Yi-Zen Chu

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Research Interests

- Theoretical Gravitation, Classical and Quantum Field Theory, Particle Cosmology, Wolfram Language Software Development.

Employment

- August 2017 - ○ Associate Professor, National Central University, Taoyuan, Taiwan
- September 2014 - May 2017 ○ Postdoctoral Associate, University of Minnesota, Duluth
- September 2011 - August 2014 ○ Postdoctoral Fellow, Center for Particle Cosmology, University of Pennsylvania
- September 2010 - August 2011 ○ Postdoctoral Scholar, Arizona State University

Education

- August 2010 ○ Case Western Reserve University: Doctor of Philosophy, Physics
- May 2006 ○ Yale University: Master's in Science, Physics
- May 2003 ○ University of California, Berkeley: Bachelor of Arts, Physics and Mathematics
    - Spring 2000: Dean's Honors List at UC Berkeley

Publications, Software, and Refereeing

- Yi-Zen Chu, "A Semi-Classical Schwinger-Keldysh Re-interpretation of the 4D Majorana Fermion Mass Term," arXiv: 1708.00338.
- Yi-Zen Chu, "Analytical Methods in Physics," arXiv: 1701.00776 [math-ph]. (A free textbook project for a class I taught with the same name. Latest version available here.)
- Yi-Zen Chu, "More On Cosmological Gravitational Waves And Their Memories," Class. Quant. Grav. **34**, no. 19, 194001 (2017), arXiv: 1611.00018 [gr-qc]
- Yi-Zen and Vitaly Vanchurin, "Ideal MHD(–Einstein) Solutions Obeying The Force-Free Condition," arXiv: 1605.08786 [gr-qc]
- Yi-Zen Chu, "Gravitational Wave Memory In dS_{4+2n} and 4D Cosmology," Class. Quant. Grav. **34**, no. 3, 035009 (2017), arXiv: 1603.00151 [gr-qc]
- Yi-Zen Chu, "Transverse-Traceless Gravitational Waves In A Spatially Flat FLRW Universe: Causal Structure from Dimension Reduction," Phys. Rev. D **92**, 124038 (2015), arXiv: 1504.06337 [gr-qc].
- Yi-Zen Chu, "Scalar Wave Tails in Even Dimensional Weakly Curved Static Newtonian Spacetimes", arXiv: 1407.2252, *submitted to Phys. Rev. D.*
- Yi-Zen Chu, "A Line Source In Minkowski For The de Sitter Spacetime Scalar Green's Function: Massive Case", Class. Quantum Grav. **32** (2015) 135008; arXiv: 1310.2939

- Yi-Zen Chu, "A Line Source In Minkowski For The de Sitter Spacetime Scalar Green's Function: Massless Minimally Coupled Case", J. Math. Phys. **55**, 092501 (2014); arXiv: 1305.6933
- Melinda Andrews, Yi-Zen Chu, Mark Trodden, "Galileon Forces in the Solar System", Phys. Rev. D **88**, 084028 (2013); arXiv: 1305.2194
- Yi-Zen Chu, Tanmay Vachaspati, "Gravitational Scattering Of Photons Off Cosmic Strings", Phys. Rev. D **87**, 083512 (2013); arXiv: 1302.3222
- Yi-Zen Chu, Mark Trodden, "Retarded Green's Function Of A Vainshtein System And Galileon Waves", Phys. Rev. D **87**, 024011 (2013); arXiv: 1210.6651
- Yi-Zen Chu, Glenn D. Starkman, "Retarded Green's Functions In Perturbed Spacetimes For Cosmology and Gravitational Physics," Phys. Rev. D **84**, 124020 (2011); arXiv: 1108.1825
- Yi-Zen Chu, James B. Dent, Tanmay Vachaspati, "Magnetic Helicity In Sphaleron Debris," Phys. Rev. D **83**, 123530 (2011); arXiv: 1105.3744
- Yi-Zen Chu, David M. Jacobs, Yifung Ng, Glenn D. Starkman, "It's Hard to Learn How Gravity and Electromagnetism Couple," Phys. Rev. D **82**, 064022 (2010); arXiv: 1007.3992
- Yi-Zen Chu, Harsh Mathur, Tanmay Vachaspati, "Aharonov-Bohm Radiation of Fermions," Phys. Rev. D **82**, 063515 (2010); arXiv: 1003.0674
- Yi-Zen Chu and Tanmay Vachaspati, "Capacitor Discharge and Vacuum Resistance in Massless QED_2," Phys. Rev. D **81**, 085020 (2010); arXiv: 1001.2559 [hep-th]
- Yi-Zen Chu, "The n-body problem in General Relativity up to the second post-Newtonian order from perturbative field theory," Phys. Rev. D **79**, 044031 (2009); arXiv: 0812.0012 [gr-qc]
- Yi-Zen Chu and Tanmay Vachaspati, "Fermions On One Or Fewer Kinks," Phys. Rev. D **77**, 025006 (2008); arXiv: 0709.3668 [hep-th]
- Yi-Zen Chu and Marco Cirelli, "Sterile neutrinos, lepton asymmetries, primordial elements: How much of each?," Phys. Rev. D **74**, 085015 (2006); arXiv: astro-ph/0608206
- Yi-Zen Chu, Walter D. Goldberger, and Ira Z. Rothstein, "Asymptotics of d-dimensional Kaluza-Klein black holes: Beyond the newtonian approximation," JHEP **0603**, 013 (2006); arXiv: hep-th/0602016
- Ongoing Software Development: $TensoriaCalc$, a tensor calculus package for $Mathematica$.
- Referee for: Physics Letters B, Revista Mexicana de Astronomía y Astrofísica, SIGMA.

