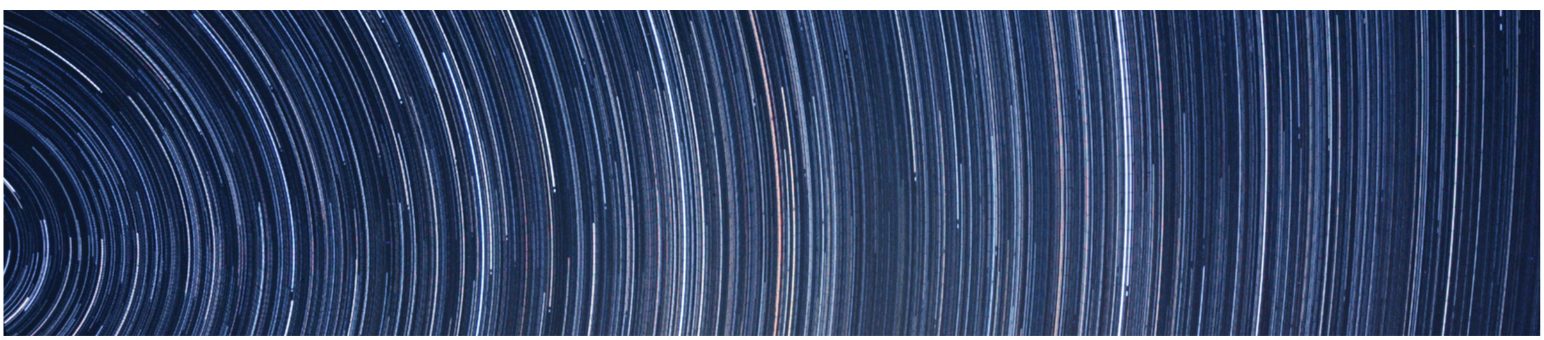
FELLOWS AT THE FRONTIERS 2016



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CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

Wednesday, August 31, 2016 Afternoon

Welcoming Remarks **2:00 – 2:10 PM**
Fred Rasio
Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)

{Moderator: Fred Rasio} **2:10 – 3:30 PM**

2:10 – 2:30 PM Peter Behroozi, Berkeley
The Connection between Galaxy Growth and Dark Matter Halo Assembly from z=0-10

2:30 – 2:50 PM Camille Avestruz, U Chicago
Stirred, not Clumped: the Evolution of Temperature Profiles in the Outskirts of Galaxy Clusters

2:50 – 3:10 PM Erik Petigura, Caltech
The Compositional Diversity of Sub-Saturns

3:10 – 3:30 PM Ann-Marie Madigan, Berkeley
Tidal disruption events in post-starburst galaxies

4:00 – 5:20 PM

4:00 – 4:20 PM Rachel Bezanson, Arizona
The Surprisingly Complex Lives of Massive Galaxies

4:20 – 4:40 PM Nia Imara, Harvard-Smithsonian CfA
Star Formation and the Evolution of Giant Molecular Clouds

4:40 – 5:00 PM Brooke Simmons, UCSD
The Merger-Free Co-Evolution of Galaxies and Supermassive Black Holes

5:00 – 5:20 PM Ilse Cleeves, Harvard-Smithsonian CfA
From Disks to Planets Through the Astrochemical Lens

6:00 – 9:00 PM
Opening Night Reception

Thursday, September 1, 2016 Morning

{Moderator: Sourav Chatterjee, CIERA} **9:00 – 10:20 AM**

9:00 – 9:20 AM Carl Rodriguez, MIT
Binary Black Holes from Dense Star Clusters

9:20 – 9:40 AM Maria Drout, Carnegie
Peculiar Transients and the Evolution of Massive Stars

9:40 – 10:00 AM Blakesley Burkhart, Harvard
The Origins and Implications of MHD Turbulence

10:00 – 10:20 AM Chat Hull, Harvard-Smithsonian CfA
Probing magnetic fields in protostellar cores with ALMA observations and next-generation simulations

11:00 – 12:20 PM

11:00 – 11:20 AM Rachel Friesen, Dunlap
Flows and fragmentation: the role of filaments in local star formation

11:20 – 11:40 AM Cristobal Petrovich, CITA
On the origin of hot and warm Jupiters

11:40 – 12:00 PM Matthew Penny, OSU
Shedding Light on Free-Floating Planets with K2 Campaign 9

12:00 – 12:20 PM Wen-fai Fong, Arizona
Electromagnetic Counterparts to Gravitational Waves

12:20 – 2:00 PM
Lunch and Conference Photo

Thursday, September 1, 2016 Afternoon

{Moderator: Fabio Antonini, CIERA} **2:00 – 3:20 PM**

2:00 – 2:20 PM Brett McGuire, NRAO Charlottesville
Life's First Handshake: Detection of the First Interstellar Chiral Molecule, Propylene Oxide

2:20 – 2:40 PM Cara Battersby, Harvard-Smithsonian CfA
Exposing Star Formation in our Galaxy's Center: A Window into the Distant Universe

2:40 – 3:00 PM Rebecca Canning, Stanford
AGN in the cluster environment

3:00 – 3:20 PM François Foucart, LBNL
Merging black holes and neutron stars: Gravitational waves and electromagnetic signals

4:00 – 5:20 PM

4:00 – 4:20 PM Hsiang-Yi "Karen" Yang, Maryland
How AGN Jets Heat the Intracluster Medium

