Waves without Energy - Einstein and the enigma of gravitational waves: Do they actually transport energy?

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Einstein Papers Project

Einstein and Gravitational Waves

- He invented the subject
- He kept making mistakes, both minor and major
- His lasting legacy was skepticism
- He asked if gravitational waves even existed.
- When he found that they did, he asked if binary stars would emit them.

Einstein and the pseudo-tensor

- Einstein's most controversial early contribution to the problem of gravitational waves was his introduction of the pseudo-tensor as a means of estimating the energy carried by a wave.
- But the pseudo-tensor is a non-invariant quantity. How do you know when you're right?

Tullio Levi-Civita

Einstein’s skepticism

- Einstein’s skepticism concerning gravitational waves came most to the fore during his infamous attempt to prove their non-existence in the pages of the Physical Review in a paper with Nathan Rosen.
- Yet even the published version of the paper expresses significant skepticism.

Herrn John T. Tate
Editor The Physical Review
University of Minnesota
Minneapolis,Minn.

Sehr geehrter Herr:

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Mit vorzüglicher Hochachtung

P.S. Herr Rosen, der nach Sowjet-Russland abgereist ist, hat mich autorisiert,ihn in dieser Sache zu vertreten.

Einstein’s Assistant meets Einstein’s Referee

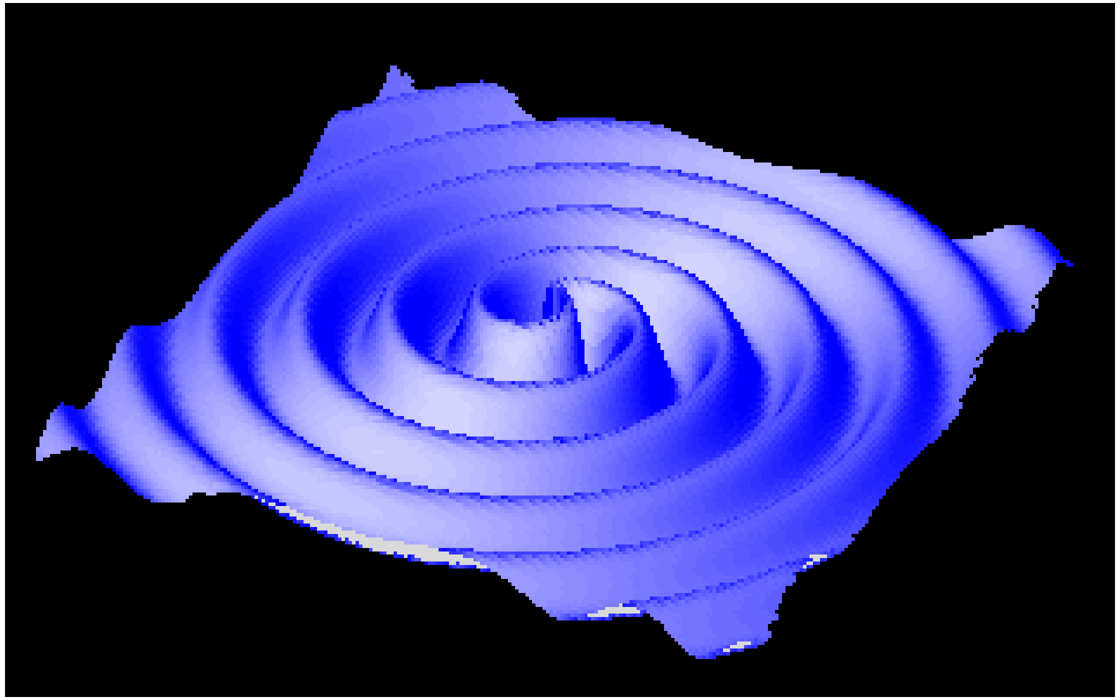
In his memoir, Leopold Infeld tells how he came to accept Einstein’s claim, and even came up with his own version of the proof.

However when he mentioned this to his new friend, the Princeton relativist **Howard Percy Robertson**, Robertson did not believe him.

Robertson found an error in Infeld’s argument. In fact, Robertson had been the referee who criticized the paper!

