SMG20 - Twenty years of Submillimetre Galaxies
Star-forming galaxies at high redshifts

31st July – 2nd August 2017

Monday 31th July

Session 1

Loretta Dunne
Cardiff

"Results from Herschel on galaxy formation and evolution"
Review talk covering results from Herschel on galaxy formation and evolution.

James Geach
University of Hertfordshire

"The SCUBA-2 Cosmology Legacy Survey and beyond"
The SCUBA-2 Cosmology Legacy Survey (S2CLS) is the largest 850 μm survey to date, detecting 1000's of sub-mm sources over about 5 square degrees and providing exceptionally deep 450+850 μm maps in several extragalactic fields. It is enabling detailed studies of the SMG population and feeds directly into ALMA follow-up programmes. Now complete, I will present an overview of S2CLS and highlight some of the key science results so far. I will conclude with a look to the future of large ground-based sub-mm surveys, in particular what could be achieved with a new large single dish located on the Chajnantor Plateau.

Scott Chapman
Dalhousie University

"Identifying the brightest galaxies in the SCUBA-2 Cosmology Legacy Survey"
Using the SMA and complemented by ALMA in the UDS, we have identified the 120 brightest SCUBA-2 sources in the SCUBA-2 Cosmology Legacy Survey. This consists of all sources with $S_{850\mu m} > 9$ mJy, and includes several unlensed sources with single component fluxes close to 20 mJy. Previous studies have had little statistical constraint on the true bright end count, and therefore on the properties of these maximal star formers. Spectroscopic surveys with Keck, Gemini, and VLT have measured redshifts and line properties for about 30% of these sources. Understanding the details of these "brightest starbursts in the universe" is a legacy to the original discovery of the SMG population, and will continue to provide important laboratories for studying the extremes of star formation and the growth of the most massive galaxies.

Steven Duivenvoorden
University of Sussex

"Red, redder, reddest: SCUBA-2 imaging of colour-selected Herschel sources"
We present follow up observation of red *Herschel* sources in the *Herschel* Multi-tiered Extragalactic Survey (HerMES) Large Mode Survey field (274 deg^2). These are likely to be high-redshift, dust-obscured, star-forming galaxies (DSFG). With the addition of new longer wavelength observations with SCUBA-2 we now have an accurate probe of the peak of the far-infrared emission, and therefore a significant improvement in the far-infrared luminosities and photometric redshift estimates. We use a novel way to incorporate the confusion noise in our SED fitting, by adding correlated randomly selected flux-density measurements from a confusion limited map to our sample flux density. We construct a new catalogue of redshifts and star-formation rates of 188 red DSFGs from the parent catalogue of 477 *Herschel* red objects. Our objects have $z > 3$ with a mean star-formation rate of 4×10^3 $M_\odot$ yr^{-1} and fall in the HyLIRG regime. Our sample represents the most extreme star formation events in the history of the Universe and provides important constraints on the extremes of galaxy formation mechanisms. We compare the number densities of the objects with predictions from galaxy formation theories. We find a significant excess of WISE and SDSS sources near our galaxy sample, giving a strong indication that lensing contributes to the extremely high Luminosities.

Session 2

Kotaro Kohno

IoA, Tokyo

"Multi-wavelength surveys of dusty star-forming galaxies using AzTEC, SCUBA2, Subary and ALMA"

Review talk covering results on galaxy formation and evolution from large-scale FIR/submm surveys and the synergies with Subaru surveys of the high-redshift Universe

James Simpson

ASIAA; EACOA Fellow

"S2COSMOS; an ongoing survey to uncover >1000 sub-mm sources in COSMOS"

The S2COSMOS survey is an on-going large project at the EAO–JCMT that has mapped the COSMOS field to ~ 1.2 mJy rms at 850 μm with SCUBA-2. I will present the initial results from the survey, which we expect to be completed in the coming months. These results with include basic properties of the observations (catalog, counts, etc) along with preliminary results from our clustering and stacking analysis of the SCUBA2 imaging.

Wei-Hao Wang
ASIAA

"STUDIES (SCUBA-2 Ultra Deep Imaging EAO Survey) Current Status and Results"

STUDIES is a 330-hr JCMT Large Program, aiming for a confusion limited 450 μm map in the COSMOS-CANDELS area for the studies of the high-z dusty galaxy population. In this talk, we will report the results derived from the data taken in 2015/2016 (140 hr). The SCUBA-2 daisy map has an rms noise of ≤ 0.9 mJy at its center, with 140 sources detected $> 3.5\sigma$ over ~ 150 arcmin^2. Nearly all $> 4\,\sigma$ sources (98) have MIPS and IRAC counterparts. They have a broad redshift distribution between $z = 0.5$ and 3.0, with a median of 1.5. The faintest ones at $z \sim 1$ have IR luminosities slightly above $10^11\,L_\odot$. The 450 μm source counts derived with $> 4\,\sigma$ sources and fluctuation analyses are consistent with a single power law between 1 and 20 mJy and show no evidence of a faint-end turn-over. Our integrated surface brightness down to 1 mJy can account for 35% to 45% of the CIB measured by *COBE* and *Planck*, implying a substantial population at < 1 mJy. On the other hand, the STUDIES field seems slightly under-dense with > 3 mJy sources and all existing counts at 1 mJy still have large error bars. The final 330-hr version of the STUDIES map should help to better pin down the unresolved fraction below 1 mJy.

Drew Brisbin
Universidad Diego Portales

"An ALMA survey of SMG redshift distributions and the effect of survey depth"

We carried out targeted ALMA observations of 129 fields in the COSMOS region at 1.25 mm, detecting 152 galaxies at S/N ≥ 5. These fields represent a S/N-limited sample of AzTEC/ASTE sources over an area of 0.72 square degrees. Given ALMA's fine resolution and the exceptional spectroscopic and multiwavelength photometric data available in COSMOS, this survey allows unprecedented power in identifying submillimeter galaxy counterparts and determining their redshifts through spectroscopic or photometric means. We have identified redshifts for 143 galaxies through photometric and spectroscopic. This allows a statistically robust determination of the redshift distribution, free of many of the selection biases and small number statistics prevalent in prior surveys. Our overall redshift distribution peaks at $z \sim 2.0$ with a high redshift tail skewing the median redshift to $z = 2.47 \pm 0.05$. We find that brighter millimeter sources are preferentially found at higher redshifts. Our faintest sources, with S(1.25 mm) < 1.25 mJy, have a median redshift of $z = 2.2 \pm 0.1$, while the brightest sources, S(1.25 mm) > 1.8 mJy, have a median redshift of $z = 3.1 \pm 0.2$. After accounting for spectral energy distribution shape and selection effects these results are consistent with several previous submillimeter galaxy surveys, and moreover, support that redshift distributions must be interpreted in context with survey depth.

Maciej Koprowski

University of Hertfordshire

"IR Luminosity Function & Star Formation Rate Density at $z = 0.5 - 4.5$ from SCUBA-2 and ALMA"

The Luminosity Function (LF) is a powerful tool, allowing the assessment of statistical properties of a given galaxy population, the most important of which is the star formation rate density (SFRD). While in the rest-frame UV the LFs of galaxies have been measured out to $z \sim 10$, in the IR/(sub)mm the relatively low resolution of the single-dish telescopes means that only a few attempts have been made at redshifts > 1. In this talk I will present the new measurements of the IR LF made using a combination of SCUBA2 CLS and ALMA HUDF data. The SCUBA2 850 μm selection waveband allowed us to probe around the peak of the SFRD in the Universe, while the ALMA data, with the rms noise of only $\sim 30\,\mu$Jy, was used to establish for the first time the faint-end slope of the IR LF at high-z. I will describe how the continuous form of the redshift evolution of the IR LF was found and hence how the cosmic evolution of the SFRD was established between $z = 0.5 - 4.5$.

