancient cathedrals and you're in a dome, somebody can talk in one direction, the sound can travel around, and you can hear it. There's a guided special mode, which can travel around the parameter of the dome. And here in the microscopic domain, it's light, which is confined in such and resonated.

So this is resonator for whispering gallery mode. And that can have a Q on the order of a billion. So the idea here is that you have either one of those mushrooms or a glass sphere and the light can, sort of, travel around.

And this is the characteristics of this mode. Well you can go from a tiny glass sphere to astronomical dimensions. And you also find oscillators. And the Q of those oscillators is not really bad.

How good is the Q of the rotation of the earth? It fulfills all of our requirements for resonance and oscillator. It's a [INAUDIBLE] phenomenon. The Earth rotates around the sun once a year. And the question is how stable is it.

Well the number is 10 to the 7. It has a Q of 10 to the 7. So the precision of the rotation of the earth is better than one part in a million. You can also look at the rotation of neutron star.

If those neutron stars emit flashes of X-rays, these are pulses, and you can measure the rotation of neutron stars, those neutron stars have a quality factor of 10 to the 10. And of course, [INAUDIBLE] says, if a resonance has a high quality factor, it can be used for quality research.

Then everywhere the line is the more sensitive you are to tiny little changes. And you probably know that this pulsar with a Q of 10 to the 10, well, has been used for the first, also indirect, observation of computation waves. The pulsar rotates with a very precise frequency. And you can measure it with one part of 10 to the 10.

And people have seen that, over the years, the frequency of rotation became smaller. And you can figure out that it becomes smaller by just one part in 10 to the 10 because you're at this position. And what happens is when the pulsar rotates-- when a neutron star rotates-- it emits gravitational waves.

And the gravitational wave is energy, which is taking away from the kinetic energy of the rotation. And therefore, the pulses slows down. So having an oscillator with such a high Q has an allowed researchers to find a small effect in the damping of this oscillator, which in this case were gravitational waves.

Of course, the story I will tell you is about very small changes of atomic oscillators, which led to the discovery of the Lamb shift and to quantum electrodynamics. But the story is the same. A high quality oscillator is the tool for discovery. OK, so we've talked about resonances.

Of course, there are resonances which are useful and others which are less useful. By useful we mean they're reproducible. We can really make a measurement and trust it and repeat and do it again. And that's not enough for being useful. You also want to learn something about it.

So usually, we got resonances as useful when they are connected by a theory to something we are interested in. It can either be fundamentally constance or let me say other parameters of interest. If you want to measure the magnetic field with very high precision and you look at atomic resonance, it's only useful when you [INAUDIBLE], which tells you how the shift or the broadening of the resonance is related to magnetic fields.

And this is, again, a specialty of AMO physics. We have plenty of resonances, which are useful by those standards. And if you compare to astrophysical oscillators, or quartz oscillators, or fabricated oscillators, in atomic physics, we have the great advantage that atoms are identical.

We know when you measure the concision atomic hydrogen in Japan and Europe and in the United States, the venue has to be the same. For other oscillators, you often don't note It. So the showcase of atomic physics is the Rydberg constant, which is the best known-- the most accurately known-- constant in all of physics.

And the reason is because it can be directly measured by performing spectroscopy and hydrogen with highly stabilized lasers. OK, of course, the question is who's interested in all those [INAUDIBLE]? Why do you want to spend all of your PhD or half of your life measuring the Rydberg constant to, maybe, 10 times more precision?

Well it depends. It's maybe not something for everybody. But there are some connoisseurs who think that every digit has provided new inside into nature. And let me just give you one example. If you measure the Rydberg constant very precisely, you can now-- and this has become the frontier of our field-- ask the question, is their change with time a fundamental constance?

So when you measure the Rydberg constant today with 10 to the minus 15 precision and measure it again in a year, who is guaranteeing to you that you will measure the same value. So with the precision which I've just given to you in this measurement of the Rydberg constant, people are now able to say whether the Rydberg constant has changed 10 to the minus 15 per year.

Of course of know, the age of the universe is 14 billion years. That's about 10 to the 10 years. So even the worst case is that if you would go back to the beginning of the universe and the Rydberg constant would change to 10 the minus 15 per year, it would've changed by 10 to the minus 5 over the age of the universe.