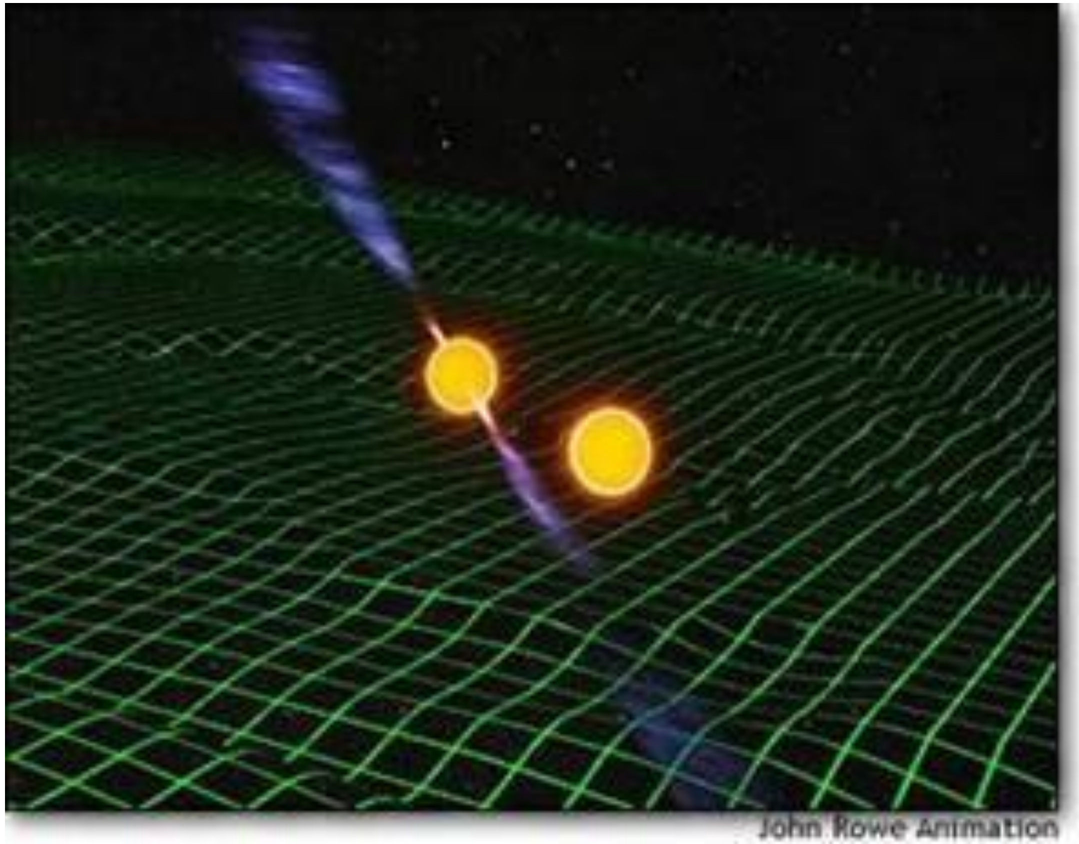
Does Gravitational Radiation Reaction Exist?

- Einstein, 1936: "… it has been concluded that … a system, in sending out gravitational waves, must send out energy which reacts by damping the motion. Nevertheless … if … there is present a second concentric wave-field which is propagating inward … this leads to an undamped mechanical process …"



Final thoughts?

- However the final words Einstein ever published on gravitational waves (1936) read as follows: “Progressive waves therefore produce a secular change in the metric. This is related to the fact that the waves transport energy, which is bound up with a systemic change in time of a gravitating mass [at the origin].”



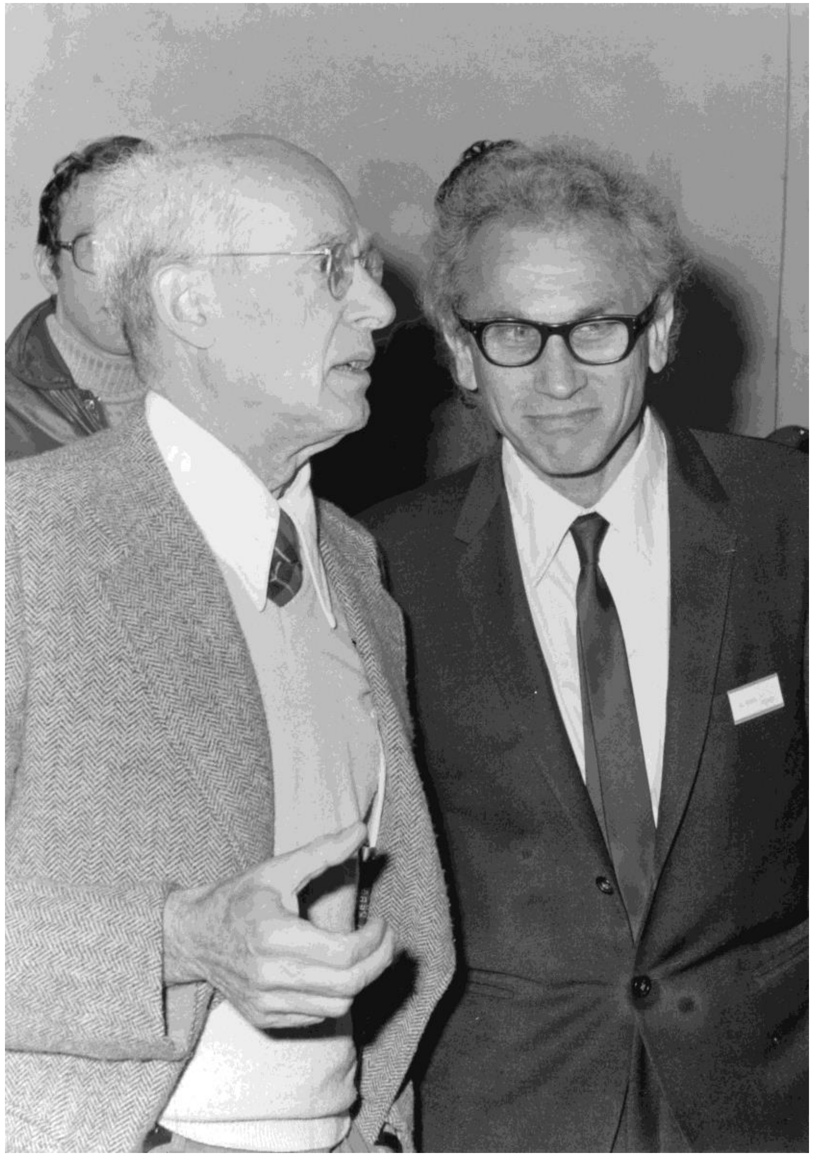
Ritz and Tetrode

- “The Sun would not shine, if it were alone in the Universe” – Tetrode.
- Arguments had been made, throughout Einstein’s career, that the natural choice of solution for electromagnetic waves is one with a combination of advanced and retarded solution.
- Later this approach was fleshed out by Wheeler and Feynman.