Darko Donevski

LAM, Laboratoire d'Astrophysique de Marseille, France

ZZZ Unveiling High-z Dusty Galaxies In The HeViCS Field"

Selection of *Herschel* sources whose thermal SED peak shifts to wavelengths longer than 500 microns (so-called "FIR-risers") is a widely used method to detect potentially $z > 4$ dusty galaxies. To build statistically significant sample of "FIR-risers" we consider one of the largest *Herschel* surveys, the *Herschel* Virgo Cluster Survey (HeViCS, Davies et al. 2010). It covers the area of 55 deg^2 with a high sensitivity, higher than the one reached in the large fields previously used to detect "FIR-risers" such are H-ATLAS or HeLMS. We implemented a new selection technique to find these very red, dusty galaxies, combining de-blending and SED fitting of sources detected in 250 μm maps, and modelling the spectral emission of each source as a modified blackbody (Donevski et al. 2017, in prep). We got a final sample of 133 "ĂIJFIR-risers" reaching a reasonable good agreement with evolutionary models (e.g. Bethermin et al. 2012, Schreiber et al. 2016). It challenges previous studies in other *Herschel* fields (e.g. Asboth et al. 2016) which claimed under-prediction of the number of "FIR-risers" by the models. We are now working on associated very deep optical data to better characterise selected population of sources.

Joshua Greenslade

Imperial College London

"Understanding the population of the highest redshift SMGs: Selection, confirmation, and optical counterparts from SERVS."

SMGs are conspicuously difficult to obtain redshifts for; fluxes can't be used as a prior owing to their negative k-correction, there exists a strong degeneracy between dust temperature and photo-zs, and typical FIR + Sub-mm beamsizes are large enough that high redshift SMGs often have upwards of 5 optical candidate counterparts. This last point is exacerbated when considering that HDF 850.1, one of the first SMGs identified, took almost 20 years to identify the correct optical counterpart; the optical source is not detected in the Hubble deep field! Here we present the results of a large SMA follow up program designed to identify the nature of 500 *mu*m risers, expected to lie at $z > 3$. With the number of sources examined in the tens, we are beginning to shift from understanding the nature of individual high redshift SMGs to the population as a whole. However, undertaking such a program for all the 500*mu*m risers would be costly, hence we also present a novel way to identify the optical counterparts to SMGs by combining optical/NIR photo-z measurements. Finally, we present a potentially even higher redshift ($z > 4$) SMG, selected by combining *Herschel* with SCUBA-2 to search for the reddest (F850 > F500) SMGs.

Tom Bakx

Cardiff University

"HerBS sample: Expanding current lensed SMG samples"

We present the *Herschel* Bright Sources (HerBS) - a sample of bright, high-redshift sub-mm galaxies selected from the 616.4 square degree H-ATLAS survey. The HerBS sample contains 209 galaxies, selected with a 500 μm flux density greater than 80 mJy and an estimated redshift greater than 2. The sample consists of a combination of HyLIRGs and lensed ULIRGs during the peak of cosmic star formation. Our aim is to extend the search for lensed galaxies in *Herschel* surveys, while keeping the contamination rate of local galaxies and blazars low. We try to achieve this by lowering the cut-off flux density, which increases the surface density of lensed sub-mm sources by between 60 and 200 per cent compared to previous studies. We keep the contamination low by imposing that SPIRE -colours are consistent with a redshift greater than two. We used SCUBA-2 observations in order to remove blazar contaminations, further reduce the uncertainty on the photometric redshift and acquire estimates on the effect of source multiplicity. We will present the results of these observations, together with the cross-identification of our sources in optical and near-IR studies of all fields, which allow us to determine the proportions of lensed ULIRGs and unlensed HyLIRGs in our sample.

Hao-Yi Wu
California Institute of Technology

"Physical and empirical models of SMGs and cosmic far-infrared background"
The anisotropies of cosmic far-infrared background (CFIRB) probe the unresolved dusty star-forming activities across cosmic time and are highly complementary to the observations of SMGs. In this talk, I will present physical and empirical models for interpreting both SMGs and CFIRB, and I will discuss the implications for cosmic star-formation history, dust-production history, and the connection between galaxies and dark matter halos. I will also present the optimal observational strategies for constraining the cosmic star-formation history for future ground-based and space-based facilities.

David L. Clements
Imperial College London

"HERUS: A *Herschel* Survey of low redshift SMGs"
Ultraluminous Infrared Galaxies at $z < 0.2$ have long been regarded as the low redshift baseline for studying redshift evolution among obscured starbursts. Comparisons with SMGs allow us to determine how starbursts have changed across the history of galaxy evolution. ULIRGs can be studied in far greater detail than SMGs and can provide insights into the more distant population that are otherwise unobtainable. HERUS is the largest *Herschel* survey of low redshift ULIRGs, providing spectroscopic and photometric data for a complete sample of 43 IRAS 60 micron selected ULIRGs. The data includes PACS spectroscopy of specific fine-structure lines, SPIRE FTS line surveys and SPIRE photometry, with complementary data from the SHINING survey for some objects. Studies made possible by this work include characterisation of AGN-driven outflows from OH profiles, scalings between emission lines and star formation rate, the origin of CO excitation, and details of dust SEDs, as well as identifying the most luminous galaxy in the local ($z < 0.2$) universe.

Laia Barrufet
RAL Space / Open University

"High-z population at the NEP"

The discovery of the high redshift sub-mm galaxy (SMG) population posed critical questions on the evolution of galaxies in the early Universe. Advances over the last 20 years have expanded this population from dozens to thousands, especially with *Herschel* and SCUBA-2 data. Chasing the redshifts of this population has meant either large samples with photometric redshifts at $z > 4$, focusing on the far-infrared peak for SED fitting; or extreme cases at $z > 6$ of single sources with spectroscopic detections. In order to fully understand and characterise the submillimetre populations a large sample of SMGs with full spectral coverage is required. We present a thorough study of 200 SMGs, in the North Ecliptic Pole field, over the range $2 < z < 6$ with full photometric coverage from optical to radio wavelengths - from SUBARU, AKARI, *Herschel*, SCUBA-2 and WSRT (together with optical spectroscopic redshifts). By using the infrared data from AKARI we are able to find the correct optical counterpart and by making use of SED fitting we have calculated stellar and dust masses, star-formation rate (SFR) allowing a detailed study of this sample regarding their location on the main sequence (MS) of galaxy evolution. We discover a subset of sources with high SFR that falls clearly above the MS, which will be the object of a spectroscopic study.

Session 3

Bunyo Hatsukade
The University of Tokyo

"Number counts of submillimeter sources revealed with ALMA surveys."

SMGs are dusty starburst galaxies at high redshifts. In the previous studies of SMGs with single-dish surveys, it is possible that multiple sources were counted as a single SMG due to the coarse angular resolution ($\sim 15''$–$30''$), which could produce "wrong" number counts. ALMA enables us to study SMGs with high angular resolution ($< 1''$), and to explore the flux regime more than an order of magnitude fainter than in previous single-dish surveys. We performed ALMA 1.1 mm (band 6) imaging of 300 bright sources detected in our AzTEC 1.1 mm surveys. I present the results and number counts at bright end. I also present the results on ALMA deep surveys in SXDS and GOODS-S fields.

Alejandra M. Muñoz Arancibia
Instituto de Fisica y Astronomia, Universidad de Valparaiso

"Lensing-corrected 1.1mm number counts in the ALMA Frontier Fields Survey"

We present galaxy number counts around three strong-lensing galaxy clusters as part of the ALMA Frontier Fields Survey. This aims to characterize the population of faint, dusty star-forming galaxies at high redshift, benefiting from the magnification power of the clusters. Our study combines the analysis of deep (rms $\sim 55 - 71\,\mu$Jy/beam) ALMA 1.1 mm continuum data over $\sim$ 4.6 square arcmin, introduced by Gonzalez-Lopez et al. 2016, with gravitational lensing models produced by different groups. We compare our results with current number counts estimates available in the literature.

Desika Narayanan
University of Florida

"The Theory of Forming Submillimetre Galaxies at High Redshift: Challenges and Successes"

I will present a review of the last two decades of theoretical efforts in modeling this enigmatic and frustrating galaxy population. I will cover the progress made by Semi Analytic Models, Cosmological Hydrodynamic Simulations, Idealized Models, and Zooms. I will conclude with a summary of the successes thusfar, and the (many) challenges yet to be met.

