

Curriculum Vitae

Aravind Natarajan

Born: Sep 27, 1978

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Residence

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Education

Ph.D (Physics) (Aug 2004 - Aug 2007)

University of Florida, Gainesville

Dissertation: Inner Caustics of Cold Dark Matter Halos

Thesis advisor: Pierre Sikivie

GPA: 4.0

Master of Science (Physics) (Aug 2002 - Aug 2004)

University of Florida, Gainesville

GPA: 4.0

Bachelor of Engineering (Electronics and Communication) (1996 - 2000)

Bangalore University, India

Class: First with Distinction

Academic positions

- **Postdoctoral fellow, Universität Bielefeld (Germany)**
Oct 2007 - present, Particle Astrophysics and Cosmology, Dept. of Physics
- **Graduate Assistant, University of Florida (Gainesville, USA)**
Aug 2003-Aug 2007, Institute for Fundamental Theory, Dept. of Physics
Aug 2002-Aug 2003, Dept. of Physics
- **Research Assistant, Indian Institute of Science (India)**
Oct 2000-July 2001, Dept. of Electrical Communication Engineering

Awards and Honors

- **Chuck Hooper Memorial Award for Distinction in Research and Teaching**
Department of Physics, University of Florida, Fall 2006
- **Award for Outstanding Academic Achievement by an International Student**
University of Florida International Center, Spring 2006
- **J. Michael Harris Fellowship Award**
Department of Physics, University of Florida, Spring 2005
- **Certificate of Outstanding Achievement**
University of Florida International Center, Academic years 2003,2004,2005,2006
- **College of Liberal Arts and Sciences Travel Grant**
Spring 2007 (Irvine), Spring 2006 (Aspen)

Technical Schools attended

- Asian School of Particles, Strings, and Cosmology, *Sep 2006, Nasu, Japan*

Conferences and Workshops attended

- 2008: 1. Dark matter at the crossroads, Hamburg, Sep 29-Oct 2
2. Cosmo 2008, Madison, Aug 25-29.
3. Kosmologietag, Bielefeld, May 8-9.
4. DESY ENTApP workshop on dark matter, Feb 25-29.
- 2007: 1. Astrophysical probes of the nature of dark matter, Irvine, March 22-24
- 2006: 1. Santa Fe Cosmology Conference, July '06, Santa Fe, NM
2. Aspen winter conference on astrophysics, Jan '06, Aspen, CO
- 2005: 1. UF-FSU symposium on high energy phenomenology, Dec '05, Gainesville, FL
2. TeV particle astrophysics, July '05, Fermilab, IL
3. PHENO '05, May '05, Madison, WI
- 2004: 1. UF-FSU symposium on high energy phenomenology, Dec '04, Tallahassee, FL
2. Santa Fe Cosmology Conference, July '04, Santa Fe, NM
- 2003: 1. Pierre Fest : A symposium in honor of Professor Pierre Ramond's sixtieth birthday, Jan '03, Gainesville, FL

Publications

Journal Articles :

1. Dark matter annihilation and primordial star formation.

Aravind Natarajan, Jonathan C. Tan, and Brian W. O'Shea

arXiv: 0807.3769 [astro-ph] (2008), accepted for publication in Astrophysical Journal