Walther Ritz

Infeld and Rosen

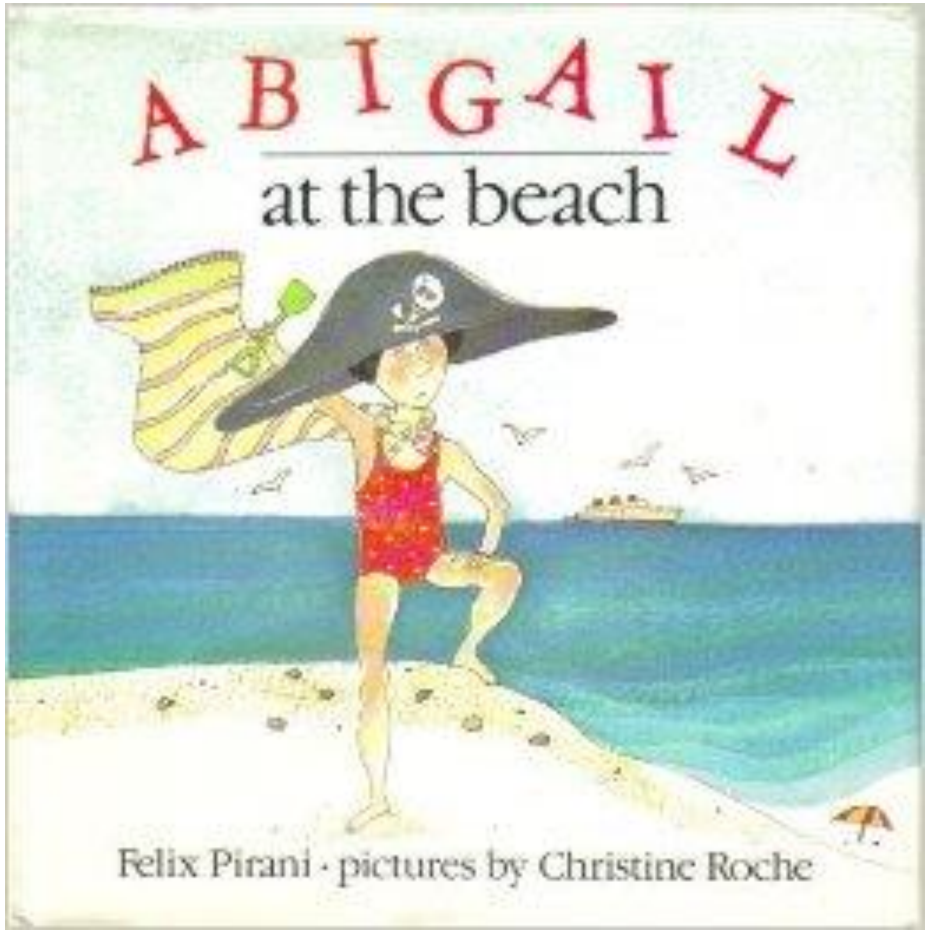
- The 1937 paper could be read as a refutation of the Ritz and Tetrode position, yet Infeld, Einstein’s assistant of the time, certainly did not read it that way. Einstein’s co-author on that paper went on to champion, with Infeld, the skeptics side in the argument over gravitational waves.



Nathan Rosen with Joe Weber

Rosen and the Pseudo-Tensor

- 1955 paper arguing that the waves do not carry energy based on the non-invariance of the pseudo-tensor
- But John Synge suggested to Felix Pirani that he look at gravitational waves using the equation of geodesic deviation to see how they reacted with a material system.



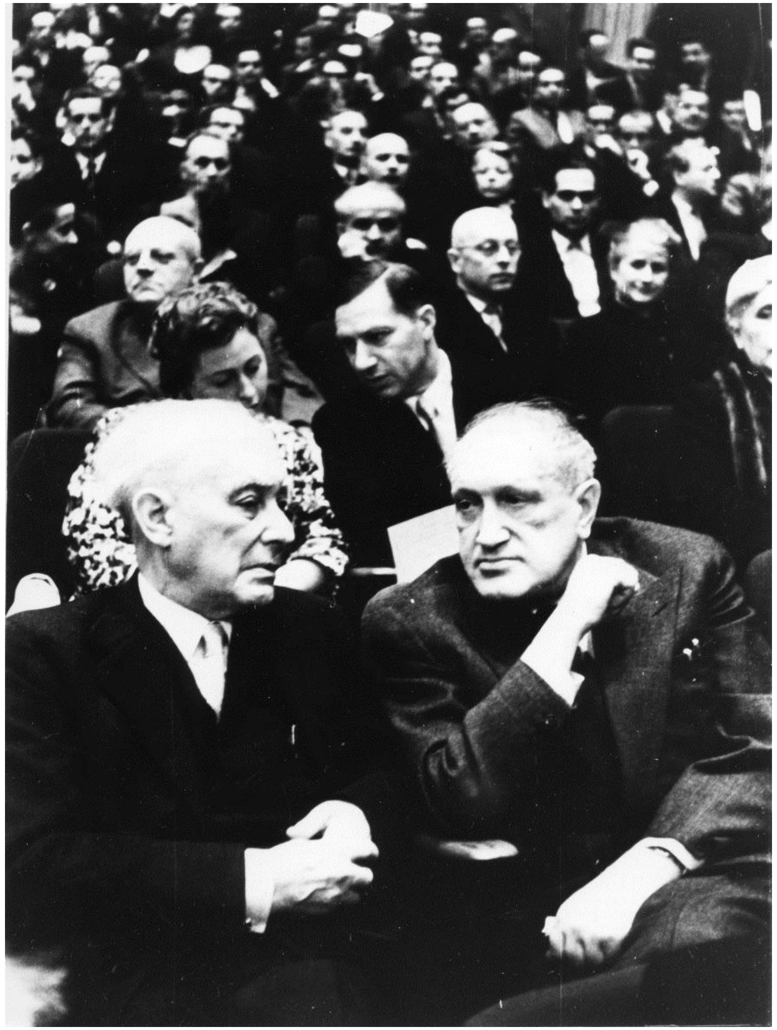
Feynman and Bondi

- Pirani presented his argument that the equation of deviation showed how gravitational waves interacted with matter at the 1957 Chapel Hill conference.
- Both Richard Feynman and Hermann Bondi picked up on Pirani’s work and put forward the “sticky bead argument” that gravitational waves carried energy that could be absorbed by a material system.