David Hughes
Large Millimeter Telescope / INAOE

"The Large Millimeter Telescope: Status and Early Science'

The Large Millimeter Telescope (LMT) Alfonso Serrano is a bi-national (Mexico & USA) telescope facility operated by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) and the University of Massachusetts (UMASS). The LMT is designed as a 50-m diameter single-dish millimeter-wavelength telescope, optimized to conduct scientific observations at frequencies between ~ 70 and 350 GHz. The LMT is constructed on the summit of Sierra Negra at an altitude of 4600 m in the Mexican state of Puebla. The site offers excellent mm-wavelength atmospheric transparency all-year round, and the opportunity to conduct submillimeter-wavelength observations during the winter months. The LMT began limited scientific operations in 2014 with a shared-risk Early Science observing program using the inner 32 m diameter of the primary reflector with an active surface control system. The LMT has also performed successful VLBI observations at 3mm with the High Sensitivity Array and at 1.3 mm as part of the Event Horizon Telescope. The LMT will enter full scientific operations as a 50 m diameter telescope in early 2018, making it the world?s largest single-dish telescope operating at 1.1 mm. I will describe the current status of the telescope project, including the early scientific results, as well the instrumentation development program, the plan to improve the overall performance of the telescope, and the on-going transition towards the formation of the LMT Observatory to support the scientific community in their use of the LMT to study of the formation and evolution of structure at all cosmic epochs.

Cristina Garcia-Vergara
Leiden Observatory

"Clustering of submillimeter galaxies"

The clustering of submillimeter galaxies (SMGs) provide information about the mass of dark matter halos where SMGs reside. This is an essential quantity that can be used to i) constrain theoretical models about the nature of SMGs, and ii) test the evolutionary sequence of these sources, in which they are usually linked with high-z quasars and low-z massive elliptical galaxies. Past studies have attempted to measure this clustering, using sources detected with single-dish telescopes, and claiming a strong auto-correlation. However, the latest ALMA observations of SMGs showed that the counterparts of many of them used in those studies were previously mis-identified, and some of them composed of multiple fainter galaxies, implying that the clustering measurement could be incorrect and probably significantly overestimated. Here, I present the measurement of the corrected SMG clustering, computed using precise spectroscopic redshift information of 52 SMGs recently identified by ALMA. I discuss the implications of the strength of this clustering on our current understanding of SMGs and I show what this measurement suggest about using SMGs as tracers of particularly massive structures in the early universe.

William Pearson

SRON Netherlands Institute for Space Research

"The Main Sequence of Star Forming Galaxies Beyond *Herschel*'s Confusion Limit"

Herschel far infrared (FIR) deep cosmological surveys are known to suffer from source confusion and blending. Infrared (IR) emission provides information on star formation rates (SFRs) via thermal dust emission, which peaks in the FIR. Thus, to gain the best constraints on the IR emission, and hence the SFR, it is necessary to de-blend the deep *Herschel* images. A recent de-blending tool is XID+, which uses a Bayesian approach to extract flux densities for all objects in a prior source list. We have modified XID+ to introduce a Gaussian prior for each object, derived from the fitting of multi-wavelength data to spectral energy distributions. The result is a statistically more reliable extracted flux density for each object and hence a more reliable IR luminosity and SFR. We use these results to examine the main sequence of star forming galaxies (MS), a tight correlation between the SFR and stellar mass, from $z = 0$ to 6 in the COSMOS field. This allows us to trace how the MS has evolved over this period and link the high redshift, star-forming universe with the local universe. This poster briefly presents the new XID+ prior along with the results of the examination of the MS.

Eric Faustino Jiménez-Andrade

Argelander Institute for Astronomy, University of Bonn

"Size evolution of star forming galaxies in the COSMOS field"

In order to constrain the physical mechanism which drives galaxy evolution we are probing trends for global star forming sizes and their evolution as a function of distance to the galaxy main sequence over the redshift range ($0 < z < 2$). We profit from the JVLA map at 3GHz (2×2 degs, $0.75''$ resolution, rms= 2.3 mJy/beam) to estimate the SFR and intrinsic size of $\sim$ 1500 resolved SFGs in the COSMOS field. Structural measurements, e.g. FWHM, are obtained through a 2D Gaussian fitting routine with pyBDSM. At all epochs we find that typical SFGs on the main sequence are larger than starburst galaxies. Overall, the size of SFGs smoothly decreases with time, having at least 2 times more compact radio sizes in the local universe than those at $z \sim 2$. By comparing the extent of the radio emitting region and the optical size we also discuss our results in terms of the inside-out growth theory of galaxy evolution.

Fangxia An
Durham/PMO

"A machine-learning method for identifying multi-wavelength counterparts of submillimeter galaxies"

We develop a machine-learning method to identify multi-wavelength counterparts of submillimeter galaxies (SMGs) bases on 712 ALMA-detected SMGs and rich ancillary data in the UKIDSS-UDS field. By utilizing high-resolution ALMA sources and their near-infrared (NIR) counterparts, we build a training set that includes the photometric redshift, absolute H-band magnitude, three NIR colors (J-K, K-[3.6], [3.6]-[4.5]) of both SMGs and no-SMGs within ALMA primary beams. We use the scikit-learn machine-learn code to "learn" the discrepancies between SMGs and no-SMGs. To test the effectiveness of our method, first, we do a self-test of the training sample. Our machine-learning method can successfully recover 78% of SMGs and the accuracy of the identification could reach to $\sim$ 80%, which are both higher than previous methods in the literature. By combining the radio identification and the machine learn results, the recovery rate increases to $\sim$ 87% with a slight decrease of accuracy ($\sim$ 76%). We find that the different observation depth of NIR data will reduce the recovery rate about 15% of the machine-learn method by applying the machine-learn method to ALESS sample in ECDFS. Fortunately, by combining the radio identifications, the total recovery rate of SMGs is still $>$ 80% which confirms that our method can successfully identify the multi-wavelength counterparts for SMGs with either high-resolution (ALMA-detected) or low-resolution (FWHM$\sim$ 15 arcsec, detected by single-dish). The accurate identification of multi-wavelength counterparts is crucial for studying the evolutionary cycle of SMGs and their evolutionary connections with other populations, like their proposed descendants: $z \sim 2$ QSOs; massive, red and dead galaxies at $z \sim 1-3$ and ultimately massive ellipticals at $z \sim 0$.

Patrick Drew
UT Austin

"Kinematics of DSFGs at $z \sim 1.5''$

We present a rest-frame optical kinematic analysis of five DSFGs at $z \sim 1.5$ using long slit spectroscopy obtained with Keck MOSFIRE. From our high signal-to-noise spectra we simultaneously fit Hα, [NII] λ6548, and [NII]λ6583 along each slit to generate position-velocity diagrams. We estimate physical parameters of the galaxies, such as dust masses, dynamical masses, and gas fraction in order to better-constrain the physics of extreme star formation in the early universe.

Alasdair Thomson

Durham

"The complex multi-frequency radio properties of ALMA-identified z>2 starburst galaxies"

In this talk, I will present multi-frequency radio observations from GMRT at 610 MHz and JVLA at 1.4 GHz and 6 GHz (probing rest-frame $\sim$ 2 GHz, $\sim$ 4 GHz and $\sim$ 20 GHz, respectively) of a sample of ALMA-identified submillimetre-selected starburst galaxies in the UDS field. Our high-frequency (6 GHz) radio observations probe a portion of the radio SED that ought to be dominated by free-free emission, with an angular resolution comparable to that of our ALMA observations ($\sim$ 0.3″), facilitating a direct comparison of the radio-emitting and dusty regions of these compact starbursts. We find the high-frequency radio sizes to be marginally more extended than the dust emission. Our three-band measurements give indications of curious steepening of the radio SEDs toward higher frequencies, in apparently conflict with the classical picture in which a growing fraction of the flux at high frequencies ought to come from (flatter-spectrum) free-free emission. At the same time, our 1.4 GHz observations appear to marginally resolve the emission on $\sim$ 1″ scales, roughly twice as large as their high-frequency (and dust continuum) sizes. I will explore possible interpretations of this unexpected finding, including suppression of free-free emission (which could depress the high-frequency radio emission) as well as boosting of the flux at low-frequencies due to the inclusion of flux not associated with the ongoing starburst, and will discuss the ways in which forthcoming radio surveys (e.g. eMERGE) will inform our interpretation of these curious systems.

