Season 3, Episode 4

Gabriel Casabona: It All Comes Down to Gravity

SPEAKERS
Sarah Webb, Gabriel Casabona

Sarah Webb 00:00
Welcome back to Science in Parallel. I'm your host, Sarah Webb. And in this episode, I'm speaking with Gabriel Casabona, an astrophysics Ph.D. student at Northwestern University. Gabriel loved space as a kid. But he tried out other fields first, as a college student, he pursued medicine and then pivot into exploring religion. But ultimately, physics fascinated him, and he's been on that path ever since.

Sarah Webb 00:27
Gabriel's research is supported by a Department of Energy Computational Science Graduate Fellowship. We discussed how his passion for physics motivated him to deepen his knowledge of math and computing, how gravity's mysteries define his current work and other big ideas he hopes to work on during his career.

Sarah Webb 00:48
Welcome to Science in Parallel, Gabriel. It's great to have you here.

Gabriel Casabona 00:51
It's great to be here. Thank you for inviting me.

Sarah Webb 00:54
How do you identify yourself to the world?

Gabriel Casabona 00:56
My research is in that field of theoretical astrophysics. And because of the nature of my work, I can't solve these kinds of problems on pen and paper. I must use a computer, and I oftentimes need to use many of them at the same time. And so that has also turned me into a computational scientist as well. So I usually tell people when they asked me what I do, I typically will combine saying that I am a computational and theoretical astrophysicist.

Sarah Webb 01:28
Let's talk about physics. Tell me how you got into physics.

Gabriel Casabona 01:34
I will say my earliest introduction to physics was from this book that my dad got me from the Scholastic

Book Fair, when I was in the first grade, that was all about space stuff and like astronauts, rocket ships. It was mind blowing the fact that it takes time for light to leave its source, and then come to your eyes. And so when you look out into space, you're looking back in time, the book said, when you look up at the sun, which you shouldn't do directly, you're looking at it as it was eight minutes ago. And so that's one of the earliest things I found fascinating in the world of physics, although I didn't really put it together that that was physics. I just thought space was cool.

Gabriel Casabona 02:20
Now physics proper, I was introduced to it. In college, I was a pre-med student biology, and I was pretty indecisive on what I wanted to do. And then while studying religion, I was watching a bunch of YouTube videos on these leaders explaining that their view of the universe and how things work. And through these videos, I ended up finding conversations and some debates with them and scientists and these physicists that I was watching people like Brian Greene, they were explaining the universe in a completely different way than I've ever heard. Like, they weren't guessing. They're pretty clear about what we're assuming. And just the things that I was learning like, like gravity, like what it really is the fact that all the atoms in our body, besides hydrogen, were all formed in the cores of stars and in some of their explosions. And a lot of these things eventually led me down the path of leaving the biology and the religion world to then focus on physics as a career.

Sarah Webb 03:24
And did you get directly into astrophysics right away? It sounds like space had been fascinating to you. Physics became fascinating to you. How did this pieces come together?

Gabriel Casabona 03:35
My interests right from the start was anything happening outside of the Earth. So I knew when I joined physics, I would want to get into astrophysics specifically. And so when I graduated, and I was looking at masters programs, I applied through the APS Bridge Program. And so when I was looking at the masters institutions that were hosting Bridge students, I was specifically looking for those that did something astro related. At the time, I was mostly focused on black holes. It's still one of my main interests. And so I ended up going to the University of Massachusetts Dartmouth. And when I got there, it was a really small department. It just so happens that I met with the DGS [director of graduate studies] of the physics department, and he and I sat and chatted about what he does. And he showed me a really cool simulation of him blowing up a white dwarf, just the way he explained it. He made it sound so simple. I didn't do a lot of coding beforehand. And so I saw him on his computer like in the terminal and I'm like, all this is like what they did in The Matrix. And then he opened up this video. So then he was the one who moves me to astrophysics proper. And so Robert Fisher, he ended up becoming my advisor.

Sarah Webb 04:49
So talk to me a little bit about this introduction to computing and coding as you were working on your master's degree and starting to think about, you know, working on these exploiting white dwarfs and things like that.

Gabriel Casabona 05:02
When I got into physics, I had no idea that computers were used, all I knew was that I'm just going to have to solve a bunch of problems on a piece of paper. And then when I was taking the junior-level physics lab at my undergrad, I was introduced to Python. And I'll be honest, I hated it. It was so scary, like coding just did not make sense to me. I was the only one in the room that had never seen coding. So I just like I felt I was so behind. But thankfully, the instructor of that lab, Dave Jones, was very patient with me, he taught me from scratch, just basically just making plots. That's really all I did. And my lab partner had a lot of experience in coding. And so he really guided me through that. So when I got into the master's program, I didn't realize that there was like way more to it than all of these problems that I was solving on paper for quantum mechanics and such. I didn't realize that you can put it in a computer and solve more complicated problems.