But this would be climatic because the connection shows that life would not have developed. The whole organic chemistry would have been different if some fundamental constant of nature had been different by one part in 10 to the minus 6, 7, or 8. So you have extremely stringent limits how much fundamental constant could have changed through the evolution of life because life would not have been the same if fundamental constant had changed.

The question, of course, is should those fundamental constant change. Well the answer is we don't know. But there is a whole research area in string theory where they say that our universe is, sort of, just one of many possible minima in a multi-dimensional space. And it's actually dynamic minima [INAUDIBLE] changes the function of time.

So there are people who wouldn't be surprised if the world is not the same in the future as it is right now because the universe or whatever defines fundamental constants is changing as a function of time. So the question is will it be during your lifetime or will it even be during, maybe, your PH.D when one researcher says you know have an [INAUDIBLE].

And we find out that, yes, we measure fundamental constant using the most accurate atomic clock. And a year later, you have measured something that's just a tiny bit but significantly different. The second aspect why you should always measure things as accurately as possible and this is, sort of the, tradition of our field.

If you can measure something very accurately, do it because, yes, there maybe surprising. And for instance, when people looked at the Zeeman shift with higher precision, they found where we talk about when we talk about atoms in the magnetic field when people looked at the anomalies Zeeman effect, the discovery of that is what nobody expected. That particles electron has a spin.

Or when people saw a tiny shift in the spectrum of atomic hydrogen, it was 1,000 megahertz splitting. It was the Lamb shift. This was the discovery of quantum electrodynamics.

And we know that precision always becomes a tool. A tool to control atomic systems control quantum mechanics with more precision. For instance, if you can completely, sort of, hyperfine structure, you can prepare atoms in a certain hyperfine state. If you don't have the resolution, you can't do that.

OK so we're now going to talk. Go back to the resonance. When we look at typical resonance, we have a frequency omega. A resonance frequency omega 0. And we measure line with delta omega.

In many cases, we will discuss in great detail the line shape is a Lorentzian. And the Lorentzian is the imaginary part of the 1 over 6 function. Omega 0 minus omega. And then there is this parameter gamma.

Gamma, which appears in the Lorentzian, is identical to the full width at half maximum. And the Q factor of a Lorentzian is omega 0 over gamma. Let me finish a few more minutes with a short note about-- we've talked about resonances. I've talked about now the two important parameters. The resonance frequency and the full widths at half maximum.

How do we measure those? And there is actually sometimes a confusion. The more systematic approach is you should measure all those frequency and line width in angular frequency units, which are technically radian per second. 2 pi per second.

But since radian has more dimension, you sometimes say we measure it in inverse seconds. So this is the measurement angular frequencies. And this is different from the unit of frequencies.

When we have a frequency, which is an angular frequency divided by 2 pi, frequencies are usually measured in hertz. The problem is that a hertz is always also 1 over a second. And this is where the confusion comes.

So then you just point out how you can avoid the confusion. You may right an angular frequency or maybe a 0. It is 2 pie times 1 megahertz. Then you exactly know what it is. Of course, this is nothing else than six times 6.28 times 10 to the 6 second to the minus 1.

But you should never say that omega 0 is 6.8 times 10 to the 6 hertz because then people don't really know and you get confused and you confuse other people if you really mean that this has a frequency of 6 times into the 6 hertz on angular frequency.

So just be clean in your thinking and your homework and all that that a frequency when you mean angular frequency is 1 over second, when you mean it as a frequency, it's hertz, and this is often the clearest form to say, yes, I know where to put the two pie and I put it in explicitly. So we often in our papers report frequencies like that.

Finally, there is the question about gamma. So what are the units for gamma? Well if you look at the exponential which decays, it has e to the minus i omega t. And then it has the imaginary part, gamma t.

So gamma is really a temporal decay. And there is no question about frequency and angular frequency. It's not a frequency. It's not an angular frequency. It's a decay of it.

So for instance, if gamma is 10 to the 4 per second, you should never say gamma is 10 to the 4 hertz. Or you should also never say gamma is 2 pi times 1.66 kilohertz. That just doesn't make any sense. Gamma is really at a damping rate.

AUDIENCE: [INAUDIBLE].

PROFESSOR: Yes? I need one more minute.

AUDIENCE: OK.

PROFESSOR: And is there for an inverse time. The damping time associated with this camera is simply the inverse of it and in the case chosen its hundred microsecond. So just keep that in mind. Time is over. Any questions? OK, great. We meet again same place, same time, on Monday.