Yiping Ao

National Astronomical Observatory of Japan

"Deep submm and radio observations towards the LABs in SSA22"

Using the submm data from JCMT/SCUBA-2 observations together with ALMA archival data, we have recently identified dust continuum sources in 11 out of 35 LABs in SSA22. With the VLA, we have detected radio counterparts in 9 out of 29 LABs. Spectroscopic data also support that these radio counterparts are associated with the LABs. The detection of submm/radio counterparts in the LABs reveals that the linear size instead of Lyman-α luminosity is a good indicator of the embedded source in a LAB. The submm detected LABs with X-ray counterparts have the radio to submm derived SFR ratios above 2.5, and in total 7 out of 10 LABs have the ratios larger than 2.5, suggesting the relative radio excess in these submm/radio detected LABs is common. Most LABs without X-ray counterparts are located in the centers of the LABs, supporting that the star formation model may dominate the powering sources and be consistent with the theoretical model for star-forming galaxies. However, it is surprising that all X-ray counterparts are not located in the center of LABs. It might be explained if the X-ray sources are always associated with merging systems which re-distribute the intergalactic medium to inhomogeneous morphology. The low escaping fraction of Lyman-α photons found in SSA22 may be due to high dust attenuation. We find that the escaping fraction of Lyman-α photons increases with the Lyman-α luminosity, which contradicts to the previous study. We suspect that this large difference is due to the high dust attenuation supported by the large SFRs as well as the large-scale environment in the dense regions in SSA22.

Session 4

Amy Barger
University of Wisconsin-Madison

"Dusty Star Formation in the Distant Universe"

I will review what we know about the formation and evolution of dusty star-forming galaxies detected in the submillimeter, their multiwavelength properties, and their connection to other populations, including radio and X-ray.

Aaron Wilkinson
University of Nottingham

"The Clustering of High-Redshift Submillimetre Galaxies; are they the Progenitors of Massive Elliptical Galaxies?"

Submillimetre galaxies (SMGs) are among the most luminous dusty galaxies in the Universe, but their true nature remains unclear; are SMGs the progenitors of the massive elliptical galaxies we see in the local Universe, or are they just a short-lived phase among more typical star-forming galaxies? To explore this problem further, we investigate the clustering of 914 SMGs identified in the coincident area of the SCUBA-2 Cosmology Legacy Survey and the UKIDSS Ultra Deep Survey (UDS). Using angular cross-correlation techniques, we estimate the halo masses for the largest sample of SMGs to date and compare them with passive and star-forming galaxies selected in the same field. I demonstrate that SMGs, on average, occupy high-mass ($M > 10^{13}\,\mathrm{M}_\odot$) dark matter halos at redshifts $z > 2.5$, consistent with being the progenitors of massive quiescent galaxies in present-day galaxy clusters. I will also show evidence of downsizing, in which SMG activity shifts to lower mass halos at lower redshifts. In terms of their clustering and halo masses, SMGs appear to be consistent with other star-forming galaxies at a given redshift. Finally, I will discuss the clustering of a rare population of recently quenched galaxies, known as post-starburst galaxies (PSBs). We have recently identified a large sample of these galaxies in the UDS using a PCA technique. I will present tentative evidence, based on their clustering properties, that these PSBs are possible descendants of SMGs.

Wiphu Rujopakarn

Kavli IPMU

"ALMA and JVLA imaging of intense galaxy-wide star formation in $z \sim 2$ galaxies in the HUDF: bridging SMGs to the Main Sequence"

We present $\sim 0.4''$ resolution extinction-independent distributions of star formation and dust in 11 main-sequence star-forming galaxies (SFGs) at $z \sim 2$. These galaxies are selected from deep ALMA and JVLA surveys of the Hubble Ultra-Deep Field at 1.3 mm and 5 cm. Morphological classification performed on spatially-resolved stellar mass maps indicates a mixture of disk and morphologically disturbed systems; half of the sample harbor X-ray AGN. We find that their intense star formation most frequently occurs at the location of stellar-mass concentration and extends over an area comparable to their stellar-mass distribution, with a median $r_e = 2.4$ kpc, thereby providing direct evidence of galaxy-wide star formation in $z \sim 2$ main-sequence SFGs. In X-ray AGN where radio emission is enhanced over the level associated with star formation, the radio excess pinpoints the AGN, which are found to be cospatial with star formation. The median extinction-independent size of main-sequence SFGs is $2\times$ larger than those of luminous SMGs, providing a constraint on the characteristic SFR of $\sim 300\,\mathrm{M}_\odot/\mathrm{yr}$ above which a significant population of more compact SFGs appears to emerge, possibly bridging the populations of SMGs to main-sequence SFGs.

Alexander Karim

AIfA Bonn/German ARC Node

"Rapidly spinning gas disks observed towards massive $z \sim 4.5$ red sequence progenitors"

The observed population of massive ($> 10^{11}\,\mathrm{M}_\odot$) and typically very compact quiescent galaxies at redshifts even above $z \sim 2$ demands a progenitor population of rapidly evolving star forming systems at even earlier cosmic epochs. Candidates may well be found among the recently established $z > 4$ tail of the SMG redshift distribution. Using $< 0.4''$ resolution ALMA band-7 and Hubble near-infrared imaging towards a small sample of such $z \sim 4.5$ sources found in the COSMOS field. I will discuss possible evolutionary pathways between these galaxy populations and their connection to very massive local elliptical galaxies. I will thereby discuss that the resolved kinematics from their [CII]158 μm emission indicate a very rapid Keplerian gas rotation around our sample of compact $z \sim 4.5$ starbursts.

Lichen Liang
University of Zurich

"Submillimeter flux as probe for molecular gas mass in high-z galaxies"

Recent long wavelength observations on the thermal dust continuum suggest that the Rayleigh-Jeans (RJ) tail can be used as a time-efficient quantitive probe of the dust and ISM mass in high-z galaxies. We use high-resolution cosmological simulations from the Feedback in Realistic Environment (FIRE) project to analyze the dust emission of galaxies with a broad range of masses at the Cosmic Noon ($z \sim 2-3$). Our simulations (MassiveFIRE) explicitly include various forms of stellar feedback, and they reproduce the stellar masses and star formation rates of high-z galaxies in agreement with observations. Using radiative transfer modeling we show that broadband sub-millimeter (sub-mm) flux and molecular gas mass are tightly correlated and that the overall normalization and slope are in quantitative agreement with observations. Our result supports the empirical approach of using sub-mm flux as a proxy for molecular gas content in high-z galaxies. However, we found that the scatter of this ratio, driven mainly by dust-molecular gas ratio in our simulations, appears to be smaller than the observed data, suggesting that further studies are needed to investigate the possible systematic uncertainties in observations. We also present the results of the $z = 2$ systems fainter than the current available observational sample for calibration as well as their younger progenitors. Future observations with ALMA may probe these regimes and lead to improved physical models of gas inflow and dust growth in high redshift galaxies.

Ana Trcka
Ghent University

"Submillimeter galaxies in the EAGLE suite of simulations"

In previous work (Camps et al. 2016, Trayford et al. submitted) we developed a procedure to calculate dust-attenuated and dust emission fluxes for galaxies in the EAGLE suite of cosmological simulations (Schaye et al. 2015), using the radiative transfer code SKIRT (Baes et al. 2011, Camps et al. 2015). We compared the results for a selection of simulated galaxies with observations in the Local Universe, finding good agreement in many areas. Employing the same post-processing procedure, we now have calculated dust-attenuated and dust emission fluxes in a wavelength range from UV to sub-mm for about 140 000 sufficiently resolved EAGLE galaxies at various redshifts up to $z = 6$. We plan to compare these synthetic observations of high-redshift EAGLE galaxies to observed galaxies. This study will include the properties of and the relevant scaling relations for star-forming galaxies at high redshifts. By the time of the workshop, we should have preliminary results available. While the ultimate aim is to improve our understanding of galaxy evolution, we hope at least to map the successes and limitations of our numerical models and to inform the design of future cosmological simulation projects. On a side note, we plan to add our dust-affected fluxes to the public EAGLE database. We will also invite third parties with access to the EAGLE simulation snapshots to calculate synthetic images and SEDs for EAGLE galaxies using our open-source post-processing procedure.