Feynman with Dirac at the 1962 conference in Warsaw. The 128 “dopes” are not pictured.

Infeld and the Standing Waves

- The person who took Einstein's musings on Ritz and Tetrode most seriously was Leopold Infeld.
- In his post-war work (first in Toronto, than in Warsaw), building on the work of EIH, he tried to show that binary stars really would not radiate gravitational waves.
- Although he was probably the most influential skeptic, most of his own students did not follow his lead.



Max Born with Leopold Infeld

The Problem of Motion

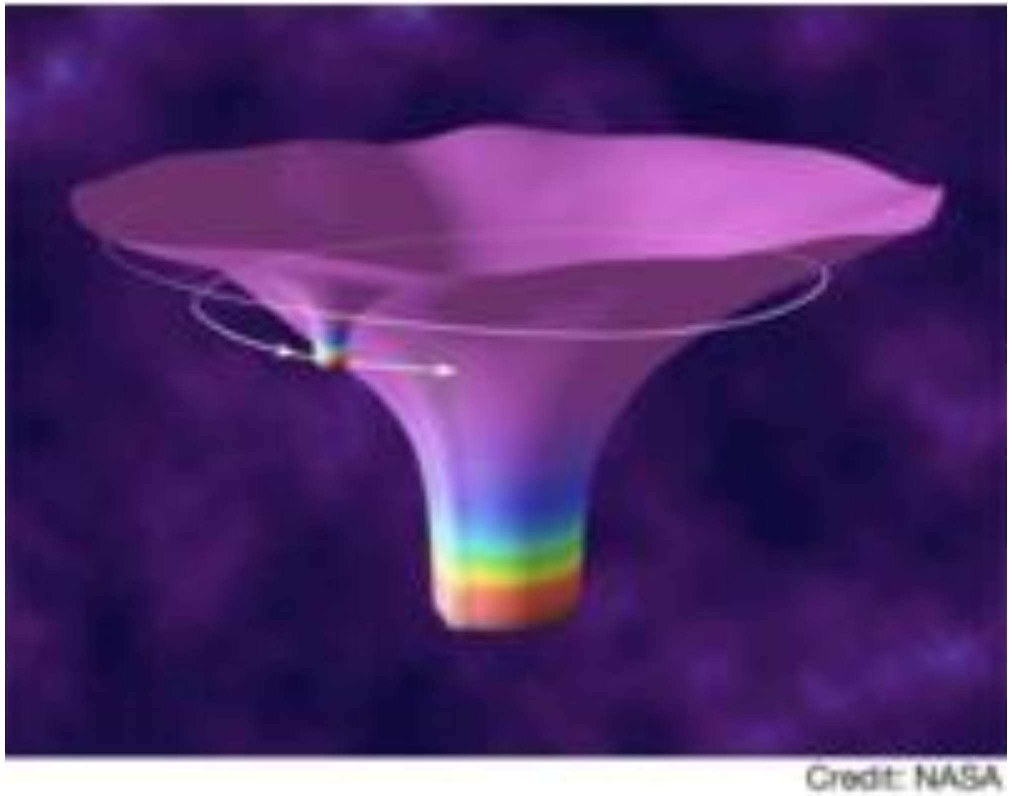
- This dispute had a healthy aspect. It encouraged people to work on the problem of motion to high enough order to include radiation reaction terms, something which might have otherwise seemed too daunting a task to contemplate.
- An amusing aspect of this work, once it was begun, was the futility of the argument over the correct boundary conditions to apply. This was futile because it emerged, after a time, that no one knew HOW to correctly apply those boundary conditions!
- There is considerable evidence that in early efforts, people often imposed boundary conditions quite different from the ones they intended to use.

Early efforts

- Hu Ning (1947) – wrong sign, anti-damping [slow motion]
- Infeld and Scheidegger (1951) – no damping [slow motion]
- Goldberg (1955) – shows that some damping cannot be simply be removed the coordinate transformations
- Fock (1955) – agreed with quadrupole formula [slow motion]
- Peres (1959) – wrong sign, anti-damping but then corrected this to agree with qf [slow motion] [matching!]
- Smith and Havas (1965) – wrong sign, anti-damping [fast motion]
- Chandrasekhar and Esposito (1970) – agree with qf [slow motion]
- Burke and Thorne (1970) – agrees with qf, introduces matched asymptotic expansions

Slow Motion versus Fast Motion

- One of the many issues confronting theorists was whether to base their theory on a post-Newtonian approximation, suitable for describing the binary but not the waves (slow motion) or a post-Minkowskian approximation, more suited to the waves, but less so to the binary (fast motion).
- A compromise was to use slow motion to describe the binary in the near zone and to use fast motion to describe the waves in the far zone.



Slow Motion versus Fast Motion

Analogy with Newtonian Gravity
Post-Newtonian

Very appropriate for the problem of motion for a binary star system, BUT

No gravitational waves until rather high order in the expansion (post-2 ½ Newtonian)

Since Newtonian gravity lacks asymptotic spacetime structure, difficulty of unambiguously imposing correct boundary conditions.