4:20 – 4:40 PM Ondrej Pejcha, Princeton
The Rugged Landscape of Core-Collapse Supernova Explosions

4:40 – 5:00 PM Laura Sampson, CIERA
Binary Black Hole Mergers in the first Advanced LIGO Observing Run

5:00 – 5:20 PM James Owen, IAS, Princeton
Vortices from low-mass planet formation in transition discs

Friday, September 2, 2016 — Morning

{Moderator: Laura Sampson, CIERA} — **9:00 – 10:20 AM**

9:00 – 9:20 AM Leo Stein, Caltech
Black hole mergers: beyond general relativity

9:20 – 9:40 AM Ruobing "Robin" Dong, LBNL
Introducing a New Field in Astronomy: Observational Planet Formation

9:40 – 10:00 AM Michael McCourt, UCSB
A "fog" of cold gas in galaxy halos

10:00 – 10:20 AM Shy Genel, Columbia
Large Universes on Large Computers

11:00 – 12:20 PM

11:00 – 11:20 AM Chris Hayward, Caltech
Starbursts, outflows, and the emergence of disk galaxies

11:20 – 11:40 AM Kent Yagi, Princeton
What do GW150914 and GW151226 tell us about extreme gravity?

11:40 – 12:00 PM Sarah Ballard, MIT
The Grand Planetary Ensemble: Using Kepler Statistics to Understand the Formation and Atmospheres of M Dwarf Planets

12:00 – 12:20 PM Maria Petropoulou, Purdue
Probing cosmic ray particle acceleration in radio supernovae

12:20 – 2:00 PM
Lunch with AAS President, Christine Jones Forman

Friday, September 2, 2016 Afternoon

{Moderator: Alex Richings, CIERA} **2:00 – 3:20 PM**

2:00 – 2:20 PM Gongjie Li, Harvard
Interaction Cross Sections and Survival Rates for Proposed Solar System Member Planet Nine

2:20 – 2:40 PM Timothy "T.J." Rodigas, Carnegie DTM
Breaking through the (Slow-Rotator) Speed Barrier: A Direct Method for Measuring Stellar V Sin i

2:40 – 3:00 PM Nicholas Stone, Columbia
Rates of Stellar Tidal Disruption

3:00 – 3:20 PM Courtney Dressing, Caltech
Characterizing Planetary Systems Orbiting Low-mass Stars

4:00 – 5:20 PM

4:00 – 4:20 PM Andreas Kuepper, Columbia
Exploding Satellites – The Tidal Debris of the Ultra-Faint Dwarf Galaxy Hercules

4:20 – 4:40 PM Diana Dragomir, MIT
Small Planets Transiting Bright Stars

4:40 – 5:00 PM Chiara Mingarelli, Caltech
The Gravitational-Wave Universe seen by Pulsar Timing Arrays

5:00 – 5:20 PM James Guillochon, Harvard-Smithsonian CfA
An Open Catalog of Supernova Data

Peter Behroozi (Berkeley): *The Connection between Galaxy Growth and Dark Matter Halo Assembly from z=0-10*
We present a method to flexibly and self-consistently connect individual galaxies' star formation rates to their host halos' potential well depths, assembly histories, and redshifts. After parameter exploration, the method is able to reproduce galaxies' observed stellar mass functions, star formation rates (specific and cosmic), quenched fractions, UV luminosity functions, autocorrelation functions (including for quenched and star-forming subsamples), and quenching dependence on environment over the full redshift range (up to z=0-10) for each observable. Presented results include revised stellar mass—halo mass relations, the dependence of average star formation histories on galaxy SSFRs and environment, quenching timescales for satellites, and predictions for the James Webb Space Telescope as well as higher-redshift galaxy correlation functions and weak lensing signals.

Camille Avestruz (U Chicago): *Stirred, not Clumped: the Evolution of Temperature Profiles in the Outskirts of Galaxy Clusters*
X-ray measurements of the intracluster medium (ICM) suggest that temperature profiles at large radii deviate from self-similar evolution. Using a mass-limited sample of galaxy clusters from cosmological hydrodynamical simulations, we show that the departure from self-similarity is due to physical processes that are driven by mergers and accretion. The dominant contribution comes from the evolution of non-thermal gas motions that have not yet thermalized (stirring). The evolution of accreting cool, dense gas substructures that bias the average temperature low (clumping), is subdominant. We can mitigate departures from self-similarity with a careful choice of halo overdensity definition that scales out the accretion dependence. These results highlight the importance of understanding non-thermal gas motions in the ICM and the use of galaxy clusters as cosmological probes.

Erik Petigura (Caltech): *The Compositional Diversity of Sub-Saturns*
Today, NASA's K2 mission is building upon the rich legacy of the prime Kepler mission. K2 will survey 20 times more sky than Kepler by 2017, casting a wider net for planets around nearby bright stars that are more amenable to precise characterization. I will present some of my group's latest K2 efforts, including a program to study sub-Saturns: a mysterious class of planets between Neptune and Saturn size, not present in our Solar System. These planets have mean densities ranging from 2.0 g/cc (concrete) to 0.05 g/cc (Styrofoam) and offer an intriguing window into the processes that form and sculpt planetary systems.