Chian-Chou Chen

European Southern Observatory

"A spatially-resolved study of cold dust, molecular gas, HII regions and stars on a $z = 2.123$ submillimeter galaxy ALESS67.1"

We present detail studies of a $z = 2.123$ SMG, ALESS67.1, using sub-arcsecond resolution ALMA, AO-aid SINFONI, and *HST*/CANDELS data to investigate the kinematics and/or spatial distributions of cold dust, CO(3-2), optical strong lines, and stars. Dynamical modelling of the optical lines suggests that ALESS67.1 is not an orderly rotating disk but mergers, consistent with the tidal features revealed in the *HST* imaging. Based on the position-velocity diagram the velocity structure of the optical lines, however, behaves differently from that of CO, such that optical lines show signs of rotation whereas CO resembles signatures of outflow and/or inflow. The sub-arcsecond resolution data allow us to measure half-light radius on all the tracers, and we find a factor of 4-6 smaller sizes in dust continuum compare to all the other tracers, including CO. While CO has a size comparable with Hα and 1.6 micron continuum, it peaks at the consistent location as cold dust but both significantly offset from Hα and 1.6 micron continuum. Assuming $\alpha_{CO} = 0.8$, we derive resolved gas and star-formation rate surface densities, and find that the core part of the galaxy (< 10 kpc) follows the trend of mergers on the Schmit-Kennicutt relationship, whereas the outskirts (> 10 kpc) lie on the locus of normal star-forming galaxies. The spatially mismatch between cold dust and UV continuum supports the postulation of geometrical effects regarding the offset of dusty galaxy on the IRX-beta diagram. Our results caution the usage of single tracer, as well as any modelling that assumes single size or morphology, and therefore argue the need to use spatially-resolved, multi-wavelength observations to interpret the properties of SMGs, and perhaps even for $z > 1$ galaxies in general.

Hugo Messias

Joint ALMA Observatory

"H1429-0028: a case for a lensed wet-dry major merger"

Today, the community has access to numerous confirmed strong-gravitationally-lensed systems appearing bright at (sub-)millimeter wavelengths. This owes to the technological and strategical improvements made in recent years. The current steps being taken are twofold, where both statistical and individual analysis are being pursued focused in this large sample. Here, I report on the latest developments on HATLAS J142935.3-002836 (aka, H1429-0028), which has so far been followed-up by a wide set of facilities covering the UV to the radio spectral regimes, also providing optical and sub-mm spectral observations. These enabled to derive physical properties such as stellar-, dynamical-, or molecular-gas masses, SFRs, or morphology. I will walk through the reasoning process which currently allows us to interpret the lensed system in H1429-0028 as a wet-dry 1:3 merger at $z = 1.027$. Given the detail one can have access to in H1429-0028, this system could well be adopted as a case study for pre-conditions giving origin to lenticular galaxies of dust-laned ellipticals.

Tuesday 1st August

Session 5

Paul van der Werf
Leiden Observatory

"Submillimetre galaxies and their local cousins: what have we learned?"
I will review what we have learned about distant submillimetre galaxies by studying their local "analogs", the ultraluminous infrared galaxies or ULIRGs. The focus will be on key diagnostics of the interstellar gas, accessible with *Herschel* in the local universe, and with ALMA out to very high redshifts. As with all analogies, the point where the analogy between SMGs and ULIRGs breaks down is at least as interesting as the analogy itself, and this will also be discussed. I will end with some key questions, which can be address observationally with present or upcoming instrumentation.

Allison Kirkpatrick
Yale University

"Why are Distant Dusty Galaxies Colder than Their Local Counterparts?"
At $z = 1 - 3$, the formation of new stars is dominated by massive, dusty galaxies whose far-IR emission indicates they are colder than their counterparts in the local Universe. This shift in spectral shape leads to a key question: Is there a fundamental change in the ISM of dusty star forming galaxies (DSFGs), so that $z > 1$ DSFGs have little in common with their present day counterparts? I explore the reasons for the evolving IR emission of similar galaxies over cosmic time using three large samples from $z = 0 - 2$. I find that despite similar infrared luminosities, $z > 0.5$ DSFGs have an order of magnitude higher dust masses. This increase in dust mass is linked with an increase in gas fractions with redshift, rather than with stellar mass. T(dust) is strongly correlated with L(IR)/M(dust), and the correlation is independent of redshift. I observe no obvious correlation between galaxy size or merger stage and T(dust). In DSFGs, the change in L(IR)/M(dust) can fully account for the colder dust temperatures at high redshift, suggesting that any evolution in the spatial extent of the ISM is a second order effect. Furthermore, a galaxy's global far-IR/submm emission alone cannot be used to distinguish between ISM geometries.

David Sanders

University of Hawaii

"New IR-Submm Spectral Energy Distributions for (U)LIRGs from *Spitzer*-WISE-*Herschel* Data"

New spectral energy distributions (SEDs) have been computed for the complete sample of 202 (U)LIRGs in the Great Observatories All-Sky LIRGs Survey (GOALS), using the latest *Herschel*-PACS/SPIRE, *Spitzer*-IRAC+MIPS24, and WISE12/22 photometry along with new *Spitzer*-IRS data. Previously published SED models for (U)LIRGs need to be significantly revised. We discuss how our updated SED models for (U)LIRGs affect inferred properties of SMGs at high redshift.

Steve Maddox

Cardiff University and Royal Observatory Edinburgh

ZZZ Revealing the inner secrets of BADGRS in the very local Universe"

We have identified a population of extremely blue galaxies with high gas fractions and remarkably strong sub-mm dust emission. This population of Blue And Dusty Gas Rich Sources (BADGRS) comprises $> 50\%$ of the galaxies in the *Herschel*-ATLAS local volume sample and so represents an important phase of galaxy evolution. We have observations from *Herschel*, VLA, ALMA, IRAM and KOALA. The Sub-mm and radio data giving information on the dust, HI and CO. The KOALA IFU data provide resolved metallicities, kinematics of ionised gas and stars, excitation conditions in the gas, dust attenuation and recent star formation histories. The observations of CO(1-0) reveal that their molecular ISM is very deficient with respect to their dust content, with $M_{H_2}/M_d \sim 10$. Intriguingly, unlike other gas rich galaxies with low CO content, these are not low metallicity galaxies; their central metallicities are $Z \sim 0.8Z_\odot$ and their M_d/M_* ratios are the highest of any known local population.

Session 6

Nick Scoville
Caltech

"Evolution of ISM and Accretion at high redshift"

ALMA observations of the long wavelength dust continuum are used to estimate the interstellar medium (ISM) masses in a sample of 708 galaxies at $z = 0.3$ to 4.5 in the COSMOS field. The galaxy sample has known far-infrared luminosities and, hence, star formation rates (SFRs), and stellar masses (M_*) from the optical-infrared spectrum fitting. The galaxies sample SFRs from the main sequence (MS) to 50 times above the MS. The derived ISM masses are used to determine the dependence of gas mass on redshift, M_*ĹŮ, and specific SFR (sSFR) relative to the MS. The ISM masses increase approximately 0.63 power of the rate of increase in SFRs with redshift and the 0.32 power of the sSFR/sSFRMS. The SF efficiencies also increase as the 0.36 power of the SFR redshift evolutionary and the 0.7 power of the elevation above the MS; thus the increased activities at early epochs are driven by both increased ISM masses and SF efficiency. Using the derived ISM mass function we estimate the accretion rates of gas required to maintain continuity of the MS evolution ($> 100\,M_\odot\,yr^{-1}$ at $z > 2.5$). Simple power-law dependences are similarly derived for the gas accretion rates. We argue that the overall evolution of galaxies is driven by the rates of gas accretion. The cosmic evolution of total ISM mass is estimated and linked to the evolution of SF and AGN activity at early epochs.

Seiji Fujimoto
University of Tokyo

"Demonstration of ALMA New Census for INfrared Galaxies (DANCING). I. FIR Size and Luminosity Relation at $z = 0 - 6$"

We present the large statistics of the galaxy effective radius in the FIR wavelength R_e(FIR) obtained from 1258 deep ALMA 1 mm band maps that are open for public by 2016 December. Our ALMA sample consists of 736 sources at $z = 0 - 6$. We homogeneously derive R_e(FIR) and FIR luminosity L_{FIR} of our ALMA sources with the same uv-visibility method over the redshift range of $z = 0 - 6$, carefully evaluating the selection incompleteness and the size measurement systematics. We find that there is a positive correlation between R_e(FIR) and $L_{\rm FIR}$ at the $> 99\%$ significance level. Fitting the power-law function, $R_e(\mathrm{FIR}) \propto L_{\rm FIR}^{\alpha}$, we obtain the best-fit value of $\alpha = 0.26 \pm 0.06$. Moreover, the average R_e(FIR) at a fixed L_{FIR} decreases toward high redshifts. The best-fit alpha and the redshift evolution trend of R_e(FIR) are similar to those of the galaxy effective radius in the UV-optical wavelengths R_e(UV-optical). We compare R_e(FIR) and R_e(UV-Opt.) of our ALMA sources on the statistical and individual bases, and identify the significant trend that R_e(FIR) is smaller than Re(UV-Opt.), which suggests that dusty starbursts take place in a compact region. We investigate the rest-frame UV and optical morphologies of our ALMA sources with deep *HST* images, and find that $\sim 30\%$ of our ALMA sources appear to be major mergers. Because the rest of the ALMA sources ($\sim 70\%$) are compact isolated sources, dusty starbursts are triggered not only by major mergers but also the other mechanisms.