Research Experiences

- Spring 2015, Summer 2017; University of Minnesota Duluth, National Central University
    - Provided a semi-classical re-interpretation of the 4D Majorana mass term as an 'influence action' in the Schwinger-Keldysh formulation of fermionic Quantum Field Theories.
- Summer-Fall 2016, University of Minnesota Duluth

- Confirmed that conformal re-scaling, dimension-reduction, and Nariai's ansatz – when exploited together – provide general formulas for the gauge-invariant linear gravitational and electromagnetic waves produced by an isolated but arbitrary astrophysical system situated in a $(d \geq 4)$-dimensional spatially flat Friedmann-Lemaître-Robertson-Walker universe with constant equation-of-state w.
- ~~Provided two explicit examples where on-the-acoustic-cone scalar gravitational wave memory effects could occur within these cosmologies.~~
- Found that scalar/acoustic gravitational wave tails in 4-dimensional radiation dominated universes are independent of spatial distance from the astrophysical source.
- Uncovered the possibility that astrophysical systems may lose their mass in an expanding universe due to scalar/acoustic gravitational radiation.
- In $(d \geq 4)$-Minkowski spacetime, pointed out a "double copy" relation between the (Liénard-Wiechert) linear graviton field generated by a point mass and the linear Yang-Mills gauge boson field generated by a colored point charge. At least in even dimensions, this also applies to their respective memories due to point masses/charges scattering off each other on unbound trajectories.
- In flat spacetime, highlighted the pure tail nature of the linear gravitational and electromagnetic gauge fields – and their gradients – in odd dimensions $d \geq 5$; and the pure null-cone nature of the same in even dimensions $d \geq 4$.
- A dimension-raising operator was identified to explain algebraically why Green's functions in flat spacetimes could all be gotten via differentiating their two and three dimensional counterparts.

- Spring 2016, University of Minnesota Duluth, with Vitaly Vanchurin
  - Discovered 2 families of analytic solutions to the ideal magnetohydrodynamics (iMHD) equations, in a general class of 4D curved spacetimes.
  - Found a self-consistent Einstein-iMHD solution: a special case of the iMHD solutions above sources the Vaidya-(anti-)de Sitter metric through Einstein's equations.
  - Implemented the curved spacetime nonlinear partial differential equations of iMHD in Tensoria-Calc, the tensor calculus Mathematica package I have been developing.
- Winter 2015-Spring 2016, University of Minnesota Duluth
  - Pointed out that linear massless gravitational waves (GWs) in all even (d $\geq$ 4)-dimensional background de Sitter (dS) spacetimes exhibit a tail-induced memory effect; there is a similar but approximate linear GW memory effect in 4D spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) matter dominated universes.
  - Suggested that all the known linear GW memory effects in 4D asymptotically flat spacetimes carry over to the spatially flat FLRW universe, except the amplitude of this on-the-null-cone portion of the GW now gets diluted by cosmic expansion as 1/(scale factor).
  - Solved Einstein's General Relativity, with a cosmological constant, linearized about any $\mathrm{dS}_{\mathrm{d}\geq 4}$.
- Spring 2014, Spring 2015: University of Pennsylvania, University of Minnesota Duluth
  - Showed that the causal structure of the transverse-traceless metric perturbations – the massless spin 2 gravitons – of the spatially flat 4-dimensional (4D) FLRW universe can be alternatively understood from both a 2D and 3D perspective.