Analogy with electromagnetism
Post-Linear or Post-Minkowski

Very appropriate for handling radiation, BUT

Correct problem of motion for binary requires higher order

Ultimately successful calculations tend to use slow-motion approximation in the “near zone” and linearized approximation in the “far zone”, with some matching in an intermediate zone

Matched Asymptotic Expansions

- An example of the technical advances which helped overcome the inconsistencies which had been encountered was the introduction of Matched Asymptotic Expansions, a technique developed by applied mathematicians interested in fluid dynamics. These gave an unambiguous means by which to impose conditions in the far zone onto he near zone.
- Blanchet and Damour showed that there were some still errors in Burke's work. The Theoreticians' Regress in action!

Bill Burke

Answers to the Skeptics' Main objections

Gravitational Waves cannot transmit energy (Rosen, 1955)

answered by - Bondi-Feynman thought experiment, 1957

Binary stars do not radiate because they are freely-falling systems

answered by – problem of motion (e.g. Fock 1955, Peres 1959)

Retarded potentials are not the right choice for binary star systems

answered by – Goldberg 1955, Trautman 1958

Only binary stars with “news,” i.e. internal structure, can radiate (Bondi)

Singularities are suspicious when used in the problem of motion

answered by – Chandrasekhar and Esposito (1970)

Too many of the post-Newtonian calculations have disagreed

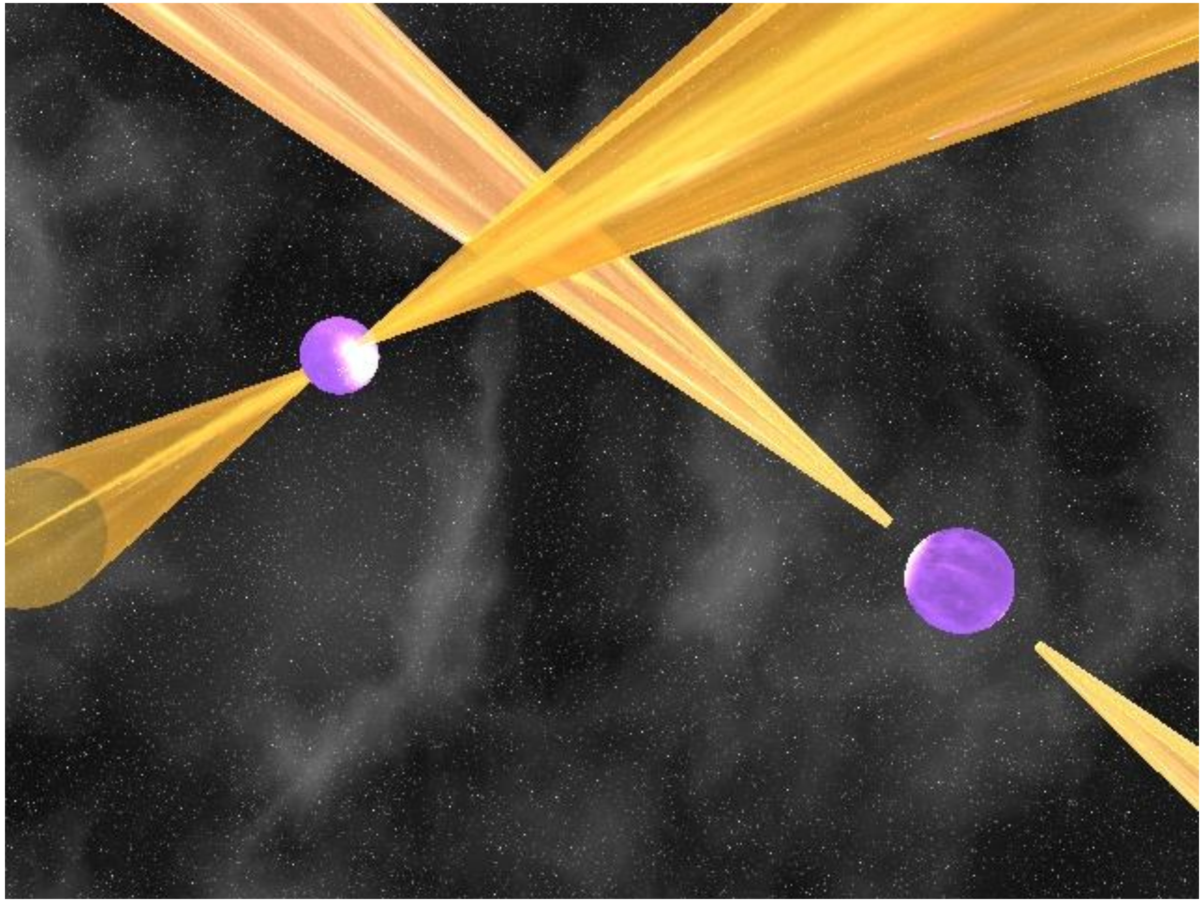
answered by – Burke (1971) and Walker and Will (1980)

Binary stars may radiate, but the quadrupole formula does not apply

answered by – Damour, Anderson and others

Binary Pulsar

- Enter some observational data
- Much to everyone's surpise, Dyson's aliens had been at work.
- Joe Taylor and Russel Hulse discovered the binary pulsar in late 1974.