Ann-Marie Madigan (Berkeley): *Tidal disruption events in post-starburst galaxies*
Recent observations show that tidal disruption events (TDEs) preferentially occur in a rare class of post-starburst, post-merger galaxies. Another unexpected finding is that many supermassive black holes host eccentric disks of stars; this is surprising because these disks "should" be violently unstable. I will suggest that these two phenomena are related: I will demonstrate a new dynamical mechanism which stabilizes eccentric stellar disks and thus explains their observational prevalence. I will also show that a corollary of this mechanism is an extremely high rate of TDEs. Finally, I will discuss how eccentric disks may be connected to galaxy mergers, explaining this association of TDEs with post-starburst,

post-mergers galaxies.

Rachel Bezanson (Arizona): *The Surprisingly Complex Lives of Massive Galaxies*
Once thought to be relics of a much earlier epoch, the most massive local galaxies are red and dead ellipticals, with little ongoing star formation or organized rotation. In the last decade, observations of their assumed progenitors have demonstrated that billions of years ago, massive galaxies were more compact and morphologically different, possibly with more disklike structures. The details of this observed evolution can place constraints on the physical processes that have driven massive galaxy evolution through cosmic time. I will describe results from deep spectroscopic studies of stellar populations and dynamics of the high-redshift progenitors of massive galaxies today. In particular I will highlight an exciting new LEGA-C spectroscopic survey of galaxies at z~1, which will bring local galaxy detail to our understanding of galaxy evolution at half the age of the Universe.

Nia Imara (Harvard-Smithsonian CfA): *Star Formation and the Evolution of Giant Molecular Clouds*
All stars are observed to form in giant molecular clouds (GMCs). Since these "stellar nurseries" set the stage for star formation in the Milky Way and other galaxies, astronomers would like to understand how they form and evolve. In this presentation, I will discuss different ways of investigating the evolution of GMCs. Local and extragalactic GMCs are observed with systematic velocity gradients, possibly indicating the large scale of rotation of clouds. In my study of GMCs in the Milky Way and M33, I demonstrate that any viable theory of cloud formation must agree with a number of interesting trends pertaining to cloud kinematics. For instance, I find that many clouds could be counter-rotating with respect to overall galactic rotation, which has important consequences for theory and galactic simulations. In separate work, I demonstrate how Galactic clouds with different star formation rates have different distributions of dense gas, another possible probe of cloud evolution. Finally, I will focus on a study of the atomic-to-molecular transition in GMCs that sheds new light on the large-scale environment in which stellar nurseries form and evolve.

Brooke Simmons (UCSD): *The Merger-Free Co-Evolution of Galaxies and Supermassive Black Holes*
Supermassive black holes and their host galaxies appear to co-evolve over many billions of years of evolution, but the origin of this co-evolution remains unknown. Studies are complicated by the fact that most galaxies' evolutionary histories include a mix of interactions and mergers of many strengths and merger-free "secular" evolution, making it hard to disentangle which of these processes contributes (or dominates) black hole-galaxy co-evolution. Using a sample of unambiguously disk-dominated galaxies hosting luminous, growing supermassive black holes provides a useful means of studying secular black hole growth. As major galaxy mergers inevitably lead to the formation of bulge-dominated galaxies, this sample cannot have had significant merger activity since z ~ 2, yet the black holes have grown significantly, up to ~10^9 M_sun. Supermassive black holes in disk-dominated galaxies correlate with total stellar mass, but even considering generous upper limits on bulge masses, these galaxy bulges are too small to support the notion that minor mergers or strong disk instabilities alone can drive the same correlation as that seen in bulge-dominated galaxies with likely histories including minor mergers. Black holes and galaxies can co-evolve even in the absence of significant mergers since z ~ 2.

Ilse Cleeves (Harvard-Smithsonian CfA): *From Disks to Planets Through the Astrochemical Lens*
During the first few Myr of a young, Sun-like star's life, it is encircled by a disk made up of molecular gas, dust, and ice. These materials form the building blocks for future planetary systems. Improvements in observational spatial resolution and sensitivity have allowed us to characterize the protoplanetary disk environment in great detail. Recent interferometric observations with both the Submillimeter Array (SMA) and the Atacama Large Millimeter/Submillimeter Array (ALMA) have shed light on disks' chemical composition and the structure of their rocky/solid and gaseous components, which together feed young terrestrial and gas giant planets. I will discuss recent results and new puzzles regarding our understanding of protoplanetary disk chemical and structural evolution, along with future avenues to detect individual young planets forming in situ.

Thursday, September 1, 2016 Morning

Carl Rodriguez (MIT): *Binary Black Holes from Dense Star Clusters*
The recent discovery of gravitational waves from merging binary black holes has the potential to revolutionize our understanding of compact object astrophysics. But to fully utilize this new window into the universe, we must compare these new observations to detailed models of binary black hole formation throughout cosmic time. In this talk, I will describe how binary black holes can be formed dynamically through gravitational interactions in dense stellar environments, such as globular clusters and galactic nuclei. I will show that the recent LIGO detections are fully consistent with the dynamical formation scenario. Finally, I will illustrate how gravitational waves from binary black holes may encode tell-tale signatures of their formation history, allowing us to discriminate between binaries formed in clusters and binaries formed from isolated stellar evolution.

Maria Drout (Carnegie): *Peculiar Transients and the Evolution of Massive Stars*
The recent advent of wide-field time-domain surveys has launched an upheaval in field of stellar evolution. These surveys are uncovering new types of astronomical transients that not only challenge existing models for supernova explosions but also our understanding of what physical processes can occur during the final years of a massive star's life. Here I describe on-going efforts to constrain the explosion properties, progenitor systems, and intrinsic rates for several classes of peculiar astronomical transients and the implications for our understanding of stellar evolution. By opening new regimes of the dynamic sky, we have increased the variety of explosions we can directly probe, challenged our views of what mass-loss can occur in the final years before core-collapse, and expanded our knowledge of what final states are possible in the evolution of massive stars.