- Estimated the magnitude of the gravitational wave (GW) tail relative to its null cone counterpart in a matter dominated universe and in de Sitter spacetime; in the latter, a memory effect exhibited by the GW tail was pointed out.

- Summer 2014: Center for Particle Cosmology, University of Pennsylvania
  - Uncovered evidence that, unlike the 4D case, the late time tail portion of the minimally coupled massless scalar Green's function in weakly curved static Newtonian spacetimes of even dimensions higher than 4, is sensitive to not only the monopole of the (isolated) matter source of the weak field geometry itself, but also to all its higher multipole moments.
  - Wrote down the general form of the minimally coupled massless scalar Green's function tail in even dimensional weakly curved spacetime – i.e., for the metric $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ – up to first order in the metric perturbation $h_{\mu\nu}$.
  - $Note\ added$: Some of the calculations in arXiv: 1407.2252 needs to be revisited and simplified.

- Spring-Summer 2013: Center for Particle Cosmology, University of Pennsylvania
  - Showed that, in certain classes of curved space(time)s embeddable in some higher dimensional flat space(time)s, the Green's functions of the scalar wave operators in the former can be obtained from their counterparts in the latter.
  - Solved the retarded and advanced $(d \geq 2)$-dimensional de Sitter scalar Green's functions for arbitrary mass m. Showed that they can be sourced by either one of two distinct massless or massive scalar line charges in the ambient $(d+1)$-dimensional Minkowski spacetime, leading to a manifest separation of the null cone and tail portions.
  - Proposed a generalized Green's function for the Laplacian on the $(d \geq 2)$-sphere, and solved the Green's function of its Helmholtz operator.

- Winter 2012-2013: with Tanmay Vachaspati
  - Computed the spectral distortion of the Cosmic Microwave Background photons' thermal distribution, due to the gravitational scattering of these photons off cosmic string loops.

- Spring-Fall 2012: Center for Particle Cosmology, University of Pennsylvania, with Mark Trodden
  - Investigated how the motion of matter would generate radiation of massless scalar fields exhibiting the Vainshtein screening mechanism: while the energy loss via short wavelength radiation is Vainshtein suppressed, long wavelength radiation is not.
  - Solved the retarded cubic Galileon Green's function of its wave operator about the background sourced by a massive spherically symmetric body, including an exact solution in the static limit.

- Fall 2011-Spring 2013: Center for Particle Cosmology, University of Pennsylvania, with Melinda Andrews and Mark Trodden
  - Solved the exact maximally-quartic Galileon static Green's function of its wave operator (the force law) about the background sourced by a massive spherically symmetric body, and developed perturbation theory for solving these Green's functions away from the cubic and maximally-quartic limits.
  - Developed field theory based methods to examine the impact of Vainshtein screened Galileon fields on the problem of motion in astrophysical dynamics. (Such scalar fields arise from many proposed modifications of gravitational dynamics.)