Abstract: We investigate the effects of weakly-interacting massive particle (WIMP) dark matter annihilation on the formation of Population III.1 stars, which are theorized to form from the collapse of gas cores at the centers of dark matter minihalos. We consider the relative importance of cooling due to baryonic radiative processes and heating due to WIMP annihilation. We analyze the dark matter and gas profiles of several halos formed in cosmological-scale numerical simulations. The heating rate depends sensitively on the dark matter density profile, which we approximate with a power law $\rho_\chi \propto r^{-\alpha_\chi}$, in the numerically unresolved inner regions of the halo. If we assume a self-similar structure so that $\alpha_\chi \simeq 1.5$ as measured on the resolved scales ~ 1 pc, then for a fiducial WIMP mass of 100 GeV, the heating rate is typically much smaller ($< 10^{-3}$) than the cooling rate for densities up to $n_H = 10^{17} \text{ cm}^{-3}$. In one case, where $\alpha_\chi = 1.65$, the heating rate becomes similar to the cooling rate by a density of $n_H = 10^{15} \text{ cm}^{-3}$. The dark matter density profile is expected to steepen in the central baryon-dominated region $\lesssim 1$ pc due to adiabatic contraction, and we observe this effect (though with relatively low resolution) in our numerical models. From these we estimate $\alpha_\chi \simeq 2.0$. The heating now dominates cooling above $n_H \simeq 10^{14} \text{ cm}^{-3}$, in agreement with the previous study of Spolyar, Freese & Gondolo. We expect this leads to the formation of an equilibrium structure with a baryonic and dark matter density distribution exhibiting a flattened central core. Examining such equilibria, we find total luminosities due to WIMP annihilation are relatively constant and $\sim 10^3 L_\odot$, set by the radiative luminosity of the baryonic core. We discuss the implications for Pop III.1 star formation, particularly the subsequent growth and evolution of the protostar. Even if the initial protostar fails to accumulate any additional dark matter, its contraction to the main sequence could be significantly delayed by WIMP annihilation heating, potentially raising the mass scale of Pop III.1 stars to masses $\gg 100 M_\odot$.

2. The effect of early dark matter halos on reionization.

*Aravind Natarajan and Dominik J. Schwarz, Phys. Rev. D **78**, 103524 (2008)*

Abstract: The annihilation of dark matter particles releases energy, ionizing some of the gas in the Universe. We investigate the effect of dark matter halos on reionization. We show that the effect depends on the assumed density profile, the particle mass, and the assumed minimum halo mass. For NFW halos and typical WIMPs, we find the effect to be quite small. However, light dark matter candidates in the MeV range can contribute significantly to reionization and can make an important contribution to the measured optical depth. This effect may be used to constrain light dark matter models. We also study the effect of varying the halo density profile on reionization.

3. Further look at particle annihilation in dark matter caustics.

*Aravind Natarajan and Pierre Sikivie, Phys. Rev. D **77**, 043531 (2008)*

Abstract: Dark matter caustics are small scale, high density structures believed to exist in galaxies like ours. If the dark matter consists of Weakly Interacting Massive Particles, these caustics may be detected by means of the gamma rays produced by dark matter particle annihilation. We discuss particle annihilation in outer and inner caustics and provide sky maps of the expected gamma ray distribution.

4. Can the second caustic ring of dark matter cause the Monoceros ring of stars?

Aravind Natarajan and Pierre Sikivie, Phys. Rev. D **76**, 023505 (2007)

Abstract: Caustic rings of dark matter were predicted to exist in the plane of the Galaxy at radii $a_n \approx 40 \text{ kpc}/n$ for $n=1,2,3,\dots$. The recently discovered Monoceros Ring of stars is located near the $n = 2$ caustic, prompting us to consider a possible connection between these two objects. We identify two processes through which the Monoceros Ring of stars may have formed. One process is the migration of gas to an angular velocity minimum at the caustic leading to enhanced star formation there. The other is the adiabatic deformation of star orbits as the caustic slowly grows in mass and radius. The second process predicts an order 100 % enhancement of the density of disk stars at the location of the caustic ring.

5. Weakly Interacting Massive Particle annihilation in caustics.

Aravind Natarajan, Phys. Rev. D **75**, 123514 (2007)

Abstract: The continuous infall of dark matter with low velocity dispersion from all directions in a galactic halo leads to the formation of caustics which are very small scale (\sim parsec) high density structures. If the dark matter is made up of supersymmetric neutralinos, the annihilation of these particles produces a characteristic spectrum of gamma rays which, in principle, could be detected. The annihilation signal at different energy bands is computed and compared with the expected gamma ray background.