Axel Weiss
MPIfR Bonn

"Determining the Molecular Gas Mass in High-z and Local Starbursts"
I will present the results of an in depth study of the molecular gas excitation in local and high-z starburst using CO, [CI] and the dust continuum emission. The focus of my talk will be on the gas mass conversion factors derived from the radiative transfer models. I will discuss the conversion factors for the three different ISM tracers in different populations of local and high-z galaxies.

David Frayer
Green Bank Observatory

"ALMA, GBT, and VLA Observations of SCUBA's First SMG SMM J02399-0136"
We will present ALMA CO(3-2), CO(7-6), and continuum observations and VLA and GBT CO(1-0) observations of the $z = 2.8$ sub-millimeter galaxy SMM J02399-0136. This is a remarkable source where the majority of the molecular gas and infrared luminosity is associated with the extremely-red component L2SW, and the luminous AGN (component L1) shows evidence of a strong radio jet that may be enhancing the star-formation activity in L2SW. The single-dish GBT CO(1-0) profile shows excess emission that may be associated with the large extended Ly-alpha cloud and/or from undetected clumps within the GBT beam.

Soh Ikarashi

Kapteyn Astronomical Institute, University of Groningen

ZZZ Empirical relations between the nature of SMGs and their millimeter sizes revealed by ALMA"

We conducted millimeter-wave size studies of 69 ALMA-identified AzTEC SMGs with L′≥ 10σ ALMA continuum detections and with 1100 micron flux of $1.7-7.4$ mJy aiming to investigate the relation between these sizes and other SMG properties. We used ALMA 1100 micron continuum images with $\sim 0\farcs2$ resolution obtained toward AzTEC SMGs in the Subaru/XMM-Newton Deep Field by our ALMA cycle2 and 3 projects. Firstly, we found that all the 69 SMGs in our sample lie well above the expected minimum sizes as a function of flux due to the Eddington limit in the ALMA flux-size plot. Secondly, we found an empirical relation between mm-wave sizes and AGN by using 26 SMGs with good photometric or spectroscopic redshifts of $z = 1-3$ which are detected in all IRAC and MIPS 24 micron bands. We divided the sample into groups of starburst dominant, composite, and AGN dominant in mid-IR continuum emission. We found that SMGs with the composite mid-IR wave features are compact, while SMGs with starburst or AGN dominant features in mid-IR light have more extended millimeter sizes. This relation between the millimeter size and AGN fraction in mid-IR light may trace starburst phase in the massive galaxy evolution scenario in which SMGs evolve to QSOs after AGN grows.

Gabriela Calistro Rivera

Leiden Observatory

"Probing the star-forming ISM at $z \sim 2-3$ with sub-arsec resolution"

We present high resolution ($\sim 0.5''$) ALMA observations of the molecular gas in four submillimeter galaxies from the ALMA-Extended Chandra Deep Field South (ALESS). The redshift range sampled ($z \sim 2-3$) and the high SFRs expected (SFR$\sim 100-900\,M_\odot$/year) allow us to probe the ISM properties in galaxies associated with the peak of the star formation history of the universe. Clumpy optical counterparts for two of the sources suggest that our sample is a great laboratory for studying the molecular gas dynamics in galaxy merger candidates. Our subarcsec resolution images reveal strong detections of the CO(3-2) transition emission of various morphologies and extensions which range from 10 to 40 kpc. While the molecular gas emission in most of the sources seems to be co-located with the optical stellar emission, these are clearly offset in one galaxy, which has important implications e.g. for the modeling of its spectral energy distributions. Preliminary analysis suggests that our sources contain molecular gas reservoirs of masses that range from 4×10^{10} to $\sim 2 \times 10^{11}$ [$M_\odot \times \alpha_{CO}$], and the variation in gas/stellar morphology and velocity widths could hint towards different merger stages. Finally, observations of different CO transition lines allow us to investigate the excitation state of the molecular gas in these sources.

Carlos Gómez-Guijarro
DARK Cosmology Centre

"Stars and dust distribution unveil minor mergers in SMGs at $z \sim 4.5$"

Submillimeter galaxies (SMGs) at $z > 4$ have been proposed as likely progenitors of the massive and compact population of quiescent galaxies at $z \sim 2$, that eventually evolve into the massive local ellipticals. In this context we have assembled a unique sample of 6 spectroscopically confirmed $z > 4$ SMGs and followed them up with high-resolution multiband *HST* and ALMA line and continuum observations. From the resolved rest-frame UV and FIR imaging, we have been able to unveil the morphologies, and fully characterise the star formation, and dust attenuation processes in these sources. At the same time, line observations have allowed us to describe the kinematics of the star formation. Together, we have uncovered the origin of these sources in the IRX/beta plane, constrained their stellar and dynamical masses, revealing a minor merger nature from the stars, extreme rotation from the gas, and set a much clearer evolutionary path towards the $z \sim 2$ quiescent galaxies from unambiguously determined dust sizes and accurate stellar masses.

Kevin Harrington

Argelander Institute für Radioastronomie

"Using CO as a Physical Probe of the SF Supply in the Extremely IR-Luminous *Planck*-LMT Identified Sources"

CO(1–0) measurements are vital for directly probing the total molecular gas mass in active SF galaxies when there were the highest gas mass fractions (up to 80% total mass) and star formation rates ($z \sim 2$–3). We use the Green Bank Telescope (GBT) to observe seven extremely luminous infrared galaxies in CO(1–0). These observations complement higher CO transitions obtained with the Large Millimeter Telescope (LMT). The GBT CO(1–0) results have not only confirmed the photometric and spectroscopic redshifts determined from our LMT study, $z_{CO} = 1.33 - 3.26$, but also show comparable profiles and line widths. With log(LIR) $> 13 - 14\,\mathrm{L}_\odot$, these are currently amongst the most luminous high-z galaxies. We report enhanced infrared to CO line luminosity ratios $L_{IR}/L'_{CO(1-0)}$ compared to normal star- forming galaxies, yet similar to those of well-studied IR-luminous: $< 110 \pm 22 > \mathrm{L}_\odot/(\mathrm{K\,km/s/pc}^2)$. The sub-thermalized r31 and r41 values are roughly half the average values for SMGs. We estimate the total gas mass content as $\mu\mathrm{M(H_2)} = (0.9 - 27.2) \times 10^{11} (\alpha_{CO}/0.8)\,\mathrm{M}_\odot$. The rapid gas depletion times, $< \tau_{cons} >= 80\,\mathrm{Myr}$, reveal a vigorous mode of starburst activity which contrasts the local, low gas mass fraction universe, with Gyr consumption timescales. CO provides an observational window into the gas excitation present in the picture of theoretical models of SF galaxies. At these redshifts there are higher mean densities and collapse is happening on the order of the gas free-fall time.

Session 7

Jacqueline Hodge
Leiden

"Recent results from ALMA on submm galaxies and dusty star-forming galaxies at high redshifts"

Review talk covering recent results from ALMA on submm galaxies and dusty star-forming galaxies at high redshifts.

Chris Hayward
Flatiron Institute

"The physical nature of SMG multiplicity"

Interferometric follow-up with e.g. ALMA has revealed that a significant fraction of submm sources identified with single-dish telescopes are blends of multiple SMGs, but the nature of this multiplicity (i.e. whether the components are physically associated or chance projections) is poorly constrained. Determining the relative contributions of physically associated vs. unassociated components is crucial for e.g. understanding whether interactions/mergers are needed to drive the high SFRs inferred for SMGs and connecting SMGs to the underlying dark matter structure. I will first review the predictions of theoretical models regarding this issue. I will then present new observational results that directly test the predictions of theoretical models and give insight into the physical nature of SMG multiplicity.