- Summer 2011 to present: Center for Particle Cosmology, University of Pennsylvania; Dept. of Physics, Arizona State University.
    - Inventor and developer of TensoriaCalc, a Mathematica package for tensor calculations within a (semi-)Riemannian geometry framework, which maintains smooth consistency with the Mathematica language itself.
    - Available at http://www.stargazing.net/yizen/Tensoria.html
- 2007-2011: Center for Particle Cosmology, University of Pennsylvania; Dept. of Physics, Arizona State University; and CERCA, Case Western Reserve University, with Glenn Starkman
    - Developed perturbation theory for solving retarded Green's functions of field theories with hermitian actions in perturbed spacetimes $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$, in terms of the Green's functions in the un-perturbed background $\bar{g}_{\mu\nu}$.
    - Via conformal symmetry and the computation of the photon Green's function in perturbed Minkowski spacetime, showed that light does not travel solely on the light cone in our inhomogeneous spatially flat FLRW universe.
    - Computed the massless scalar, photon and graviton retarded Green's functions in the weak field Kerr black hole geometry, up to first order in its mass and angular momentum.
- Spring 2011: Dept. of Physics, Arizona State University, with James B. Dent and Tanmay Vachaspati
    - Developed analytic techniques and evaluated magnetic helicity produced from sphaleron transitions.
- 2007-2010: CERCA, Case Western Reserve University, with David M. Jacobs, Yifung (Bess) Ng and Glenn Starkman
    - Enumerated the most general set of couplings between electromagnetic fields $F_{\mu\nu}$ and geometric tensors – Riemann and Ricci tensors – up to mass dimension 6.
    - Showed that the propagation of light over cosmological distances and solar system tests of General Relativity do not provide useful constraints on their coefficients.
- 2009-2010: CERCA, Case Western Reserve University, with Harsh Mathur and Tanmay Vachaspati
    - Computed fermion pair production rates due to a thin magnetic flux tube in motion – i.e. the Aharonov-Bohm interaction – for a infinite straight solenoid and cosmic string loops.
    - Obtained general solutions to the Dirac equation with a gauge potential in the presence of a thin, infinite, straight solenoid.
- 2008, 2009: Institute for Advanced Study, Princeton, and CERCA, Case Western Reserve University; with Tanmay Vachaspati
    - Considered two toy models for capacitors within 1+1 dimensional quantum electrodynamics, and examined their discharge due to the Schwinger process: the electric field decayed as $t^{-1/2}$ and the vacuum obeyed Ohm's law.
    - Implemented on Mathematica, the implicit Crank-Nicholson numerical algorithm for evolving PDEs.
- Summer 2006, and Spring, Fall 2008

- Used perturbative field theory methods to compute, up to certain integrals, the n-body general relativistic effective Lagrangian to the second post-Newtonian order (2 PN).
- Developed algorithm that would in principle be able to generate the Feynman diagrams contributing to the n-body effective Lagrangian to an arbitrary PN order. Implemented some Mathematica code to this end.

- Summer 2007 to Fall 2007: CERCA, Case Western Reserve University, with Tanmay Vachaspati
  - Solved the full spectrum of bound state energy eigenstates of the Dirac equation, $(i\partial\!\!\!/ - g\phi)\psi = 0$, in kink and antikink ($\phi = \pm$ tanh[z]) backgrounds.
  - Proved, contrary to recent claims that kink-antikink bound states do not exist at all, that at least one fermion bound state has to exist for all non-zero values of the Yukawa coupling g and that the ground state energy goes to zero faster than e^{-aL} for some a>0 as the kink-antikink distance L increases to infinity.
  - Numerically solved the fermion ground and excited states on the kink-antikink ($\phi =$ tanh[z+L] - tanh[z-L] - 1) for a range of Yukawa couplings and kink-antikink separations.

- Summer 2004, Spring 2006 to Summer 2006: Particle Theory Group at Yale University with Marco Cirelli
  - Computed the excess of anti-neutrinos over neutrinos needed in the early universe to suppress sufficiently the production of the LSND sterile neutrino to reconcile its possible existence with the observed abundances of ^{4}He and deuterium. (Having more than 3 species neutrinos in the early universe would alter the light element formation rates.)
  - Introduced neutrino density matrix equations that took into account scattering and annihilation processes while preserving lepton number conservation.

- Summer 2005 to Spring 2006: Particle Theory Group at Yale University with Walter Goldberger
  - Used effective field theory techniques to compute mass, tension, and thermodynamics of black holes in $\mathbb{R}^{1,d-2} \times \mathbb{S}^1$ spacetimes.
  - Devised algorithm and implemented Mathematica code to generate the Feynman rule for the N graviton vertex in Minkowski space, where N is an arbitrary integer greater than one.