6. Inner caustics of cold dark matter halos.

Aravind Natarajan and Pierre Sikivie, Phys. Rev. D **73**, 023510 (2006)

Abstract: We prove that a flow of cold collisionless particles from all directions in and out of a region necessarily forms a caustic. A corollary is that, in cold dark matter cosmology, galactic halos have inner caustics in addition to the more obvious outer caustics. The outer caustics are fold catastrophes located on topological spheres surrounding the galaxy. To obtain the catastrophe structure of the inner caustics, we simulate the infall of cold collisionless particles in a fixed gravitational potential. The structure of inner caustics depends on the angular momentum distribution of the infalling particles. We confirm a previous result that the inner caustic is a tricusp ring when the initial velocity field is dominated by net overall rotation. A tricusp ring is a closed tube whose cross section is a section of an elliptic umbilic catastrophe. However, tidal torque theory predicts that the initial velocity field is irrotational. For irrotational initial velocity fields, we find the inner caustic to have a tentlike structure which we describe in detail in terms of the known catastrophes. We also show how the tent caustic transforms into a tricusp ring when a rotational component is added to the initial velocity field.

7. Robustness of Discrete Flows and Caustics in Cold Dark Matter Cosmology.

Aravind Natarajan and Pierre Sikivie, Phys. Rev. D **72**, 083513 (2005)

Abstract: Although a simple argument implies that the distribution of dark matter in galactic halos is characterized by discrete flows and caustics, their presence is often ignored in discussions of galactic dynamics and of dark matter detection strategies. Discrete flows and caustics can in fact be irrelevant if the number of flows is very large. We estimate the number of dark matter flows as a function of galactocentric distance and consider the various ways in which that number can be increased, in particular, by the presence of structure on small scales (dark matter clumps) and the scattering of the flows by inhomogeneities in the matter distribution. We find that, when all complicating factors are taken into account, discrete flows and caustics in galactic halos remain a robust prediction of cold dark matter cosmology with extensive implications for observation and experiment.

8. Role of the Cesium Antimonide Layer in the Na₂KSb / Cs₃Sb photocathode.

Aravind Natarajan, A.T. Kalghatgi, B.M. Bhat and M. Satyam, Journal of Applied Physics, 90, 6434 (2001)

Abstract: When radiation of sufficiently high energy is incident on the surface of a semiconductor photocathode, electrons are excited from the valence band to the conduction band and these may contribute to the photocurrent. The photocurrent in a single-layer cathode is found to be small, because of collisions within the cathode material, the electron affinity condition, etc. It is observed that when a thin layer of n-type cesium antimonide (Cs₃Sb) is deposited over a p-type layer of sodium potassium antimonide (Na₂KSb), there occurs a sharp rise in the photocurrent. The causes for the dramatic increase in the photocurrent obtainable from a sodium potassium antimonide cathode, by depositing a thin layer of cesium antimonide are analyzed in this article. It has been shown that the interface between sodium potassium antimonide and cesium antimonide can result in lowering of the electron affinity to a level below the bottom of the conduction band of sodium potassium antimonide. The drift field that arises at the heterointerface enables the electrons to reach the surface, leading to the emission of almost all the photogenerated electrons within the cathode. The processes involved in photoemission from such a double-layer cathode are examined from a theoretical point of view. The spectral response of the two-layer cathode is also found to be better than that of a single-layer cathode.

Presentations

Seminar talks:

- *The effect of dark matter halos on reionization and the H21 cm line.*
Particle Astrophysics seminar, September '08,
Dept. of Physics and Astronomy, Case Western Reserve University, Cleveland.
- *The effect of dark matter halos on reionization and the H21 cm line.*
ISCAP noon Seminar, September '08,
Dept. of Physics/Astronomy, Columbia University, New York
- *The effect of dark matter halos on reionization and the H21 cm line.*
High Energy Theory Seminar, September '08,
Dept. of Physics, University of Florida, Gainesville.
- *Dark matter caustics and their relevance to dark matter searches*
Particle Theory Seminar, October '07,
Dept. of Physics, Bielefeld University, Germany.
- *Caustics and the search for dark matter*
Astrophysics Theory Lunch Seminar, March '07,
Dept. of Physics, University of Florida, Gainesville.
- *Can a dark matter caustic form a ring of stars?*
Astrophysics Theory Lunch Seminar, October '06,
Dept. of Astronomy, University of Florida, Gainesville.
- *Can a dark matter caustic form a ring of stars?*
High Energy Theory Seminar, October '06,
Dept. of Physics, University of Florida, Gainesville.

Conference talks:

Invited:

- *The effect of early dark matter halos on reionization.*
Kosmologietag, May '08
Bielefeld, Germany.
- *Dark matter annihilation in clumps.*
DESY ENTApP workshop on dark matter, Feb '08
Hamburg, Germany.