Gabriel Casabona 05:59
And so when I first arrived at UMass, I shared an office with these older grad students. And one of them did work in numerical relativity, he was a great coder. And he told me that you have to learn how to code and that, in fact, if you want a career in science and this domain in physics, you need to know how to use a computer. He was the first person to mention the word computational physics and HPC. And such, it just so happened that both of the people that did astro work, were both computational specialists. And so when I met with Dr. Fisher, he was showing me all these cool simulations and talking about detonation about turbulence. Turbulence is also my other passion. It's the last great mystery of classical physics. And so the fact that we're using turbulence to blow up stars, which is a wild idea, but it turns out, it kind of works. I told my DGS, I was like, you know, this is really interesting and all but I, I'm like, I gotta be honest, like, I don't know how to code, I saw him going through the terminal. I'm like, I have no idea what you're doing. And I'm pretty sure I was his first student that came in not knowing anything about coding.

Gabriel Casabona 07:04
And I got very lucky that he's a great instructor and advisor, he's very patient with me. And the program was pretty small. And so he only had one grad student when I joined. And so he really took the time with me and just taught me basics from learning my way through the command terminal to then learning how to use Python properly. And then the code that we use is called Flash. It's written in Fortran. And so he taught me the majority of what I know, and then gave me resources. He let me borrow his book on Linux, his book on just all the different commands that I can put in the terminal. And from there, that's when I began getting comfortable in it that first semester, I also took a course in computational physics. And so that was when I started learning, proper solving techniques. So we did a lot of numerical workshop learning things like the LeapFrog method, all the way through their RungeKutta methods. And once I became comfortable, and started running my own simulations, I was like, "Oh, this is amazing." The fact that can solve all these complicated problems on a computer, I knew that it was it was a good choice to make.

Sarah Webb 08:07
It sounds like there's a theme for you here. I think there can be a narrative sometimes that people get excited about math and science because they have some sort of natural gift and it comes to them

easily. You weren't interested in this, because it was easy for you initially. So can you talk a little bit about that?

Gabriel Casabona 08:25
Yeah, it did not come easy at all. Really. I mean, I was not a great student. And it took me three tries to pass college algebra. The language of physics is mathematics. And so I knew I needed to learn this to then go on and solve the kinds of problems I want to address. And so that was my main motivation. I need to learn this math in order to be able to do what I actually want to do. And so I was not very talented. But I did have a professor, my calc professor told me practice until making a mistake is impossible. And so that was the method I use to learn math. I just did all the assigned problems, the unassigned problems until things started to make sense, like the day that the integral and the derivative made sense to me. That was when things started to click.

Sarah Webb 09:16
So let's talk about these problems that you're so interested in solving. What are you working on? What are you excited about?

Gabriel Casabona 09:23
I am excited about gravity in the mysteries of gravity and all the extreme manifestations that we know of in the universe. My first research when I was in my master's was studying what are called Type 1A supernovae. A supernova is essentially when a star dies, it blows up in very powerful explosions. One core collapse supernova will be brighter than the entire galaxy itself. So these are very powerful explosions and Type 1A are when a white dwarf explodes. Now what's Interesting about white dwarfs exploding is that it's a completely different mechanism, two stars at the end of their lives, they'll swell up into a red giant after they've fused most of the hydrogen at the core. And then when that nuclear pressure runs out, it'll collapse down. And we call it the big bounce, where it comes down into a very small condensed, high energetic ball of gas and it explodes. A white dwarf doesn't do that a white dwarf is what gets left behind by most stars, when they die. The overall goal of that group led by Dr. Fisher is trying to develop a way of detonating a white dwarf.

Gabriel Casabona 10:36
And so the one thing we do know is that a Type 1A are the explosions of white dwarfs. And these white dwarfs are in binary systems. Because they're in binary systems, they will accrete mass from its companion. And so the idea is that when this material starts crashing down on the white dwarf, it will violently mix with the fluid of that white dwarf. And because of his violent mixing, you have a lot of turbulence, and there's something in the world of turbulence. So we call it the cascade. And so when you have large-scale vortices, they will cascade down to smaller and smaller vortices. And so that means that the length scale and timescale gets shorter and shorter. And so the basic idea of the research is that when the timescale of the turbulence reaches the timescale of the nuclear burning, which for a white dwarf is mostly just carbon, you end up with supersonic combustion, or in other words, detonation, that was the main focus of the group.