Blakesley Burkhart (Harvard): *The Origins and Implications of MHD Turbulence*
Magnetic fields and turbulence are vital components in galactic processes, including cosmic ray transport, interstellar medium (ISM) structure formation and star formation. However turbulence is difficult to measure observationally and the role of simulations is vital for both testing theories of ISM turbulence and gauging observational diagnostics via synthetic observations. In this talk I will discuss the origins of turbulence in galaxies, and its connection to the star formation process, both from the perspective of observations of star

forming molecular clouds and also from numerical simulations of magnetized turbulence. I will highlight how turbulence can be measured in the ISM using new statistical tools.

Chat Hull (Harvard-Smithsonian CfA): *Probing magnetic fields in protostellar cores with ALMA observations and next-generation simulations*
The first polarization data from ALMA were delivered to PIs this (northern) spring. The data are already both expanding and confounding our understanding of the role of magnetic fields in low-mass star formation. Here I will show the highest resolution and highest sensitivity polarization images ever made of a Class 0 protostellar source. These new ALMA observations achieve ~150 AU resolution, allowing us to probe polarization — and thus magnetic field orientation — in the innermost regions surrounding the protostar. The ALMA data reveal magnetic fields that are parallel with filamentary structures in the source; these fields lead to the central source, indicating that we may be witnessing magnetized accretion flows onto a protostar for the first time. We compare these observations with cutting-edge AREPO simulations that match the ALMA resolution, and find not only that the source most likely originated in a weakly magnetized, turbulent envirnoment; but also that the initial conditions at the parsec scales of clouds can greatly influence source morphology at protostellar scales.

Rachel Friesen (Dunlap): *Flows and fragmentation: the role of filaments in local star formation*
The conversion of gas into stars is a key process driving the evolution of structures in the universe, from the global star formation history of galaxies to the formation of planetary systems like our own. Recent surveys of dust continuum emission of Galactic star-forming regions have revealed the ubiquity of filamentary structures in molecular clouds. The prevalence of filaments within star-forming regions raises the tantalizing possibility that the star formation efficiency in molecular clouds is strongly dependent on how these dense filaments form and evolve. I will show how combined analysis of gas dynamics and chemistry in star-forming regions tests models of filamentary formation and evolution. I will further present first-look results from the Green Bank Ammonia Survey (GAS), a Large Program on the GBT to study the structure, kinematics, and chemistry of dense gas in nearby star forming regions.

Cristobal Petrovich (CITA): *On the origin of hot and warm Jupiters*
The first exoplanet discovered in a main sequence star was a hot Jupiter (Peg b in 1995). After ~20 years of research and the discovery of >600 gas giant planets, the origin of the close-in Jupiters remains a fundamental and highly debated open problem in planet formation. First, I will review our current understanding from the orbital architecture of the planetary systems with hot Jupiters (periods <10 days) and warm Jupiters (periods ~10-100 days). Second, I will show that gravitational interactions between planets coupled with tidal friction can account for most of the hot Jupiters and a population of eccentric warm Jupiters with outer planetary companions. I describe two observational tests that can further constrain our model.

Matthew Penny (OSU): *Shedding Light on Free-Floating Planets with K2 Campaign 9*
Campaign 9 of K2 observed a contiguous 3.7 deg^2 region of the Galactic bulge in order to search for microlensing events and measure microlens parallaxes. It also performed

targeted follow-up of over 50 microlensing events spread throughout the Kepler focal plane. Parallax measurements are a critical ingredient for measurements of both the lens mass and distance, which contribute to our understanding of the formation of cold exoplanets, and the formation of planets as a function of Galactic environment. Additionally, as the first un-targeted, space-based microlensing survey, K2C9 offers us the first chance to measure the masses and kinematics of a large population of free-floating planet candidates, whose large abundance has been a puzzle since their discovery. I will review the scientific goals of the K2C9 survey and give a preview of the results that can be expected from the survey.

Wen-fai Fong (Arizona): *Electromagnetic Counterparts to Gravitational Waves*
Thanks to the advent of the Advanced LIGO/VIRGO network, the era of gravitational wave discovery is upon us. Their continued discovery will bring unprecedented information about the basic properties of compact objects and their mergers. However, the detection of a counterpart at electromagnetic wavelengths will significantly leverage the gravitational wave event by providing a precise position, enabling redshift determination, association to a host galaxy, and invaluable astrophysical context. Here, I describe ongoing observational efforts to chase and characterize the counterparts of gravitational waves across the electromagnetic spectrum.

Thursday, September 1, 2016 Afternoon

Brett McGuire (NRAO Charlottesville): *Life's First Handshake: Detection of the First Interstellar Chiral Molecule, Propylene Oxide*
Life on Earth relies on chiral molecules, that is, species not superimposable on their mirror images. This manifests itself in the selection of a single molecular handedness, or homochirality, across the biosphere, and is perhaps most readily apparent in the large enhancement in biological activity of particular amino acid and sugar enantiomers. Yet, the ancestral origin of biological homochirality remains a mystery. The non-racemic ratios in some organics isolated from primitive meteorites hint at a primordial chiral seed, but even these samples have experienced substantial processing during planetary assembly, obscuring their complete histories. To determine the underlying origin of any enantiomeric excess, it is critical to understand the molecular gas from which these molecules originated. Here, we present the first extra-solar, astronomical detection of a chiral molecule, propylene oxide (CH3CHCH2O), in absorption toward the Galactic Center. We discuss the implications of the detection on searches to determine a primordial chiral excess, as well as the state of laboratory efforts in these areas.