- Spring 2002 to Spring 2003: Solenoidal Tracker at RHIC (STAR) group at Lawrence Berkeley National Laboratory (LBNL) with Nu Xu, Kai Schweda, and Eugene Yamamoto
  - Analyzed ϕ meson, proton and anti-proton production rates from proton-proton collisions at the Relativistic Heavy Ion Collider (RHIC)

- Summer 2001: BaBar Group at Lawrence Berkeley National Laboratory (LBNL) with Yury Kolomensky
  - Calibrated the silicon wafers of the BaBar SVT at the Stanford Linear Accelerator Center (SLAC)

- Fall 2000 to Spring 2001: E158 Experiment at SLAC with Gilbert Shapiro
  - Designed and oversaw construction of an electron beam monitor

Teaching Experiences

- Fall 2015: Taught Analytical Methods for Physics (Phys 3033) at the University of Minnesota Duluth. This included (re-)designing the course from scratch; writing and posting lecture notes online, so that students did not have to purchase a textbook.
- Fall 2014, Spring 2015, Spring 2016: Instructor, Discussion sections for General Physics I and II at the University of Minnesota Duluth.
- Fall 2003 through Spring 2008: Graduate Teaching Assistant at Case Western Reserve University and Yale University
    - Quantum Field Theory, Modern Cosmology, Mathematical Methods and Laboratory Sections.
- Fall 2001, Spring 2002
    - Founder and Instructor of official amateur astronomy class at UC Berkeley (Astro 99)
- 1997 to present
    - Rich experience tutoring physics and mathematics, including: training a high school sophomore for Physics Olympiad qualifying exams; official tutor at UC Berkeley dormitory.

Professional Activities

- Fall 2015-Spring 2016: Cosmology group of the University of Minnesota Duluth
    - (Co-)organized theory journal clubs and seminars.
    - Co-organized visitors' program.
- Fall 2011-Spring 2014: Center for Particle Cosmology, University of Pennsylvania
    - Organized Case-Columbia-NYU-UPenn December 13, 2011 meeting hosted by UPenn.
    - Co-organizer of weekly High Energy Theory Seminar series.
- Fall 2010-Spring 2011: Arizona State University (ASU)
    - Member of organizing committee for Primordial Magnetism Workshop (30 March - 2 April 2011).
    - Co-organizer of the ASU Particle Astrophysics and Cosmology Seminar.
    - Set up and maintained Wiki and listserv for the ASU Cosmology Group.

Skills

- Computing
    - Extensive experience with Mathematica: Certified at the Advanced Foundations Level, with an outstanding score of 95.3%.
    - Some experience with: C/C++, ROOT, LaTeX, UNIX and MS Office software
- Languages
    - Fluent in English and Mandarin