Gabriel Casabona 11:36
I then added in helium. Helium plays a role because it's most white dwarfs, we will typically model it as just a carbon-oxygen ball of gas. And then there's a thin helium shell around it. And so some work was done a couple of decades ago that proposed the idea that you could have the detonation of carbon initiated by the detonation of helium. And so I now work on that problem, how to take this mechanism that we came up with and looking at all the different ways that we can blow up various combinations of helium, carbon and oxygen. But that will be the main goal of that. What I do now is I focus on neutron stars, neutron stars are the objects that are left behind by stars dying. So in order of density and complexity, you have the white dwarf. And so for reference, a white dwarf of one that has one solar mass is about the size of the Earth. Aneutron star, which is what Thor's hammer is made out of, is one solar mass neutron star would fit inside of Manhattan.

Sarah Webb 12:37 Oh,
wow.

Gabriel Casabona 12:37 it's about 25 kilometers in diameter. And then a black hole is even smaller than that as the size of a few city blocks. So I now study neutron stars, and mostly in the context of binary neutron star mergers. So there's an event we know of, we call it GW 17087. It's a gravitational wave that was detected on August 17, 2017. And what happened here was that these two neutron stars merged, and one of them blew up. And in this explosion, we were able to detect it in three different ways. One was in electromagnetic radiation; the other was neutrinos, and, finally, gravitational waves. One problem I'm addressing is the fact that it may not be specific to this kilonova. But in general, there have been instances where gamma ray bursts. Gamma rays, being the most energetic form that a photon can take are sometimes preceded by X rays, X rays being the next lower one. And so what we're looking at is if you have a binary system of neutron stars, so in the process of coalescence, each neutron star will feel a gravitational perturbation from its companion.

Gabriel Casabona 13:53
Neutron stars are very dense, and so they warp space time in a very extreme way. So when these gravitational perturbations reach a frequency that matches the resonance frequency of the crust of the neutron star, we believe that it should break it allowing for a surge of energy to be released. So I work on that modeling the crustal dynamics in dynamical spacetime. And so this is a relatively new field. I don't really know anyone that does this kind of work, but I'm calling it general relativistic solid dynamics. The other part of my research with neutron stars is developing a fully general relativistic fluid model. Currently, there isn't one. It's a very complicated problem. Neutron stars are very complicated. They're the most dense objects that we know of. super energetic, magnetic is degenerate is just a lot of complicated stuff happening.

Gabriel Casabona 14:45
And so I am trying to develop one fully descriptive model that we can then use potentially who figure out other cool things about neutron stars. So we're interested in looking at what's the critical mass and density for neutron stars. and seeing if that if we combine it with fast rotation-- so like if you have a pulsar-- can this maybe explain certain phenomenon that we see like the different kinds of radiation and

glitches that we see in the crust? Those are the two main things I work on. And then the last thing is my group at Northwestern under Shane Larson works on LISA.

Sarah Webb 15:19
LISA is an acronym for the Laser Interferometer space antenna, a mission funded by the European Space Agency and NASA scheduled to launch in the 2030s. It will use orbiting instruments to measure gravitational waves in the cosmos at lower frequencies than those that are currently measured with the Earth-based Laser Interferometer Gravitational Wave Observatory. That's known as LIGO.

Gabriel Casabona 15:47
And we use a code called Cosmic that looks at population synthesis as it population synthesis, where we focus on binary compact objects. So any binary system with a combination of white dwarfs, neutron stars and black holes, and so I am looking at as far as computationally I'm trying to scale it up. I want to parallelize it on GPUs so that it's more powerful, and then also to develop a full data analysis framework so that it can be more efficient that we can get answered more quickly. And with that, I'm looking at systems in which a star collapses down to a black hole, we call these systems collapsars and a collapsars are will form the black hole, and then some of that material from the star will get trapped in orbit as an accretion disk. And then that can cause potentially tidally disrupting the companion star in very complicated process can form jets and gamma ray bursts. So I'm studying that, so that I can then go to help tell the astronomers where to look,and how many we expect to find.

Sarah Webb 16:51
These simulations and these models will basically, based on the kind of signatures that you're seeing, help the astronomers who are running the telescopes go, oh, okay, this is how we go for these phenomena.