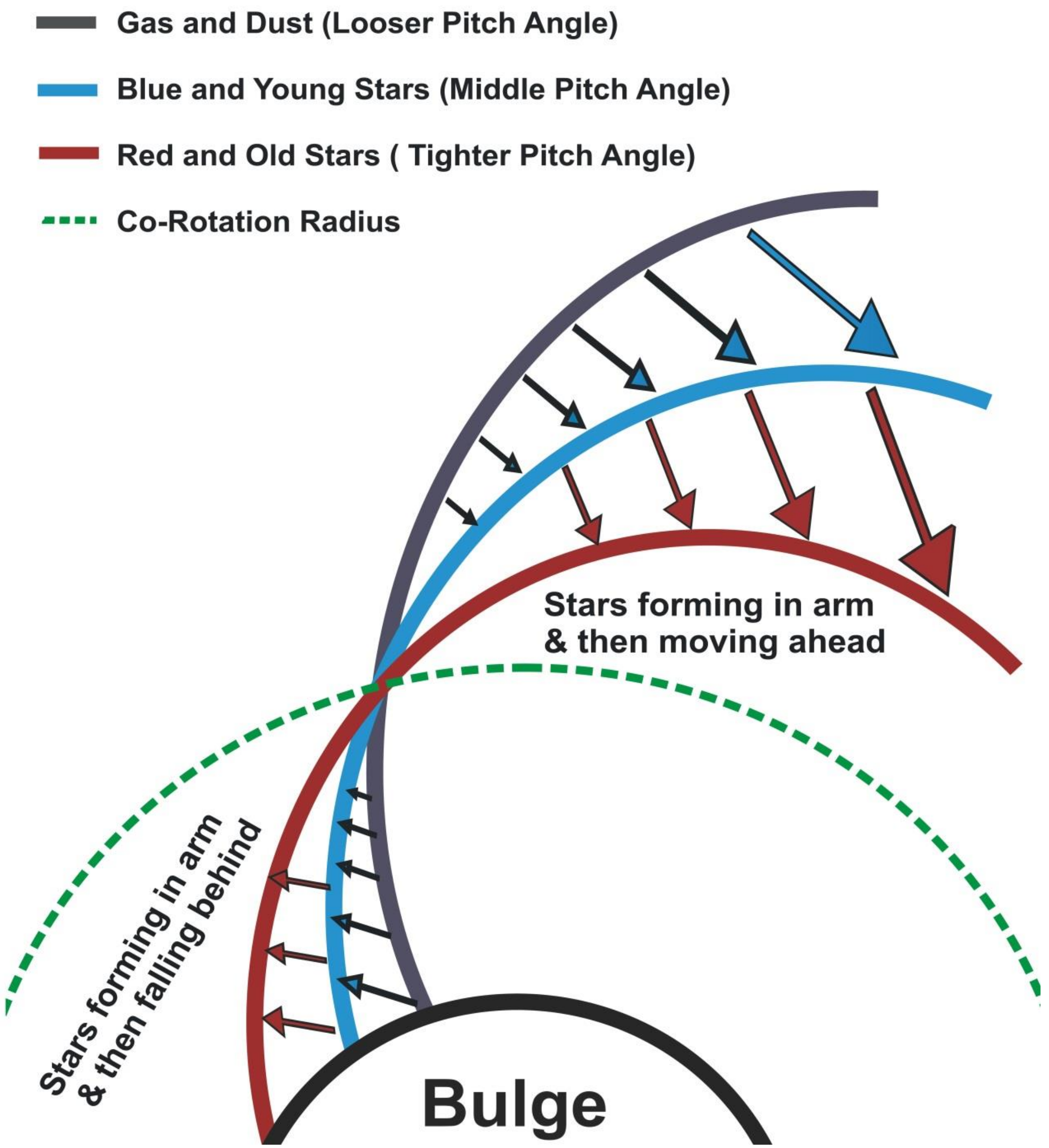
Quadrupole Formula Controversy

- Even if radiation damping in binaries exists, is it correctly described by Einstein's formula of 1918?
- Taylor and Hulse framed their measurement of orbital decay in the binary pulsar system as a theory testing experiment.
- Taylor has said he did not even know there was skepticism about the status of the quadrupole formula as a prediction of General Relativity until he was confronted with questions from skeptics at a conference. Until then none of the theorists he had spoken to had mentioned this debate.

Joe Taylor, Nobel Prize Winner 1993

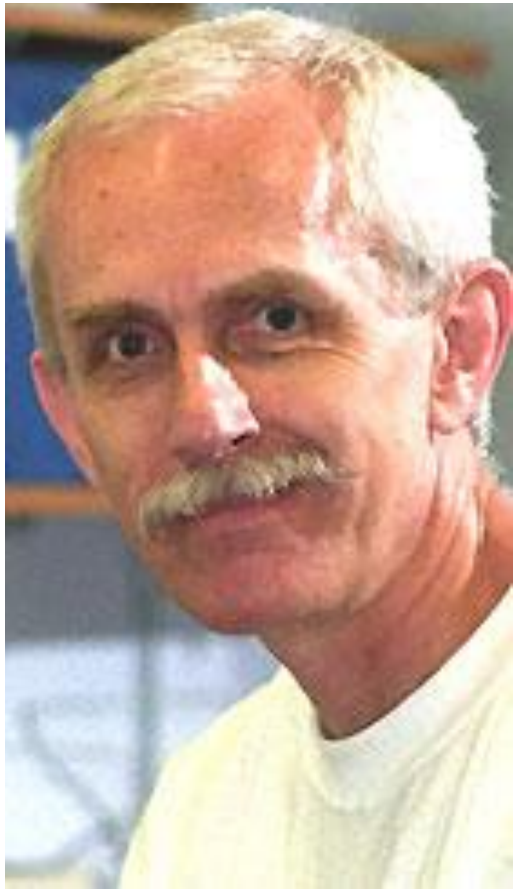
Theory testing

- There are two sides to theory testing, the measurement and the calculation. Theories don’t make predictions, Theorists make predictions. But do they do so correctly?
- This was a key question in the quadrupole formula controversy.
- Confirmation not Falsification