Cara Battersby (Harvard-Smithsonian CfA): *Exposing Star Formation in our Galaxy's Center: A Window into the Distant Universe*
Cosmic star formation peaked around a redshift of 2, in conditions vastly different from those we observe in our solar neighborhood. Yet our understanding of this fundamental physical process, the conversion from gas into stars, is rooted in detailed observations of our solar neighborhood. The inner few hundred parsecs of the Milky Way, known as the Central Molecular Zone (CMZ), is our closest laboratory for understanding star formation in the extreme environments (hot, dense, turbulent gas) that once dominated the universe. I present preliminary results from the first survey to expose the sites of star formation across the CMZ using the SMA, CMZoom. We identify the location of dense cores in the CMZ and

search for embedded signatures of star formation. These measurements allow us to address fundamental questions regarding the nature of star formation in extreme environments.

Rebecca Canning (Stanford): *AGN in the cluster environment*
SMBHs lurk in the centres of all massive galaxies, a fraction of these SMBHs are actively accreting which can result in powerful outbursts and has important consequences for the host galaxy's evolution. Statistics of X-ray AGN populations have been hindered by small sample sizes so the conditions under which they are triggered is not well understood. We have undertaken a survey of 11,000 X-ray AGN in the vicinity of 135 of the most massive galaxy clusters, where the high galaxy and gas densities offer a unique opportunity to examine how environment affects the triggering of these powerful AGN. We investigate the how the radial distribution and overdensity of X-ray AGN varies as a function of the cluster mass and redshift. We find no significant redshift dependent evolution of the cluster and field populations and the radial distribution scales self-similarly, however, we find a strong dependence of the overdensity of X-ray AGN on cluster mass, scaling as M^{-1}. This non self-similar scaling is similar in form to that of the galaxy merger rate in clusters suggesting that galactic mergers and interactions are important for the triggering of cluster X-ray AGN.

François Foucart (LBNL): *Merging black holes and neutron stars: Gravitational waves and electromagnetic signals*
The recent detection by the LIGO collaboration of gravitational waves emitted by merging black holes opened a new way to observe the universe. In the coming years, gravitational wave detectors are expected to observe many more black hole mergers, as well as the first binary neutron star and black hole-neutron star mergers. In the presence of at least one neutron star, the gravitational waves will sometimes be followed by bright electromagnetic signals, which can provide additional information about the properties and environment of the mergers. Neutron star mergers can also help us understand nuclear interactions, and may be the main production site of many heavy elements. In this talk, I will provide an overview of the many ways in which neutron star mergers can be detected, and discuss what we can learn from them and how numerical simulations can help us interpret upcoming observations. I will discuss current frontiers in the simulation of these mergers, and what remains to be done in order to extract as much information as possible from the observation of their gravitational wave and electromagnetic signals.

Hsiang-Yi "Karen" Yang (Maryland): *How AGN Jets Heat the Intracluster Medium*
Feedback from active galactic nuclei (AGN) is believed to prevent catastrophic cooling in galaxy clusters. However, how the feedback energy is transformed into heat, and how the AGN jets heat the intracluster medium (ICM) isotropically, still remain elusive. In our recent work, we gain insights into these processes using state-of-the-art simulations of AGN feedback in clusters. I will present what we have learned about the relative importance of all relevant mechanisms, including radiative cooling, advection, adiabatic compression/expansion, turbulence, shock heating, and mixing with hot bubble gas. I will also show how the heat provided by the bipolar AGN jets is isotropized by the process of 'gentle circulation' within the cluster core.

Ondrej Pejcha (Princeton): *The Rugged Landscape of Core-Collapse Supernova Explosions*

The collapse of the core and the associated supernova explosion mark the end of life of most massive stars, but the mechanism of explosion is poorly understood and perhaps even unknown. By parameterizing the systematic uncertainty in the explosion mechanism, we study how the explosion threshold maps onto observables – fraction of successful explosions, remnant neutron star and black hole mass functions, explosion energies, nickel yields – and their mutual correlations. Successful explosions are intertwined with failures in a complex but well-defined pattern that is not well described by the progenitor initial mass and is tied to the pre-collapse structure of the progenitor star. We present a new method to extract the supernova parameters from light curves and expansion velocities, and illustrate how can these observables constrain the explosion mechanism in the future.

Laura Sampson (CIERA): *Binary Black Hole Mergers in the first Advanced LIGO Observing Run*

I will discuss the results from LIGO's first observing run – detections, parameter estimation, and astrophysical implications.

James Owen (IAS, Princeton): *Vortices from low-mass planet formation in transition discs*

Transition discs are protoplanetary discs that show evidence for dust trapping in their outer regions. Recent high angular resolution mm imaging of these discs has indicated that dust particles, as well being trapped radially, are also concentrated in non-axisymmetric features, and it has been suggested that the dust particles are trapped in a large scale vortex. Since the dust particles that naturally accumulate in transition disc dust traps have Stokes numbers close to unity, there is naturally a large reservoir of pebbles in transition disc dust traps. I will argue that the transition disc dust traps are prime sites for rapid pebble accretion onto low-mass planetary embryos. At the planetary accretion rates expected in nominal transition discs, the accretion luminosity is sufficiently high to heat the surrounding disc to radii well outside the planet's Hill sphere. This makes the disc locally baroclinic and can lead to vortex formation.