Elizabeth Cooke
Durham University

"Presenting the largest sample of ALMA-detected SMGs"

Submillimetre galaxies (SMGs) are host to some of the most extreme star formation in the Universe. We have undertaken an ALMA survey of $\sim$ 700 submillimetre sources in the Ultra Deep Survey (UDS), resolving $\sim$ 1000 SMGs, a factor of 10 larger than previous surveys. SMGs are predicted to be the progenitors of today's massive elliptical population and therefore provide unique constraints on galaxy evolution. In particular $z > 4$ SMGs may help to explain the formation of $z = 2 - 4$ compact quiescent galaxies. I will present the first exciting results of our ALMA survey of the largest sample of SMGs to date, including multiplicity measurements, multiwavelength properties of SMGs and our [CII] emission line search in SMGs at $z = 4.4 - 4.6$.

Bitten Gullberg
Durham University

"High resolution ALMA imaging of SMGs"

I will present high resolution ($0.03''$) continuum maps of four $z \sim 4$ sub-mm galaxies (SMGs) selected from the ALMA-LESS and ALMA-UDS surveys. These cycle 3 observations resolve the gas and dust within the ISM of these galaxies on 0.2-1 kpc scales. The data reveal an apparent range of morphologies. Though the continuum morphologies appear to be: smooth and compact or extended and "clumpy", comparison with simulations reveal that all four sources are consistent with exponential disks. From the morphologies and dynamics of the gas and dust, I will show that these SMGs are most likely to contain dust disks which are smooth on scales of ~ 200 pc.

Wednesday 2nd August

Session 8

Dominik Riechers
Cornell

"Results on the gas properties of high-redshift galaxy populations (including lensed samples)"

Review talk covering results on the gas properties of high-redshift galaxy populations (including lensed samples).

Joaquin Vieira
University of Illinois

"SPT SMGs: High-redshift star formation under the cosmic microscope"

Recent facilities such as the South Pole Telescope (SPT), the *Herschel* Space Observatory, and the Atacama Large Millimeter Array (ALMA) have opened a window to the millimeter (mm) sky and revealed a unique and unprecedented view of the Universe. In a 2500 square degree cosmological survey, SPT has systematically identified a large number (> 100) of high-redshift strongly gravitationally lensed starburst galaxies. We are conducting a unique spectroscopic redshift survey with ALMA, targeting carbon monoxide line emission in these sources, across the 3mm spectral window. To date, we have obtained spectroscopic redshifts for 54 sources from $1.8 < z < 6.9$, with a median of $z = 3.9$. This sample comprises 70% of the total spectroscopically confirmed DSFGs at $z > 4$ and extends into the epoch of re-ionization. We are systematically measuring low-J CO, [CII], and [NII] for these sources with ATCA, APEX, and ALMA, making this the largest and most well-studied samples of high-redshift starburst galaxies. We are also using the lensing magnification to study these sources at the highest possible resolution with CO, [CII], and H_2O. We are undertaking a comprehensive and systematic followup campaign to use these "cosmic magnifying glasses" to study the physical conditions and chemical evolution of the dust-obscured universe in unprecedented detail. I will describe our team's latest science results and discuss the scientific potential of these strongly lensed starburst galaxies within the context of future instruments and facilities.

Matt Bothwell
Cambridge

"ALMA observations of atomic carbon in $z \sim 4$ dusty star-forming galaxies"

I will discuss ALMA [CI]1-0 observations for a sample of 13 strongly-lensed dusty star-forming galaxies originally discovered at 1.4 mm in a blank-field survey by the South Pole Telescope. Comparing these new data with available [CI] observations from the literature allows a study of the ISM properties of $\sim$ 30 extreme dusty star-forming galaxies spanning a redshift range $2 < z < 5$. Using the [CI] line as a tracer of the molecular ISM, we find a mean molecular gas mass for SPT-DSFGs of $6.6 \times 10^{10}\,\mathrm{M}_{\odot}$. This is in tension with gas masses derived via low-J CO and dust masses; bringing the estimates into accordance requires either (a) an elevated CO-to-H_2 conversion factor for our sample of $X_{\mathrm{CO}} \sim 2.5$ and a gas-to-dust ratio ~ 200, or (b) an high carbon abundance $X_{[\mathrm{CI}]} \sim 7 \times 10^{-5}$. Using observations of a range of additional atomic and molecular lines (including [CI], [CII], and multiple transitions of CO), we use a modern Photodissociation Region code (3D-PDR) to assess the physical conditions (including the density, UV radiation field strength, and gas temperature) within the ISM of the DSFGs in our sample.

Kirsten Knudsen

Chalmers University of Technology

"The challenge of studying the interstellar medium and star formation in $z \sim 7$ galaxies."

The increasing number of redshift $z \sim 7$ galaxies is resulting in the possibility to study the early stages of galaxy evolution and thus potentially the galaxies that 1-2 billion years later are seen as intensely star-forming galaxies at $z = 2 - 3$. Predictions for the properties of galaxies at such early epochs are partly based on the knowledge from the local universe. In this talk I will show some of the recent results on $z = 6 - 7.5$ galaxies obtained with ALMA. Observations of the far-infrared structure lines of the interstellar medium and the gas fuelling the star formation have yielded surprising results, often much fainter than predicted. Also dusty, star-forming galaxies in the early epochs remain a puzzle. I will show the latest results for the lensed A1689zD1 as an example of a normal galaxy with a large dust mass during the epoch of reionization. I will discuss how this challenges our understanding of the properties of galaxies at early times as well as our expectations of how to observe these galaxies.

Minju Lee
The University of Tokyo

"Radio-to-mm properties of star forming galaxies in a protocluster"

A cluster of galaxies is an ideal place to understand the formation and evolution of elliptical and S0 galaxies with their high abundance. Galaxy archaeology and simulations suggest that such cluster members have experienced intensive star formation during the cluster formation epoch $z > 2$. I present mm-to-cm properties of star forming galaxies from ALMA (1.1 mm and CO(3-2)) and JVLA (S and C band continuum) observations, which are follow-up observations of several SMGs that are detected near a protocluster 4C23.56 at $z = 2.49$ with AzTEC/ASTE (1.1 mm) and SCUBA-2/JCMT (850 μm). By pin-pointing the galaxies with sub-arcsecond resolution, we present detailed properties of these galaxies. We measure gas content, size, kinematics and radio spectral index, those subject to be compared with star forming galaxies in general fields at similar redshift and those in nearby. By constraining these, I discuss the role of the intensive star formation and the environment in galaxy evolution at high redshift.

Tai-An Cheng
Astrophysics Group, Imperial College London

"Starbursting Galaxies in Candidate High-z Clusters/Protoclusters"

Crossmatching between *Planck* and *Herschel* data has uncovered 42 candidate clusters/protoclusters with starbursting galaxies. Normally Starbursting galaxies can have SFRs$\sim$ 1000 solar masses per year but their elevated SFRs are found to last only for $\sim$ 100 Myr, thus they are rare to be found in a cosmological volume. They are also thought to be progenitors of today's massive ellipticals in the cores of today's massive galaxy clusters, so are representative of the dense cluster environment at earlier times. In this poster, we present how we crossmatched *Planck* and *Herschel* data and then searched for overdensities of far-infrared-luminous starbursts to select candidate high-z clusters/protoclusters. We also present follow-up observations in optical/NIR and radio, which also probe quiescent/radio galaxies in these starbursting clusters/protoclusters. We use these follow-up data to optimise photo-z estimates with more flux points in the SED fitting, and cross-identify each map to find counterparts. These observations enable us to resolve possible merging systems, to confirm their cluster/protocluster memberships, and to constrain environmental relations such as SFR-density relation, in high-z clusters/protoclusters.

Jaclyn Champagne
University of Texas at Austin

"Molecular Gas Content of SMGs in a $z = 2.5$ Starbursting Protocluster"

Cosmological simulations suggest that the most massive galaxy clusters in the Universe assemble rapidly at early times ($z > 2$). Although previous studies have identified a number of protoclusters in these epochs, presumed to be in the nascent stages of cluster development, we are still lacking observational evidence of the assembly history of massive virialized clusters. We present follow-up observations of the COSMOS $z \sim 2.47$ protocluster, rich in submillimetre galaxies (7 spectroscopically confirmed) and AGN, with JVLA observations of CO(1-0) and radio continuum. One of two pointings is centred on one line-of-sight filament in the protocluster, which has an SFR of 196+88 $M_\odot$. We report preliminary results of the molecular gas content of galaxies in this filament and report multiple continuum detections. We address the claim put forth in Wang et al. (2016) that associates X-ray emission as a virialized cluster core at $z \sim 2.5$ in the same field, which we assertăis more likely attributable to inverse Compton scattering from a ghost radio galaxy along that filament. We discuss how observations of molecular gas, specifically CO(1-0), in SMGs in non-virialized overdensities can be uniquely constraining to the assembly history of the most massive clusters in the present-day Universe.