Contributed:

- *The effect of dark matter halos on reionization.*
Dark Matter at the Crossroads, Sep 29 - Oct 2, '08
DESY, Hamburg, Germany.
- *The effect of early dark matter halos on reionization.*
Cosmo '08
Madison, WI.
- *Dark matter caustics in galaxies.*
Aspen winter conference on astrophysics, Jan '06,
Aspen, CO.
- *Detecting galactic caustics.*
UF-FSU conference on high energy phenomenology, Dec '05
Gainesville, FL
- *Caustics in galactic halos.*
TeV particle astrophysics conference, July '05 Fermilab.
- *Applying catastrophe theory to dark matter.*
PHENO, May '05 Madison, WI.
- *Cold dark matter caustics.*
UF-FSU conference on high energy phenomenology, Dec '04
Tallahassee, FL

Conference posters:

- *Dark Matter Caustics.*
Astrophysical probes of the nature of dark matter,
May 2007, Irvine, CA.
- *Caustics in galactic halos.*
TeV particle astrophysics conference,
July 2005, Fermilab.

Computational skills

Languages: C , C++

Packages: Mathematica, Gnuplot

Teaching experience

- Introductory Lab, Mechanics : Fall '02, Spring '02
- Introductory Lab, E & M : Spring '03
- Physics without Calculus, E & M : Fall '05, Spring '05
- Physics with Calculus, Mechanics : Summer '03
- Physics with Calculus, E & M : Spring '04, Fall '06, Spring '06

Other activities

- Completed a course on Professional Photography from New York Institute of Photography, 2007.
- Judge of Kanapaha middle school science fair, Gainesville, 2006.

References

1. **Pierre Sikivie** (Thesis advisor) Professor, Department of Physics,
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2. **Dominik Schwarz** Professor, Fakultät für Physik,
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3. **Jonathan Tan** Assistant Professor, Department of Astronomy,
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4. **Richard Woodard** Professor, Department of Physics,
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Statement of Research Interests

I received my Ph.D in Physics in August 2007 from the University of Florida (Gainesville), under the supervision of Pierre Sikivie. In October 2007, I joined the Particle Astrophysics and Cosmology group of Dominik Schwarz, at the University of Bielefeld (Germany) as a postdoctoral fellow.

My Ph.D dissertation involved a study of caustics in cold dark matter halos. In collaboration with my supervisor Prof. Sikivie, I studied the properties and observational relevance of dark matter caustics, resulting in 5 publications in the Physical Review D.

In my first year as a postdoctoral fellow, I worked on other aspects of dark matter physics. In collaboration with Jonathan Tan (University of Florida) and Brian O'Shea (Michigan State University), I studied the effect of WIMP dark matter annihilation on the formation of the earliest stars, a topic first considered by Spolyar, Freese, & Gondolo (2008). We considered the effect of particle annihilation on star forming halos seen in numerical simulations, and obtained results for the expected luminosity, minimum mass, and expected baryonic core radius of early stars. Our results have been accepted for publication in the Astrophysical Journal. I also worked on the importance of dark matter annihilation on early reionization, in collaboration with Dominik Schwarz (University of Bielefeld). We showed that the WMAP measurement of optical depth may be used to constrain particle and halo parameters, particularly when the dark matter particle is light (1-100 MeV). Our results have been published in the Physical Review D. I am currently involved in studying the effects of dark matter minihalos and dark matter annihilation on the Hydrogen 21cm line, and whether these effects can be detected using future Hydrogen 21cm experiments.

I have broad research interests which include dark matter, cosmology, astronomy, and astrophysics. I am keen to learn new methods and to contribute to projects, both theoretical and observational. I describe in brief, my published work and proposed plan for future research.