Gabriel Casabona 17:03
Yeah, there are two things. One is, for example, in my department, in Northwestern, there are people who look at neutron stars and their mergers, so like in kilonova, and there are the observers who will look at the electromagnetic radiation and trying to extract as much information as possible about these systems. And then they are the theorists that are just trying to understand the finer mechanics of what's happening. The idea is that we both do this individually, and then we come together to then create a full picture. So that's the first thing. And then what I was mentioning about cosmic is one thing about these systems I was mentioned about collapsars and the formation of jets and GRBs.

Sarah Webb 17:44 GRBs
are gamma ray bursts.

Gabriel Casabona 17:47
That unless the jet is facing us, more or less, it will be invisible to us. And so they're very hard to detect. And so ideally, this project will allow astronomers to know where to look, that's really one of the biggest challenges in observational astronomy is just knowing where to look, because space is just too big. And you have to be focused in a given direction to be able to detect whatever it is that you're looking for.

Sarah Webb 18:14
You're doing so many things here, all of these projects have been interesting and challenging in different ways. Can you pick one and talk me through the challenges in that work? And basically, was there a moment in any one of these projects, where there was just one particular challenge and how you solved it?

Gabriel Casabona 18:33
Well, I can't say I solved it, but I'm in the process of solving it. And I would say the developing the relativistic fluid model is that's been extremely difficult. The first thing is that I've taken a course in general relativity. But to address this kind of problem, I've taken a deeper dive. And so I've been self studying, reading through textbooks and workbooks, trying to really get a solid grasp of relativity. And I've also been teaching myself to fluids, like in a proper way. I've never taken a course in fluids, although it's part of my research. And so I'm learning all these things. And then there's also the fact that these objects are so dense that a lot of quantum effects take over because they're degenerate. And so understanding the finer mechanics of degeneracy has also been pretty difficult. And so that's probably what's the hardest thing right now is that I'm just trying to learn all these things and put it all together. It's been taken a while, but thankfully, I mean, I guess I have a couple of years left before I need to graduate.

Sarah Webb 19:41
It's interesting, right? In any sort of Ph.D., I mean, you're working at the fringes of what people know. Otherwise, why do this? Are there existing fluid models that you're building of? Or to what extent are you having to build it from scratch?

Gabriel Casabona 19:54
So the starting point of this is based off of a paper from I'm back in the 70s written by a relativist last name Hartle. And Hartle has the most robust fluid model for neutron stars. So that's been my starting point, you could say. And actually, part of the reason that I've taken a deeper dive in general relativity is really to understand his paper. As it happens. He also has a textbook in relativity. And so I've been going through that, mostly because relativity is just one of those topics that professors will teach you different ways.

Sarah Webb 20:30
The book is called Gravity: An Introduction to Einstein's General Relativity. We've included a link in the show notes.

Gabriel Casabona 20:38
And so I'm trying to learn from him since it's his model that I'm basing this off of, and also my advisor, this is a project that my advisor started looking at back when he was in grad school. And he told me that the Hartle textbook is what he learned from and so that's that's also the reason why I have been going through that.

Sarah Webb 20:56
You just finished up your practicum. So tell me about that work and the experience of being at the national labs.

Gabriel Casabona 21:04
Yeah, so I was at Los Alamos from July through October. And it was very exciting to go there, Los Alamos. It's one of the biggest centers for astronomy, and especially neutron stars as a lab. It's my understanding that Oppenheimer was one of the first people to study neutron stars, and it may have been his idea that they existed. In fact, the main equation of state that we use for neutron stars is called the Tolman-Oppenheimer-Volkoff equation of state,. He was one of the pioneers, and he was at Los Alamos working on this. And so to be there working on what I do was like being a kid in a candy store, it was so amazing. Staff scientists at labs are very different than professors. And one of those ways that's different is that they are extremely passionate about what they do. And my advisor down there, Oleg Korobkin, this project that I mentioned about oscillating neutron star cross, it was his idea. And I love that so much that I've decided to just continue working on it, and then adding it into my thesis. Geing around them learning so much from him and the people around me both in science, but also computation and numerical techniques. I probably learned more math and coding than I did science, which that was kind of the point of going there. Overall, it was extremely exciting to be in that environment.

Sarah Webb 22:29
I don't know that I've ever heard anybody talk about the crust of stars before hadn't ever thought about stars having a crust.