Parametrized post-Newtonian approximation

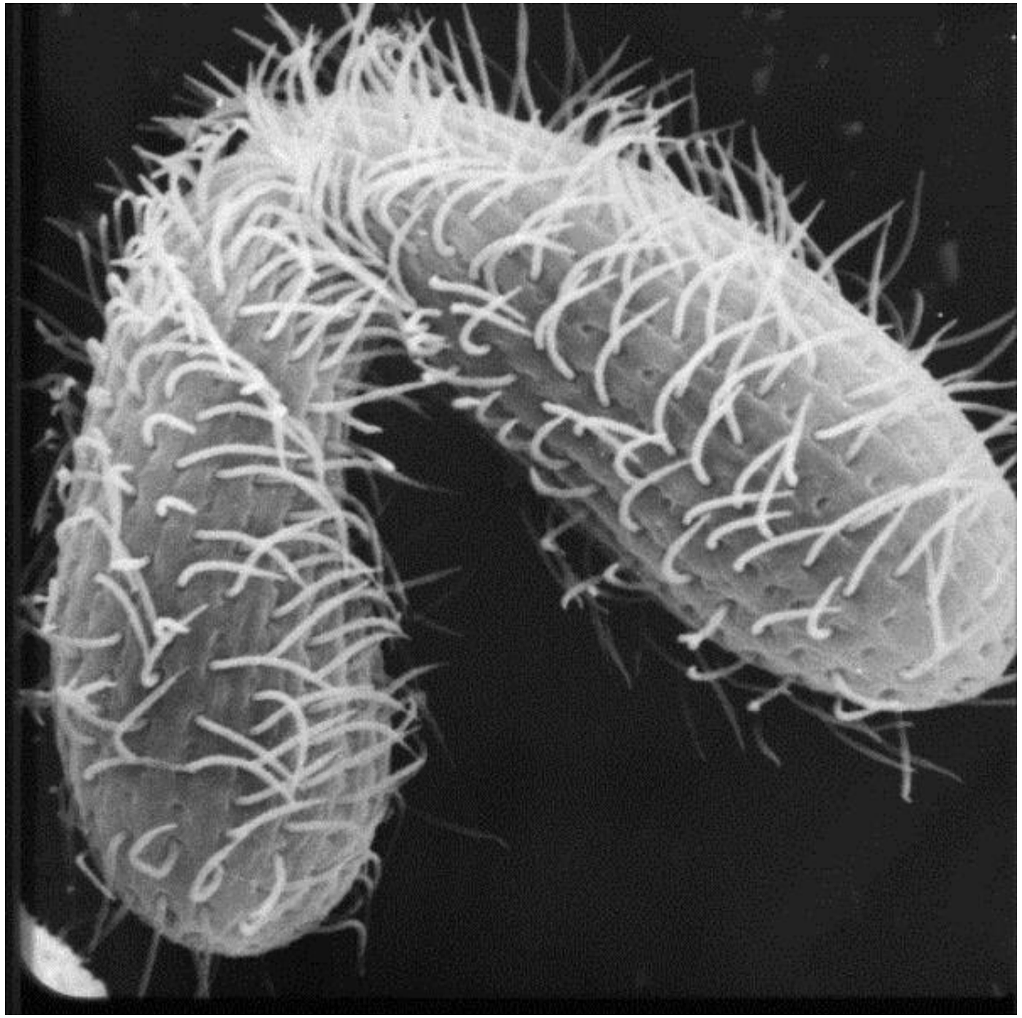
- Is there a way to bridge the language gap between experimenters who make measurements and theorists who do calculations?
- One effort to do so is the ppN formalism. Theorists merely have to calculate a few parameters predicted by their theory. Relatively straightforward formulas permit experimenters to do the rest themselves.



Cliff Will

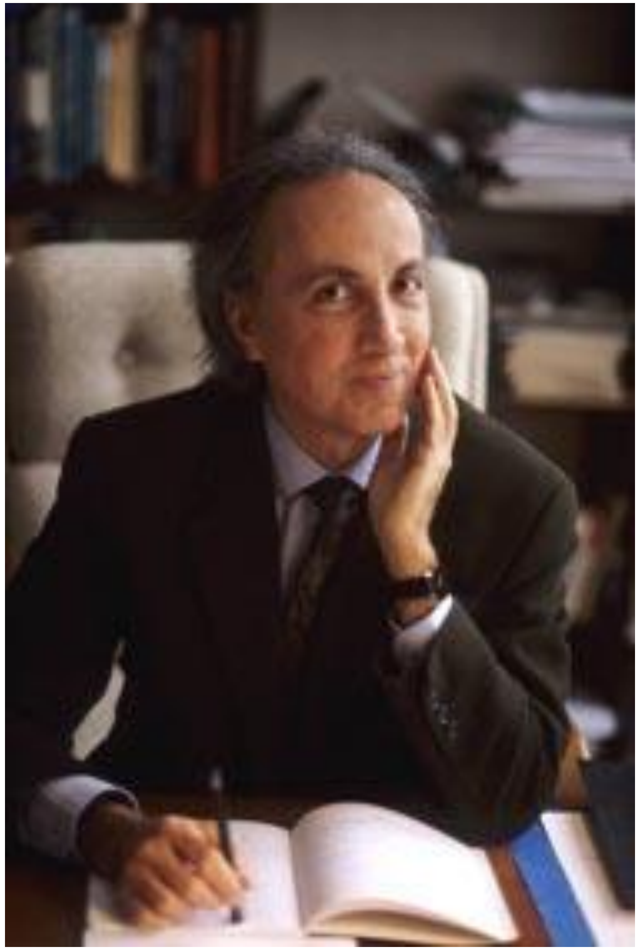
Sociology

- The QFC was a rather slow-burning controversy until the binary pulsar data became available.
- The experimental data did not close the controversy, it gave it new urgency instead.
- Of course this new urgency probably helped bring about this closure, or crystalization.



