AlbaNova University Center
Stockholm University

Lyman Continuum Leakage and Cosmic Reionization

13-15 August 2014

#lycleak

Workshop Programme

Oskar Klein centre

Vetenskapsrådet

Wenner-Gren Stiftelserna

The contribution from star-forming galaxies to the reionization of the Universe depends on the galaxy luminosity function and on the Lyman continuum (LyC) escape fraction of galaxies at redshifts greater than z~6. While most activity in this field has so far focused on quantifying the luminosity function, this 3-day workshop focuses on current and future efforts to constrain the LyC escape fraction of galaxies at both low and high redshift, and the impact that this is likely to have on our understanding of cosmic reionization.

Topics to be explored include:

- Direct and indirect methods to constrain LyC leakage (from the local to the high-redshift Universe)
- Observations of LyC leakage
- Theoretical perspectives on LyC leakage mechanisms
- Simulations and observational probes of reionization: How can empirical data on LyC escape fractions help? Is it necessary to know the galaxy LyC escape fraction to prove that galaxies reionized the Universe?
- Complications: Anisotropic leakage, IGM clumping factors, gravitational lensing etc.

Invited speakers (confirmed):

- Nils Bergvall
- Renyue Cen
- Jeff Cooke
- Elizabeth Fernandez
- Kristian Finlator
- Nick Gnedin
- Akio Inoue
- Ikuru Iwata
- Tucker Jones
- Han-Seek Kim
- Sourav Mitra
- Jan-Pieter Paardekooper
- Brian Siana
- Eros Vanzella
- John Wise
- Hide Yajima

Format

3-day workshop with invited and contributed talks. There is no conference fee.

Important dates

- Abstract submission deadline: 25 May 2014
- Final programme announced: 7 June 2014
- Registration deadline: 20 June 2014

Scientific organizing committee

Erik Zackrisson (co-chair), Garrelt Mellema (co-chair)

Local organizing committee

Nina Nowak (co-chair), Garrelt Mellema (co-chair), Erik Zackrisson, Hannes Jensen, Suman Majumdar, Juan Gonzalez, Johannes Puschnig

Supported by

The Oskar Klein Centre, The Wennergren Foundation, Vetenskapsrådet

Conference logo: Genoveva Micheva

Dates: from 13 August 2014 08:00 to 15 August 2014 18:00

Location: AlbaNova University Center, Stockholm University, Stockholm, Sweden

Workshop Agenda

Venue: Room FB 42 on the 4th floor of the AlbaNova building. From the main entrance (5th floor) go straight to the stairs, down to the 4th floor, pass by the elevator on the right side, cross the bridge and then turn right. FB 42 is one of the lecture rooms on the left side.

Wednesday, August 13

08:30-09:00 **Registration**

09:00-09:30 Garrelt Mellema (Stockholm University)
Welcome + introductory talk

09:30-10:00 Nick Gnedin (Fermilab) — invited
Cosmic Reionization On Computers

10:00-10:20 Robin Mostardi Rehagen (UCLA)
A Critical Test of LyC Leakage in Star-forming Galaxies at z~3

10:20-10:40 Erik Zackrisson (Stockholm University)
Probing LyC leakage from galaxies in the reionization epoch

10:40-11:10 **Coffee break**

11:10-11:40 John Wise (Georgia Institute of Technology) — invited
Propelling Reionization with the Faintest Galaxies

11:40-12:10 Eros Vanzella (INAF) — invited
Investigating the ionizing escaping radiation at high redshift (z>3)

12:10-12:30 Gonzalo Diaz (Swinburne University of Technology)
The environment of CIV absorption systems in the post-reionization Universe: discovery of the galaxies that dominate the ionizing flux density at z~6

12:30-14:00 **Lunch break**

14:00-14:30 Nils Bergvall (Uppsala University) — invited
Lyman continuum escape and the local starburst population