Talks

- Cosmological Gravitational Waves: Causal Structure And Memories
  - 25 September 2017: LeCosPA Cosmology and Particle Astrophysics Seminar, National Taiwan University
  - 10 April 2017: TianQin Research Center for Gravitational Physics, Sun-Yat Sen University
  - 5 April 2017: 2017 Hangzhou Symposium for Young Researchers, Zhejiang University
  - 25 February 2017: National Central University, Taiwan
  - 18 February 2017: Kavli Institute of Cosmological Physics Seminar, University of Chicago
  - 27 January 2017: High Energy Theory Seminar, University of Minnesota Twin Cities.
- Causal Structure Of Gravitational Waves In Cosmology
  - 29 November 2016: Particle Astrophysics Seminar, Case Western Reserve University.
- Green's Functions In Curved Spacetime And Gravitational Waves
  - 8 December 2016: Math-Physics Journal Club Seminar, Dept. of Mathematics, University of Minnesota Twin-Cities
  - 6 October 2016: Graduate Colloquium, Dept. of Mathematics and Statistics, University of Minnesota Duluth
- Wave Tails in Minkowski, de Sitter, FLRW and QED_2
  - 24 June 2014: 17th Capra Meeting on Radiation Reaction in General Relativity, Caltech, Pasadena, CA.
  - 5 May 2014: Physics Colloquium, University of Minnesota Duluth.
  - 25 April 2014: Joint Cosmology and Particle Physics Meeting, Columbia University, NYC.
  - 22 April 2014: AstroLunch Seminar, Carnegie Mellon University, Pittsburgh, PA.
  - 4 April 2014: Neighborhood Workshop on Astrophysics and Cosmology, Penn State University, State College PA.
  - 14 March 2014: Strings Seminar, National Taiwan University, Taipei, Taiwan
  - 12 March 2014: Gravity Seminar, Fudan University, Shanghai, China
  - 11 March 2014: Institute of Natural Sciences, Shanghai Jiaotong University, China
  - 10 March 2014: Center for Astronomy and Astrophysics, Shanghai Jiaotong University, China
  - 6 March 2014: HKUST Jockey Club Institute for Advanced Study, Hong Kong, China
- The Problem of Motion in the Presence of the Vainshtein Mechanism
  - 24 August 2012: Workshop on Cosmic Acceleration, Carnegie Mellon University, Pittsburgh, PA
- Light Does Not Always Propagate On The Light Cone
  - 25 April 2012: Case-Columbia-Penn-NYU Meeting, New York University, NY
  - 22 April 2012: 15th East Coast Gravity Meeting, Syracuse University, Syracuse, NY
  - 14 November 2011: Particle Astrophysics Seminar, Case Western Reserve University

- 1 October 2010: Particle Astrophysics and Cosmology Friday Talks, Arizona State University
- 10 April 2009: CERCA Seminar, Case Western Reserve University

- The N Body Problem In General Relativity From Perturbative Field Theory
  - 7 February 2011: Fermilab, Center for Particle Astrophysics (Part II of II)
  - 8 December 2010: UCLA, High Energy Physics Seminar (Part II of II)
  - 30 November 2010: Perimeter Institute, Cosmology Seminar (Part II of II)
  - 29 November 2010: University of Toronto, High Energy Physics Seminar (Part II of II)
  - 11 November 2010: Columbia University, ISCAP Seminar
  - 1 September 2010: National University of Singapore, Physics Department Seminar
  - 28 May 2010: Princeton University, Gravity Group Astrophysics/Cosmology Lunch
  - 30 June 2009: Perimeter Institute Summer School 2009, Student Talks
  - 22 January 2009: Theory Seminar, Washington University in St. Louis.
  - 9 December 2008: Buffalo-Case-Cornell-Syracuse Workshop on Cosmology and Astro-Particle Physics, Case Western Reserve University
  - 24 June 2008: Prospects in Theoretical Physics (PiTP) 2008 Participants' Talks, Institute for Advanced Study, Princeton
- Don't Shake That Solenoid Too Hard: Particle Production From Aharonov-Bohm
  - 7 February 2011: Fermilab, Center for Particle Astrophysics (Part I of II)
  - 8 December 2010: UCLA, High Energy Physics Seminar (Part I of II)
  - 30 November 2010: Perimeter Institute, Cosmology Seminar (Part I of II)
  - 29 November 2010: University of Toronto, High Energy Physics Seminar (Part I of II)
  - 4 November 2010: Tufts Institute of Cosmology Seminar, Tufts University
  - 6 October 2010: Particle Astrophysics and Cosmology Seminar, Arizona State University.
- Fermions On One Or Fewer Kinks
  - 2 November 2007: CERCA Seminar, Case Western Reserve University
- Asymptotics of Kaluza-Klein black holes
  - 22 February 2007: Cosmology Seminar, Tufts University
  - 16 January 2007: Syracuse University
  - 10 January 2007: Cosmo Lunch, University of California, Irvine
  - 10 November 2006: CERCA Seminar, Case Western Reserve University

Leadership Experiences, Community Service

- Spring 2005, Spring 2006
  - Organized star parties for people with disabilities, in collaboration with STARRY, Yale's undergraduate astronomy club.
- Spring 2000 to Summer 2002
  - Founder and Leader of Astronomers at Berkeley, an amateur astronomy club at UC Berkeley. Organized frequent on-campus stargazing sessions and off-campus dark sky observing trips; ran official amateur astronomy class; initiated telescope making project.