1. Dark matter, reionization, and the Hydrogen 21cm line.

If dark matter particles annihilate into standard model particles, some of the released energy goes into ionization of gas atoms (Mapelli, Ferrara, & Pierpaoli 2006; Ripamonti, Mapelli, & Ferrara 2007, Chuzhoy 2008). In our article Phys. Rev. D 78, 103524 (2008) (Aravind Natarajan & Dominik Schwarz), we calculated the contribution of dark matter annihilation to early reionization. We fitted dark matter halos with NFW-like profiles, and computed the luminosity of halos due to particle annihilation. We used the Press-Schechter formalism to estimate the number density of dark matter halos, and calculated the optical depth resulting from particle annihilation. We found that typical SuSy neutralinos do not produce significant reionization unless the halo density profile is very cuspy. Significant reionization is however possible with particle masses in the 1 – 100 MeV range, particularly when s -wave annihilation is unsuppressed. The cosmology of MeV dark matter has been investigated by many authors (Hooper & Zurek 2008; Hooper, Kaplinghat, Strigari, & Zurek 2007). Constraints obtained on the particle mass may be used in conjunction with other studies such as observations of the soft gamma ray background (Ahn & Komatsu 2005) and the 511 keV line (Beacom, Bell, & Bertone 2005). The optical depth also depends on the minimum halo mass. Since the minimum halo mass is determined by the particle physics of the theory, future observations may be able to place constraints on MeV dark matter models. Our model also predicts a gradual reionization scenario, different from the ionized bubble framework.

Plan for further research:

I propose to study ways of constraining early reionization models by using the polarization sky maps produced by the WMAP experiment. Early reionization scenarios allow for more photon-electron scattering, and hence affect the E-mode polarization power spectrum (Haiman & Holder 2003). Reionization scenarios based on dark matter annihilation at high redshifts may produce some characteristic signature in the EE and TE power spectra. Another powerful probe of early reionization is the Hydrogen 21cm signal from neutral regions. Cross correlation of the H 21cm maps with the CMB doppler anisotropy (Alvarez, Komatsu, Doré, & Shapiro 2006) and the E-mode polarization maps (Tashiro, Aghanim, Langer, Douspis, & Zaroubi 2008) may help us exclude, or constrain these very early reionization scenarios. Since many of these early reionization scenarios involve dark matter models, this work is also relevant to dark matter phenomenology and MeV dark matter theories.

I am also interested in the effect that dark matter minihalos may have on the Hydrogen 21cm signal. Minihalos containing baryons are expected to form at a redshift ~ 20 in Λ CDM cosmology. The hot neutral gas in these minihalos produces H 21cm radiation in emission, potentially serving as a probe of the high redshift Universe. However this signal is expected to be small (Iliev et al. 2002, 2003; Shapiro et al. 2006; Furlanetto & Oh 2006). I would like to find out whether individual slices of redshift contain sufficient fluctuations, so that the minihalo signature may be separated from the background. For light dark matter models (~ 10 's of GeV), dark matter annihilation in early micro-halos may be able to raise the temperature of the IGM and produce an observable spectrum of fluctuations. Planned experiments such as the Square Kilometer Array may be able to achieve the required sensitivity to test these theories.

2. Dark matter and stars.

Population III stars are the earliest stars that formed, and are composed almost entirely of Hydrogen and Helium. These stars are thought to reionize the Universe, and enrich the IGM with heavy elements. They may also explain the formation of supermassive black holes and quasars. In Λ CDM cosmology, Pop.III stars are thought to form within dark matter halos of mass $\sim 10^6 M_{\odot}$. If the dark matter is made up of WIMPs (such as the neutralino), the annihilation of these particles can alter the formation and evolution of the stars. Much work has been done in this area in recent years, by several authors (Spolyar, Freese, & Gondolo '08; Iocco '08, Iocco et al. '08; Freese et al. '08; Taoso et al. '08; Scott, Fairbairn, & Edsjo '08).

In recent work arXiv:0807.3769 [astro-ph] (Aravind Natarajan, Jonathan Tan, & Brian O'Shea, accepted for publication in *Astrophysical Journal*), we investigated the effect of dark matter annihilation on primordial star formation. We derived an expression for the heat absorbed by the gas at a point r due to particle annihilation in the halo. This is in general, different from the heat generated at r , since not all the generated heat is absorbed. Conversely, it is also possible for photons from other parts of the halo to contribute to the heating rate at r . The cooling function includes rotational and vibrational cooling (Hollenbach & McKee 1979), collision induced emission cooling (Yoshida, Omukai, Hernquist, & Abel 2006), and also takes into account the opacity of the gas to cooling radiation (Yoshida et al. 2006).