14:30-15:00 Elizabeth Fernandez (Kapteyn Astronomical Institute) — invited
Modeling Infrared Observations of High Redshift Galaxies to Determine the Escape Fraction

15:00-15:20 Claus Leitherer (STScI)
Pushing the Cosmic Origins Spectrograph to the Lyman Limit

15:20-15:40 Sanchayeeta Borthakur (Johns Hopkins University)
A Local Clue to the Reionization of the Universe

15:40-16:10 **Coffee break**

16:10-16:30 Christoffer Fremling (Stockholm University)
The Escape of Ionizing Radiation from Local Starburst Galaxies: Revised Lyman Continuum Escape Fractions for Tololo 1247-232 and Haro 11

16:30-16:50 Janice Lee (STScI)
A New Look at Diffuse Ionized Gas in Dwarf Galaxies

16:50-17:10 Laura Keating (University of Cambridge)
The role of environment in the near-zones of z ~ 7 QSOs

Thursday, August 14

09:00-09:30 Kristian Finlator (Dark Cosmology Centre) —invited
Metal Absorbers in Inhomogeneous Reionization Models

09:30-10:00 Brian Siana (University of California, Riverside) —invited
Deep HST Searches for Lyman Continuum from Galaxies at z~2–3

10:00-10:20 Andreas Faisst (ETH Zürich)
Constraints on re-ionization at z~8 using Lyman-alpha emitters

10:20-10:40 Sally Oey (University of Michigan)
*Constraints on Lyman Continuum Optical Depth from Ly-alpha, C II, and C II**

10:40-11:10 **Coffee break**

11:10-11:30 Genoveva Micheva (Subaru Telescope, NAOJ)
New analysis of LyC leaking z~3 galaxies in the SSA22 field

11:30-12:00 Ikuru Iwata (Subaru Telescope, NAOJ) — invited
Constraints on LyC escape fraction from direct observations of z~3 galaxies

12:00-12:30 Hidenobu Yajima (University of Edinburgh) — invited
The Escape of Ionizing Photons from Lyman-alpha Emitters at the Epoch of Reionization

12:30-14:00 **Conference photo & Lunch break**

14:00-14:30 Jeff Cooke (Swinburne University of Technology) — invited
Not the usual suspects: Uncovering key contributors to cosmic reionization

14:30-15:00 Hansik Kim (University of Melbourne) — invited
Variation in the escape fraction of ionizing photons from galaxies and the redshifted 21-cm power spectrum during reionization

15:00-15:20 Jaehong Park (University of Melbourne)
The cross-power spectrum between 21cm emission and galaxies in hierarchical galaxy formation models

15.20-15:40 Michael Rutkowski (University of Minnesota)
Lyman-Continuum Leakage in Dwarf Star-Forming Galaxies at z~1.2

15:40-16:10 **Coffee break**

16:10-16:30 Brian Fleming (University of Colorado)
A Study of Lyman Alpha Emission from Low-redshift Galaxies and its Potential use as a Tracer of Lyman Continuum Escape

16:30-16:50 Alexander Kaurov (University of Chicago)
Comparison of numerical and analytical methods for studying cosmic Reionization

16:50-17:10 Nitya Hariharan (MPA)
Enabling Radiative Transfer on AMR grids in CRASH

18:00 **Workshop dinner**

Friday, August 15

09:00-09:30 Renyue Cen (Princeton University) — invited
Effects of Stellar Feedback and Runaway OB Stars on Ionizing Photon Escape Fraction

09:30-10:00 Jan-Pieter Paardekooper (MPE) — invited
The Escape Fraction of Ionising Photons from the First Billion Years Simulation

10:00-10:20 Anne Verhamme (Geneva University)
On the use of Lyman-alpha to detect Lyman continuum leaking galaxies

10:20-10:40 Ivana Orlitova (Astronomical Institute ASCR)
Modelling of HST/COS Lyman-alpha spectra of low-z LyC leakers