Friday, September 2, 2016 — Morning

Leo Stein (Caltech): *Black hole mergers: beyond general relativity*

One hundred years after the birth of general relativity, advanced LIGO has finally directly detected gravitational waves. The source: two black holes merging into one. Advanced LIGO will soon provide the opportunity to test GR, using gravitational waves, in the dynamical strong-field regime—a setting where GR has not yet been tested. GR has passed all weak-field tests with flying colors. Yet it should eventually break down, so we must look to the strong-field. To perform strong-field tests of GR, we need waveform models from theories *beyond* GR. To date there are no numerical simulations of black hole mergers in theories which differ from GR. The main obstacle is the mathematical one of "well-posedness." I will explain how to overcome this obstacle, and demonstrate the success of this approach by presenting the first numerical simulations of black hole mergers in a theory beyond GR.

Ruobing "Robin" Dong (LBNL): *Introducing a New Field in Astronomy: Observational Planet Formation*
Planets form in gaseous protoplanetary disks surrounding newborn stars. As such, the best way to learn how they form from observations, is to watch them forming in disks. By doing so, we can directly address the three most fundamental questions in planet formation: when, where, and how do planets form. In the past, due to the difficulties in directly detecting planets in gas disks, planet formation was largely a subject of theoretical astrophysics. Now, thanks to a fleet of new instruments with unprecedented resolving power that have come online in the past few years, we have just started to be able to directly resolve structures in protoplanetary disks that are mostly likely associated with embedded (unseen) planets, such as gaps and spiral arms. By comparing observations with theoretical models of planet-disk interactions, the locations and masses of these still forming planets can be constrained. This is the onset of a new field — observational planet formation. I will introduce some latest highlights in this field, in particular hydrodynamic and radiative transfer modeling of planet-induced structures in disks, and the current status of model-observation comparisons.

Michael McCourt (UCSB): *A "fog" of cold gas in galaxy halos*
Absorption studies of galaxies and galaxy clusters at high redshift have unexpectedly found that their halos are full of cold gas, in addition to the theoretically-predicted virialized plasma. These observations typically indicate a relatively modest total amount of cold gas (~0.01% by volume), yet find it in essentially every sightline through the galaxy. I will show that cold gas clouds are prone to "shattering" into tiny fragments, and that the resulting small clouds naturally reproduce the large area-covering fractions and small volume-filling fractions inferred from observations. This same effect enhances the drag force coupling the dynamics of cold and hot gasses; I will also discuss potential applications to entrainment of cold gas in galaxy winds, and the possibility of using cold gas to constrain the kinematics of the hot ICM.

Shy Genel (Columbia): *Large Universes on Large Computers*
The multi-scale, multi-physics, and non-linear nature of galaxy formation requires immense computing power for calculating the formation and evolution of representative galaxy populations in cosmological volumes. I will describe the state of the art in this field and in particular its realization in the publicly available Illustris simulation and the next generation simulations of the Illustris project. I will then touch on two fundamental outstanding problems in galaxy formation on which these simulations can provide unique insights: the acquisition of angular momentum of galactic disks, and the physical origin of observed IMF (initial mass function) variations between galaxies of different kinds.

Chris Hayward (Caltech): *Starbursts, outflows, and the emergence of disk galaxies*
A complete theory of galaxy formation requires understanding the details of how gas is converted into stars over cosmic time, which is affected by gas supply, star formation, and feedback-driven outflows. Based on the results of state-of-the-art cosmological zoom simulations, I will argue that galaxy formation is a violent process: at high redshift, stellar feedback causes all star-forming galaxies to undergo rapid fluctuations in their star formation rates on ~10-Myr timescales. Bursts of star formation are followed by strong outflows, which cause the star formation rate to drop precipitously. Fresh gas supply from

galactic fountains rejuvenates star formation and restarts the cycle. At z ~ 1, simulations of massive galaxies exhibit a qualitative transition: outflows are no longer driven effectively, and the galaxies transition to steadily star-forming, well-order disk galaxies. I will present an analytic theory that potentially explains the reasons for this transition.

Kent Yagi (Princeton): *What do GW150914 and GW151226 tell us about extreme gravity?*
Advanced LIGO's recent discovery of the direct detection of gravitational waves from binary black hole coalescences allow us to probe gravity, for the first time, in extreme gravity where the field is both strong and dynamical. In this talk, I will describe how well GW150914 and GW151226 probe fundamental pillars of General Relativity, such as the equivalence principle. I will then explain current limitations of probing extreme gravity with gravitational wave observations and discuss what needs to be done in future.

Sarah Ballard (MIT): *The Grand Planetary Ensemble: Using Kepler Statistics to Understand the Formation and Atmospheres of M Dwarf Planets*
The Solar System furnishes the most familiar planetary architecture: many planets, orbiting nearly coplanar to one another. However, the most common planetary systems in the Milky Way orbit much smaller M dwarf stars, and these may present a very different blueprint. The Kepler data set has furnished more than 100 exoplanets orbiting stars half the mass of the sun and smaller. Half of these planets reside in systems with at least one additional planet. The data much prefer a model with two distinct modes of planet formation around M dwarfs, which occur in roughly equal measure. One mode is one very similar to the Solar System in terms of multiplicity and coplanarity, and the other is very dissimilar. Given this so-called "Kepler Dichotomy," we examine the broadband transmission spectra (with data from Kepler and hundreds of hours of Spitzer observations) of dozens of M dwarf planets: half of which reside in one type of planetary system, and half in the other. Although the data set is too small and the observational uncertainty too large to characterize any one system alone, we examine ensemble trends between planetary dynamics and atmospheric content.