We considered 3 different cosmological simulations performed using the Enzo code, which is an adaptive mesh refinement code (O'Shea et al. 2004; O'Shea & Norman 2007), to obtain the dark matter density, baryon density, temperature, and molecular hydrogen fraction, as a function of distance from the center of the halo. We showed that dark matter heating can

overwhelm gas cooling in the inner regions of the halo, and computed the heating and cooling rates, for different particle masses. We also calculated the heating and cooling luminosities for these 3 simulations. We found that peak luminosities may exceed $1000 L_{\odot}$. We expect a core to form at the point where the enclosed dark matter heating luminosity equals the enclosed cooling luminosity, and this core is of order ~ 10 's of A.U. As a result of dark matter heating, we find that the mass of Pop.III stars may exceed $100 M_{\odot}$. Our results show that computer simulations of star formation need to include particle annihilation in a self-consistent way.

Plan for further research:

I plan to continue my work on dark matter and Pop.III stars. Many aspects of these dark matter powered stars remain to be studied. A future project would be to determine whether the dark matter powered stars would become ordinary stars when the dark matter power source is exhausted. This is a non-trivial question considering the extreme mass of the stars ($> 100 M_{\odot}$). It is unclear whether these extremely massive stars can enter the main sequence. Dark matter annihilation in early star forming clouds may raise the mass scale of primordial stars to a regime important for the formation of supermassive black holes. The WIMP depletion time scale due to particle annihilation is comparable to the growth time of the protostar in some of the models we considered. This is an interesting scenario which needs to be carefully examined. We plan to study the formation of proto-stars in greater detail within the context of neutralino dark matter halos, in order to determine the likely masses of the stars, and the fate of the stars when the energy supply from particle annihilation is exhausted. Another situation in which dark matter annihilation could be important is when stars form near a supermassive black hole. The high dark matter density in this region may significantly affect the star formation rate. The connection between star formation and supermassive black holes is a fascinating topic requiring both observations and theoretical modeling. I propose to examine these ideas in detail.

Another project I am interested in, is the effect of dark matter accretion by compact objects such as white dwarfs and neutron stars (Moskalenko & Wai 2007, Bertone & Fairbairn 2008). A problem I want to consider is the effect that dark matter accretion would have on white dwarf stars in binary systems, and near supermassive black holes. If a white dwarf accretes both baryons and dark matter, the energy released by particle annihilation could serve as a power source, possibly helping to support the star against collapse, and possibly altering the structure and evolution of the star. I plan to study these theories to find out whether certain dark matter candidates can produce observable effects.

3. Dark matter caustics.

Dark matter caustics are regions where the dark matter density is very large. They occur because cold dark matter particles occupy a thin 3-dimensional hypersurface in 6-dimensional phase space. The projection of the phase space hypersurface onto 3-dim. physical space results in the formation of singularities, or catastrophes (Arnold, Shandarin, & Zeldovich 1982; Shandarin & Zeldovich 1984; Sikivie & Ipser 1992; Sikivie 1999). A caustic is in general, built up of sections of catastrophes. Since catastrophes are known to be stable topological objects (for e.g. Poston & Stewart 1996), and occur commonly with collisionless media such as light (e.g. a rainbow, ripples on the bottom of a swimming pool, etc), we expect caustics to exist in galaxies. In reality, the density is not infinite, but is limited by the finite velocity dispersion of the dark matter particles. The thin arcs or shells sometimes seen around giant elliptical galaxies (Malin & Carter 1980; Hernquist & Quinn 1987) are caustics in the distribution of stars.

The occurrence of caustics with stars implies that the same could occur with dark matter as well. Recent high resolution simulations also point to the existence of caustics in galactic halos (Vogelsberger, White, Helmi, & Springel 2008).