Helmut Dannerbauer
Instituto de Astrofísica de Canarias

"The surprising existence of a large, massive CO disk in a distant, gas-rich protocluster"

Galaxies in local clusters are significantly affected by environmental effects. However, we do not yet know when these physical processes are initiated and what mechanisms in clusters directly impact the course of galaxy evolution. Through deep observations with the Australian Telescope Compact Array (ATCA), we discovered a very massive, $M_{mol} = 2.0 \times 10^{11}\,M_*$, very extended, 40 kpc, CO(1-0)-emitting disk in the protocluster surrounding the radio galaxy, MRC1138-262, at $z = 2.2$. A significant fraction of the cold molecular gas lies outside the visible UV/optical region. The discovery is unexpected as gas truncation and stripping was predicted. I discuss what our results imply about the quiescent mode of star formation in submillimeter galaxies, the importance of environmental processes in protoclusters, how this detection may change our view of ram pressure stripping, and what this implies about the source of the metal-rich intracluster medium observed in local clusters.

Session 9

Alexandra Pope
UMass

"Signatures of supermassive black hole growth in high redshift dusty galaxies"
Review talk covering links between AGN and dusty star-forming galaxy populations at high redshifts.

Manda Banerji

IoA, Cambridge

"Heavily Reddened Quasars: Observing the Connection Between Star-Formation & AGN Activity In-Situ"
Dust-obscured quasars have long been hypothesized to represent the missing evolutionary link between SMGs and unobscured quasars, although evidence for a direct link between the two populations remains scarce. The majority of SMGs do not show evidence for luminous AGN activity, and conversely, the majority of quasars are not sub-millimeter bright. Thus, if the two populations are connected, the overlap between them must be short-lived. I will present our efforts to identify exactly such a transitory, overlap population by using very wide-field infra-red surveys (UKIDSS, VISTA) to select a population of heavily reddened quasars with similar levels of dust extinctions as SMGs ($A_v = 1 - 6$ mags). Our spectroscopic sample now totals ~ 60 such obscured, high-luminosity quasars (e.g. Banerji et al. 2012, 2015a) at redshifts of 2-3. In this talk I will focus on far infrared and sub-millimeter follow-up studies of this population, which have allowed us to demonstrate that gas-rich, dusty "SMG-like" hosts are ubiquitous in these systems and the interplay between star-formation and luminous AGN activity can therefore be studied synchronously. I will describe the first ALMA observations of the population (Banerji et al. 2017) as well as the results of currently ongoing programs with SCUBA-2, ALMA and the VLA that are allowing us to probe the dust properties, gas morphologies and ISM conditions in these unique hybrid systems.

Chelsea Sharon

McMaster University

"The Evolutionary Connection Between SMGs and AGN as Probed by Molecular Gas Excitation"

Theoretical work has suggested that AGN play an important role in quenching star formation in massive galaxies. Direct evidence for AGN affecting the molecular ISM has so far been limited to detections of molecular outflows in low-z systems and extreme excitation regions that represent a tiny fraction of the total gas. Indirect evidence for AGN's impact on their host galaxies' cold gas phase may be provided by measurements of the gas excitation and dynamics. At $z \sim 2-3$, SMGs and AGN host galaxies were observed to have different low-J CO line ratios, and thus different abundances of cold and warm gas phases, potentially supporting an evolutionary connection between these two populations. I will present a recent VLA sample (Sharon et al. 2016) that nearly doubles the number of CO(1-0) detections in SMGs and AGN-host galaxies and allows us to better compare the cold gas properties of these systems. With our expanded sample of CO(3-2)/CO(1-0) line ratio measurements, we do not find a statistically significant difference between SMGs and AGN host galaxies for either the mean line ratio or distribution of line ratios. The similarities between these two populations, both for the low-J CO excitation and for relations like the Schmidt-Kennicutt law, suggests that future attempts to identify their evolutionary connection require better tools for disentangling the effects of intense star formation vs. AGN.

Benny Trakhtenbrot

ETH Zurich

"ALMA Observations Reveal Major Mergers Among the Host Galaxies of Fast-growing, High-redshift Supermassive Black Holes"

I will present new ALMA results that are part of a multi-wavelength project to understand the epoch of fastest growth of the most massive black holes, at $z = 4.8$. These luminous quasars have rather uniform BH-related properties, with typical accretion rates and black hole masses of $L/L_{Edd} \sim 0.7$ and $M_{BH} \sim 10^9\,\mathrm{M}_\odot$. The sample consists of "FIR-bright" sources which were individually detected in previous *Herschel*/SPIRE observations, with star formation rates of SFR$> 1000\,\mathrm{M}_\odot$/yr, and "FIR-faint" sources for which *Herschel* stacking analysis implies a typical SFR of $\sim 400\,\mathrm{M}_\odot$/yr. The ALMA data for six of these quasars provides clear detections of the dusty ISM in all quasar hosts, in both continuum and [CII]157.74 μm line emission. We detect companion, spectroscopically confirmed sub-mm galaxies (SMGs) for three sources, separated by $\sim 14-45$ kpc from the quasar hosts, which we interpret as major galaxy mergers. The continuum emission is in good agreement with the expectations from the *Herschel* data, confirming the intense SF activity in the quasar hosts, and suggesting SFR(quasar)$\sim (2-11)\times$SFR(companion). Our ALMA data therefore clearly support the idea that major mergers are important drivers for rapid early SMBH and host galaxy growth, although other fueling processes may still be required. I will finally mention the forthcoming steps in this long-term project.

Session 10

Caitlin Casey
UT Austin

"The ubiquity of coeval starbursts in massive galaxy cluster progenitors"
Review talk covering results on dusty star-forming galaxies in dense proto/cluster environments.

Hideki Umehata
The Open University of Japan

"ALMA Deep Field in SSA22"
The environment where galaxies inhabit is expected to play a critical role in shaping their evolution. Galaxies and nuclei in the dense environment at high redshift (i.e., proto-clusters) provide a good laboratory to investigate the accelerated, most extreme evolution of galaxies at a given epoch. Using ALMA band 3 and band 6, we mapped a $2' \times 3'$ region within the node at the junction of the 50 Mpc-scale filamentary three-dimensional structure traced by Lyman-α emitters (LAEs) in this field. We obtained 18 robustly detected 1.1 mm sources (here after submillimeter galaxies, SMGs) with a signal-to-noise ratio (SNR) > 5. Eleven such ALMA SMGs have spectroscopic redshifts of $z = 3.09$ and six of them host a X-ray luminous active galactic nuclei (AGN). We also find that multiple $z = 3.09$ ALMA SMGs contribute to two AzTEC sources, supporting that interaction may be responsible for a significant fraction of multiplicity in single-dish sources. Our results suggest that the vigorous star formation activity and the growth of super massive black holes (SMBHs) occurred simultaneously in the densest regions at $z \sim 3$, which is likely to correspond to the most active historical phase of the massive galaxy population found in the core of the clusters in the present universe.

Yuichi Matsuda
National Astronomical Observatory of Japan

"The environment of submillimetre galaxies"

We will introduce our environmental studies of SMGs from galaxy halo (~ 100 kpc) scale to protocluster (~ 10 Mpc) scale. We used ALMA to search for SMGs toward 4 giant (> 100 kpc) Lyman alpha emitting haloes (Lyman-α blobs or LABs) in the SSA22 protocluter at $z = 3.1$. We detected 11 SMGs (1-5 sources per LAB) with peak flux densities of $S_{860\,\mu m} = 0.3 - 4$ mJy/beam. For larger-scale studies, we have obtained an ALMA 1.1 mm map in $2' \times 3'$ (1×1.5 Mpc at $z = 3.1$) toward the core region of the SSA22 protocluster. We found that more than 10 SMGs are aligned with diffuse Lyman-alpha emitting filaments with a length of > 1 Mpc. These results suggest that, in protocluster environment, intense star-formation activities in SMGs may be fueled by the surrounding gas filaments and increase the covering fraction of Lyman-α emitting gas in the halo through interactions between gas outflows from the central galaxies and gas inflows from the surrounding gas filaments. We also briefly introduce our new SCUBA-2 survey to map out SMGs in $z > 4$ protoclusters which have been selected from the on-going Subaru / Hyper Suprime Cam survey.

End of workshop