Maria Petropoulou (Purdue): *Probing cosmic ray particle acceleration in radio supernovae*
I will present model predictions about the radio light curves and spectra that can serve as diagnostics for the acceleration of cosmic rays at shocks of interaction-powered supernovae (SNe). These are associated with an unusually dense circumstellar medium (CSM) and have been only recently observed at radio frequencies. Their radio emission is powered by relativistic electrons that can be either accelerated at the SN shock (primaries) or injected as a by-product (secondaries) of inelastic pp collisions. The temporal evolution of the radio emission is expected to depend on the origin of the radiating electrons. For a SN shock propagating through the progenitor wind, the secondary electrons control the early radio signatures, whereas primary electrons power the radio emission at later times.

Friday, September 2, 2016 — Afternoon

Gongjie Li (Harvard): *Interaction Cross Sections and Survival Rates for Proposed Solar System Member Planet Nine*

Motivated by the report of a possible new planetary member of the solar system, this work calculates cross sections for interactions between passing stars and this proposed Planet Nine. Evidence for the new planet is provided by the orbital alignment of Kuiper belt objects, and other solar system properties, which suggest a Neptune-mass object on an eccentric orbit with a semimajor axis $a_9 \approx 400–1500$ au. With such a wide orbit, Planet Nine has a large interaction cross section and is susceptible to disruption by passing stars. Using a large ensemble of numerical simulations (several million) and Monte Carlo sampling, we calculate the cross sections for different classes of orbit-altering events: (A) scattering the planet into its proposed orbit from a smaller orbit, (B) ejecting it from the solar system from its current orbit, (C) capturing the planet from another system, and (D) capturing a free-floating planet. Results are presented for a range of orbital elements with planetary mass $m_9 = 10 M_\oplus$. Removing Planet Nine from the solar system is the most likely outcome. Specifically, we obtain ejection cross sections $\sigma_{int} \sim 5 \times 10^6$ AU^2 (5×10^4 au^2) for environments corresponding to the birth cluster (field). With these cross sections, Planet Nine is likely to be ejected if the Sun resides within its birth cluster longer than $\Delta t \gtrsim 100$ Myr. The probability of ejecting Planet Nine due to passing field stars is $\lesssim$3% over the age of the Sun. Probabilities for producing the inferred Planet Nine orbit are low ($\lesssim$5%).

Timothy "T.J." Rodigas (Carnegie DTM): *Breaking through the (Slow-Rotator) Speed Barrier: A Direct Method for Measuring Stellar V Sin i*

The projected rotational velocity, *V* Sin *i*, of a star is a proxy for rotation, which is an important physical property on par with stellar mass, radius, effective temperature, metallicity, and age. *V* Sin *i* is predominantly measured by comparing the widths of observed stellar absorption lines with the theoretical lines of model rotating stars. This method works well for fast-rotators (*V* Sin *i* > 2 km/s). However, the method is inaccurate for slow-rotators like the Sun. Because such stars are becoming the favored targets of current radial velocity (RV) and transit searches for Earth-like exoplanets, *V* Sin *i* is likely to remain ambiguous for many interesting exoplanet hosts. We have developed a novel method to directly measure *V* Sin *i* using high-resolution echelle slit spectroscopy. Because our method is direct, it makes no use of complicated stellar models and is not limited by the level of macroturbulent velocities on the stellar surface. Therefore there is no velocity threshold precluding the measurement of *V* Sin *i*. I will describe how the method works and discuss its future applicability to exoplanet and stellar astrophysics. I will also present new VLT/UVES data acquired for the purposes of testing the technique. If verified, the technique will offer a cheap and accurate method for measuring *V* Sin *i* on hundreds of nearby slowly-rotating Sun-like stars.

Nicholas Stone (Columbia): *Rates of Stellar Tidal Disruption*

Stars are tidally disrupted in galactic nuclei when they are perturbed onto low angular momentum orbits that bring them dangerously close to supermassive black holes. After the star is torn apart by tidal forces, the debris rains back onto the black hole; these tidal disruption events (TDEs) power multiwavelength flares comparable in luminosity to the brightest supernovae. As our observational sample of TDEs has grown, two parallel dilemmas have emerged. On the one hand, observationally inferred TDE rates are one to two orders of magnitude below those predicted semi-empirically by dynamical modeling of nearby galactic nuclei. On the other hand, an order unity fraction of observed TDEs reside in rare E+A galaxies; this post-starburst galaxy type makes up a mere ~0.1% of low redshift galaxies, hinting at exotic dynamical processes in their nuclei that enhance the TDE rate by orders of magnitude. I will discuss my recent and ongoing theoretical and observational work aimed at resolving these discrepancies.