In Phys. Rev. **D72**, 083513 (2005) (Aravind Natarajan & Pierre Sikivie), we investigated the relevance of dark matter caustics in galactic halos. We found that for small velocity dispersions (< 10 km/s), individual dark matter streams are sufficiently well resolved in velocity space, so that the caustics associated with these streams are resolvable. We investigated the effect of baryonic structures such as giant molecular clouds in increasing the velocity dispersion, and found the effect to be small. We therefore conclude that dark matter caustics are a robust prediction of cold dark matter cosmology. In article Phys. Rev. **D73**, 023510 (2006) (Aravind Natarajan & Pierre Sikivie), we described the catastrophe structure of caustics. We proved that a continuous infall of dark matter particles from all directions in a galactic halo necessarily leads to the formation of a singularity in the limit of zero velocity dispersion. To study the geometry of these caustics, we modeled the galactic halo by means of a density profile, and simulated the infall of a single cold stream in the halo potential. We provided a detailed study of the structure of dark matter caustics based on the form of the initial angular momentum distribution. Our study is significant to observations. If the ring-like structure seen in the galaxy cluster Cl 0024+1654 is interpreted as a dark matter caustic (Onemli & Sikivie, arXiv:0710.4936 [astro-ph] 2007), it would mean that the angular momentum distribution of dark matter in that galaxy cluster is dominated by a rotational term, thus helping us better understand the process of angular momentum transfer in galaxies.

We then worked on the possibility of detecting caustics, and their astrophysical relevance. In articles Phys. Rev. **D75**, 123514 (2007) (Aravind Natarajan) and Phys. Rev. **D77**, 043531 (2008) (Aravind Natarajan & Pierre Sikivie), we studied the gamma ray flux produced by the annihilation of WIMP dark matter in caustics. It was shown that it may be possible to detect the nearest inner caustic by experiments such as the Fermi satellite (GLAST). We also obtained sky maps of the expected gamma ray flux. In article Phys. Rev. **D76**, 023505 (2007) (Aravind Natarajan & Pierre Sikivie), we discussed a possible interpretation of the Monoceros ring of stars in terms of the second inner caustic of the Milky Way. We identified two mechanisms which could result in the formation of the Monoceros ring. The first mechanism is the effect of viscous torques on baryonic material close to the caustic. The second mechanism is the adiabatic deformation of star orbits as the caustic moves outward, which leads to an order 100% increase in star density at the caustic.

Plan for further research:

I plan to study the possibility of caustics forming as a result of the infall of clumps, particularly early dark matter microhalos (Green, Hofmann, & Schwarz 2004) which are extremely compact, and may survive to the present day. They also possess a very small velocity dispersion. The movement of these micro-halos in the potential of our galaxy leads to the formation of caustics. While the density is not divergent, it may be sufficiently enhanced, so as to be observationally relevant. It is important to investigate whether an enhancement in the clump density at the caustic locations can lead to observable effects.

Caustics are also relevant to WIMP direct detection experiments. In the vicinity of a caustic, the dark matter velocity distribution is dominated by a single cold stream. This affects the annual modulation signature, and the effect depends on the WIMP mass (Savage, Freese, & Gondolo 2006; Lewis & Freese 2004). If the WIMP mass can be established from accelerator experiments, one may be able to learn more about dark matter, and about possible caustics in

the solar neighborhood. Directional detectors such as DRIFT may also be able to detect the presence of a nearby caustic.

Another project I am interested in, is the possibility of studying caustics using N-body simulations. Certain N-body simulations that use special techniques to increase the resolution in the relevant regions of phase space are able to resolve discrete streams (Stiff & Widrow 2003). The technique of Stiff and Widrow may also be used to study the properties of caustics. This would allow us to reduce the mass per simulation particle and ensure that particles are collisionless, a crucial requirement for the formation of caustics. I propose to work on this problem to resolve the structure of galactic caustics, and also to determine the velocity distribution of dark matter in the solar neighborhood.

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M.A. Alvarez, E. Komatsu, O. Doré, P.R. Shapiro, ApJ **647**, 840 (2006)
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K. Freese, D. Spolyar, A. Aguirre, P. Bodenheimer, P. Gondolo, J.A. Sellwood, N. Yoshida, arXiv:0808.0472
S. Furlanetto, P. Oh, ApJ **652**, 849 (2006)
A.M. Green, S. Hofmann, D.J. Schwarz, MNRAS, **353**, L23 (2004)
Z. Haiman, G.P. Holder, ApJ, **595**, 1 (2003)
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