Two of the seven sexes of *Tetrahymena thermophile* in action.

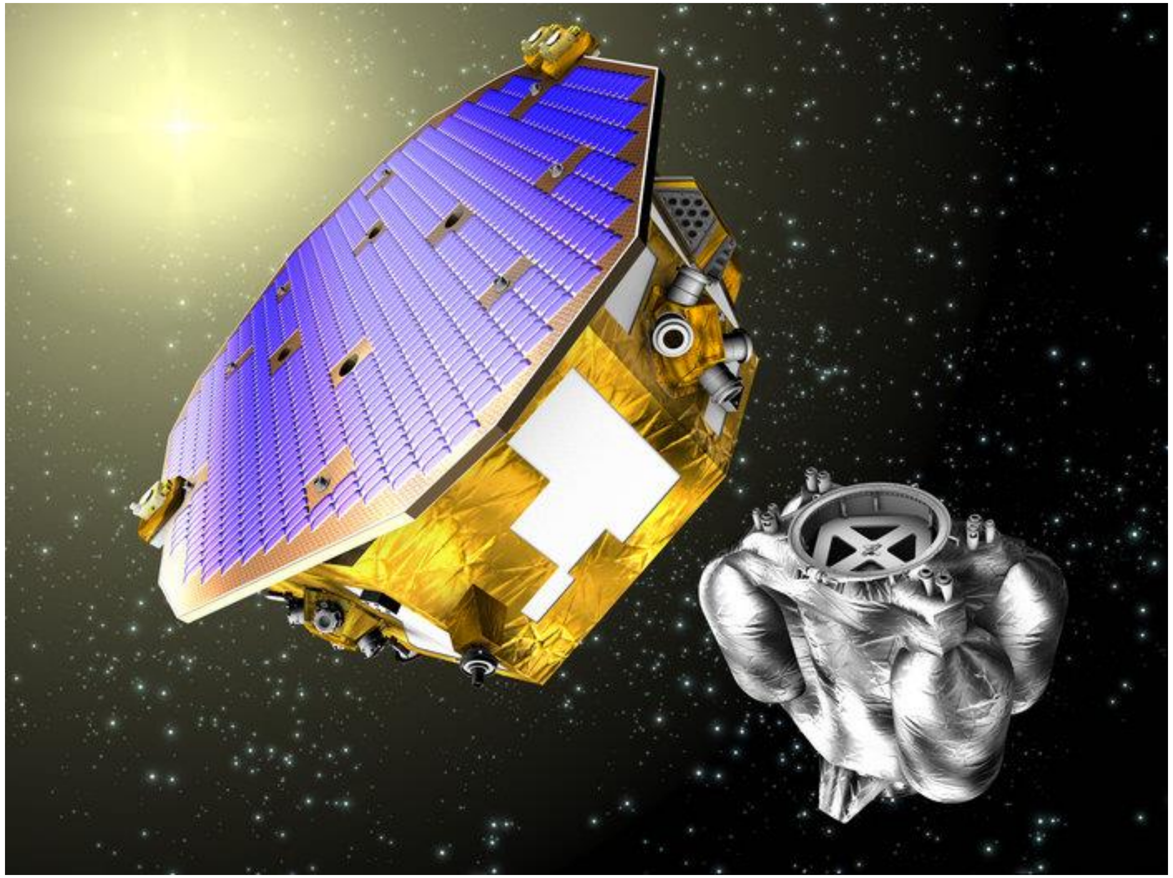
- So experimental data helped end a theoretical controversy. This is unproblematic for realists.
- But can the theory influence the reception of the experimental results?
- Skeptics did not make much effort to challenge the BP data, even when openings might have been available.
- Despite the alleged language barrier, close cooperation between theorist Damour and experimentalist Taylor did permit long term close agreement between theory and observation in the binary pulsar.
- Interestingly, if one presumed the QF to be correct then one could use the BP data to measure the distance to the center of the galaxy (Damour and Anderson 1991). Once one is *certain* about a result, one can use it as a tool.



Thibault Damour

LISA Pathfinder

- Advanced LIGO first science run currently happening.
- To achieve the levels of funding required to detect gravitational waves required closure of controversies.
- The act of closing a controversy is clearly a sociological act, even if you regard sociology's role as insuring the "right" people are in to the field, while excluding the "dopes."



Improvement makes strait roads, but the crooked roads without Improvement, are roads of Genius.

- Ehlers once commented that scientists dislike looking back on past controversies.
- Sometimes they deny they ever existed.
- But the roads taken and not taken are revealing for the historian.
- Amongst those turns in the road are not only intellectual puzzles, but ones which involve the building of disciplinary structures, as we shall hear from our hosts tomorrow.

The Last Word ... from Hell

Another of Blake’s Proverbs of Hell provides the motto for this field, and is actually quoted at the end of Misner, Thorne and Wheeler’s textbook “Gravitation”

“What is now proved was once only imagin’d.”

Gravitational waves provide an interesting example, in the history of science, of a phenomenon discovered, not by experiment, but by imagination, and perhaps because of the lack of guiding experiments, the proving took a very long time to achieve, but it came in the end.