Courtney Dressing (Caltech): *Characterizing Planetary Systems Orbiting Low-mass Stars*
The NASA K2 mission has detected dozens of planet candidates orbiting moderately bright low-mass stars. Some of these candidates are potentially exciting targets for subsequent atmospheric characterization, but the initial properties of many K2 systems are poorly constrained due to uncertainties in the host star parameters. We are improving the characterization of K2 planetary systems orbiting low-mass stars by using SpeX on the NASA Infrared Telescope Facility and TripleSpec on the 200-inch Hale Telescope at Palomar Observatory to acquire near-infrared spectra of K2 target stars. We then employ empirically-based relations to determine the temperatures, radii, metallicities, and surface gravities of K2 planet candidate host stars. Refining the stellar parameters allows us to identify astrophysical false positives and improve our estimates of the radii and insolation flux environments of the bona fide transiting planets. I will present our resulting catalog of stellar properties and discuss the prospects for studying the atmospheres of the associated planets in more detail with the Hubble Space Telescope, the James Webb Space Telescope, and the next generation of extremely large ground-based telescopes.

Andreas Kuepper (Columbia): *Exploding Satellites – The Tidal Debris of the Ultra-Faint Dwarf Galaxy Hercules*
The ultra-faint satellite galaxy Hercules has a strongly elongated and irregular morphology with detections of tidal features up to 1.3 deg (3 kpc) from its center. This suggests that Hercules may be dissolving under the Milky Way's gravitational influence, and hence could be a tidal stream in formation rather than a bound, dark-matter dominated satellite. Using Bayesian inference in combination with N-body simulations, we show that Hercules has to be on a very eccentric orbit (ecc ~ 0.95) within the Milky Way in this scenario. On such an orbit, Hercules "explodes" as a consequence of the last tidal shock at pericenter 0.5 Gyr ago. It is currently decelerating towards apocenter of its orbit with a velocity of V = 157 km/s – of which 99% is directed radially outwards. Due to differential orbital precession caused by the non-spherical nature of the Galactic potential, its debris fans out nearly perpendicular to its orbit. This explains why Hercules has an elongated shape without showing a distance gradient along its main body: it is in fact a stream that is significantly broader than it is long. In other words, it is moving perpendicular to its apparent major axis. In this scenario, the dominant debris component that formed throughout the last pericenter passage shows a spike in the radial velocity profile, similar to kinematic substructure observed for Hercules. Modeling a satellite on such a highly eccentric orbit is strongly dependent on the form of the Galactic potential. We therefore propose that detailed kinematic investigation of Hercules and other exploding satellite candidates can yield strong constraints on the potential of the Milky Way.

Diana Dragomir (MIT): *Small Planets Transiting Bright Stars*
The number of known transiting planets has increased manyfold in the years since Kepler was launched, mainly thanks to the abundant harvest delivered by the mission itself. Statistical analyses of the planets discovered by Kepler and K2 indicate that smaller

planets are more common than large ones. Exoplanets with radii between 1 and 4 Earth radii are of particular interest because they constitute a class of objects which are not represented in our Solar System. Moreover, they can theoretically have a wide range of compositions. Studies based on Kepler data have revolutionized many areas of exoplanet research, but tight constraints on the radii and masses of small planets – essential for understanding their formation, evolution and composition – are only possible for exoplanets transiting bright stars. The launch of TESS will significantly increase the number of known small exoplanets with bright host stars, which will be amenable to a variety of follow-up observations. In this talk, I will review the state of knowledge for the handful of such exoplanets that are currently known. I will then discuss how TESS will improve our knowledge of small exoplanets by enabling a rigorous exploration of trends between their density, composition, orbital parameters and the properties of the host star.

Chiara Mingarelli (Caltech): *The Gravitational-Wave Universe seen by Pulsar Timing Arrays*
Pulsar Timing Arrays (PTAs) are currently the only way to search for gravitational radiation in the nanohertz band. Sources of interest include gravitational wave (GW) backgrounds generated by supermassive black hole binaries (SMBHBs) and processes in the early universe such as relic GWs and cosmic strings. Limits on the GW background continue to improve, and searches of increasing sensitivity are ongoing. Here I will discuss recent limits on the stochastic GW background, how we can characterize the stochastic GW background from SMBHBs on any angular scale to search for anisotropy, and how environmental interactions with SMBHBs affect the GW strain spectrum, and thus become observable. I then discuss how PTAs can place limits on the amplitude of the relic GW background and may eventually be a valuable tool for cosmology by providing independent constraints on the tensor-to-scalar ratio "r", and the spectral index of the tensor fluctuation spectrum "n_t". Finally, I present recent NANOGrav limits on cosmic string tension, which are a factor of 4 more constraining than the Planck (2014) results.

James Guillochon (Harvard-Smithsonian CfA): *An Open Catalog of Supernova Data*
The Open Supernova Catalog is a new webpage with a collection of published observations and metadata for presently 36,000+ supernovae (SNe) and SNe candidates. The catalog is freely available on the web (http://sne.space), with its main interface having been designed to be a user-friendly, rapidly-searchable table accessible on desktop and mobile devices. In addition to the primary table which contains SNe metadata, an individual page is generated for each SN which displays its metadata, light curves, and spectra. The data presented in the catalog is automatically rebuilt on a daily basis and is constructed by parsing several dozen sources, including the data presented in the supernova literature, i.e. "primary" sources, and from "secondary" sources such as other web-based catalogs. Individual SN data is stored in the hierarchical, human- and machine-readable JSON format, with the entirety of each SN's data being contained within a single JSON file bearing its name. The setup I'll present, which is based upon open source software maintained via git repositories hosted on GitHub, enables anyone to download the entirety of the supernova dataset to their home computer in minutes, and to easily make contributions of their own data back to the catalog. I'll describe how the catalog framework we have developed will be an important pillar for supporting upcoming transient surveys.