Gabriel Casabona 22:36
It's specifically neutron stars, that's one of the many things that make them unique is that it's fluid and then crust, whereas most objects in the universe typically have a solid core. And then the density is as you go out radially. Only about 0.9% of stars are in the mass range to leave behind a neutron star. So they're very rare, and it's hard to find them. For the most part, they're invisible to us. The only times that we're able to see them is if they're rapidly rotating. We call these pulsars because they release radiation along the axes of their rotation, and they usually process as well. So they typically have like a spinning top that's blasting out lasers. And it's been difficult to study them, because we just can't find them. And the ones that we do find it's very limited on how much information you can extract from them.

Gabriel Casabona 23:24
The binary neutron star merger, it was the first and only one that's been confirmed. Thankfully, we've been able to learn a lot from it, the major thing that came out of it was that we were able to detect the nucleosynthesis of some of the heavier elements. So it was called the actinides and lanthanides, which are synthesized through a process called the R process. That is the first time that we've seen elements that heavy like gold and platinum be formed in the universe, which is why they're so rare here on Earth, because not too many systems will make them. And the other thing was the problem of the equation of state, the equation of state basically tells you the distribution of matter. And although the TOV is the main one that we use, there are a few dozen that have been modeled over the years. And one thing

that we were able to do was constrain the equation of state. Let's say we're at like 10 possible candidates for good equations of state and so hopefully, in the future, given the upgraded gravitational wave interferometers on earth, and the big one that's coming out in space in about 10 years, which is the major mission that I'm a part of called LISA. And that will help us pinpoint them before they emerge so that we have time to tell the astronomers to look in this direction.

Sarah Webb 24:40
I want to ask you one more Ph.D. related question. What would you say are your biggest lessons learned either about life or about science from the last two years?

Gabriel Casabona 24:51
The first is that you need a good community around you. You can't go through life can't be a researcher by yourself. You need a Team. You need a team to work on problems together and exchange ideas and you need people around you. And the second thing is that you need to do something that you're passionate about,

Sarah Webb 25:12
What do you see yourself doing after the Ph.D.?

Gabriel Casabona 25:15
I want to continue working in this field of relativity. A part of the reason that I work on neutron stars are because of their density-- they're a very good source to study gravity and relativity. I believe that in order to understand black holes, and why they exist, and what's inside, we need to understand the other two compact objects. By studying white dwarfs and neutron stars, I will then be able to move on and then address black holes so that I can be an expert in all three objects moving forward. As far as research, I'll continue working on that. As far as a career, I'm very excited about this LISA mission. It's been in the works for a few decades, it should be going up somewhere in the 2030s, and is being led by the European Space Agency, and the United States just recently joined. So NASA will be starting a lab somewhere in the Marshall Center beginning next year, and that will be their focus. And so I would like to continue working on it.

Sarah Webb 26:15
Even with so much to explore in the area of gravity and gravitational waves. Gabriel's interests, like the universe are constantly expanding. Some of these ideas are futuristic and controversial in the physics community, as Gabriel admits.

Gabriel Casabona 26:30
In order for humans to survive long term, are going to have to leave the planet, and we need to find a way to do so effectively and efficiently. Right now, all the technologies are based off of propulsion, theoretically, it should be possible to develop some form of warp drive. There are some models out there, but they're requiring an immense amount of energy. But I would like to study that on my own time. Realistically, I won't solve it. But I feel like thinking about my species long term, that's something that I would like to work on. So that at least it's a stepping stone for the next generation to then continue going down so that when the time comes, and we can effectively shoot the cosmos without

having to wait a lifetimeto leave the solar system. Like the Voyager right now, it was launched back in the 70s. It only recently left the solar system. So I'd like to significantly condense that time.

Sarah Webb 27:26
Way to go after a grand challenge. You were talking about passion. And you were talking about physics, and you were talking about gravity you're talking about all of that is wrapped up in a very meaningful mission there at the end.

Gabriel Casabona 27:38
The problem is that there's only 24 hours in a day, right? And I can't live forever. But there are a lot of questions I would like to address as well. You know, like there's the warp drive problem. There's black holes, what's inside of them? What's really happening with the singularity, that should exist, and they're also cosmological questions as well, like, like, what is the universe? How did he get here? How long has it been here? Is it infinite? In a perfect world, I would just have a supercomputer out in the mountains with an infinite amount of a chalkboard and paper, and I would just try to solve these problems.

Sarah Webb 28:14
Gabriel, thank you so much for your time. It was such a pleasure talking with you.

Gabriel Casabona 28:19
Thank you for inviting me I had a great time.

Sarah Webb 28:23
To learn more about Gabriel and his work, extreme gravity in the universe and the LISA mission. Check out our show notes at scienceinparallel.org.

Sarah Webb 28:34
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