10:40-11:10 **Coffee break**

11:10-11:40 Tucker Jones (UCSB) — invited
Observational constraints of Lyman continuum leakage at redshift 4

11:40-12:10 Akio Inoue (Osaka Sangyo University) — invited
On the correction for the intergalactic attenuation of the direct Lyman continuum observation

12:10-12:30 Alan Duffy (Swinburne University of Technology)
Escape Fractions and Supernova Feedback in the Epoch of Reionization

12:30-14:00 **Lunch break**

14:00-14:30 Sourav Mitra (University of Western Cape) — invited
Escape fraction of ionizing photons from high-redshift galaxies from reionization models

14:30-14:50 Jens Melinder (Stockholm University)
Escape of ionising radiation from star formation selected galaxies at redshift 2.2

14:50-15:10 Michael Rauch (Carnegie Observatories)
Messy Lyman alpha Emitters at z~3 as Likely Sites of Lyman Continuum Leakage

15:10-15:30 Yumi Choi (University of Washington)
The Power of Panchromatic Imaging: Intrinsic UV flux and its leakage from NGC4214

15:30 Concluding remarks

19:00 **Rooftop tour**

List of Participants

Bergvall, Nils	Uppsala University
Borthakur, Sanchayeeta	Johns Hopkins University
Cen, Renyue	Princeton University
Choi, Yumi	University of Washington
Cooke, Jeff	Swinburne University
Das, Arpan	Department of Physics and Astrophysics, University of Delhi
Diaz, C. Gonzalo	Swinburne University of Technology
Duffy, Alan	Swinburne University of Technology
Faisst, Andreas	ETH Zurich
Fernandez, Elizabeth	Kapteyn Astronomical Institute
Finlator, Kristian	Dark Cosmology Centre
Fleming, Brian	University of Colorado
Freeland, Emily	Department of Astronomy, Stockholm University
Fremling, Christoffer	Department of Astronomy, Stockholm University
Gnedin, Nick	Fermilab
Gonzalez, Juan	Stockholm University
Guaita, Lucia	Osservatorio di Monte Porzio
Hariharan, Nitya	Max Planck Institute for Astrophysics
Hayes, Matthew	Stockholm University
Inoue, Akio	Osaka Sangyo University
Iwata, Ikuru	Subaru Telescope, NAOJ
Jensen, Hannes	Department of Astronomy, Stockholm University
Jones, Tucker	UCSB
Kaurov, Alexander	University of Chicago
Keating, Laura	Institute of Astronomy, University of Cambridge
Kehrig, Carolina	Instituto de Astrofísica de Andalucía (CSIC)

Keszthelyi, Zsolt	Ludwig-Maximilians-University / University Observatory Munich
Kim, Hansik	University of Melbourne
Lee, Kai Yan	Department of Astronomy, Stockholm University
Lee, Janice	STScI
Leitherer, Claus	STScI
Majumdar, Suman	Department of Astronomy, Stockholm University
Melinder, Jens	Department of Astronomy, Stockholm University
Mellema, Garrelt	Department of Astronomy, Stockholm University
Micheva, Genoveva	Subaru Telescope
Mitra, Sourav	University of Western Cape (UWC)
Mostardi Rehagen, Robin	UCLA
Nowak, Nina	Department of Astronomy, Stockholm University
Oey, Sally	University of Michigan
Orlitova, Ivana	Astronomical Institute ASCR
Paardekooper, Jan-Pieter	Max Planck Institute for Extraterrestrial Physics
Park, Jaehong	The University of Melbourne
Puschnig, Johannes	Department of Astronomy
Rauch, Michael	Carnegie Observatories
Rodríguez-Espinosa, José-Miguel	Instituto de Astrofísica de Canarias
Rutkowski, Michael	University of Minnesota
Shah, Ekta	Indian Institute of Technology Bombay, India
Shapley, Alice	UCLA
Siana, Brian	University of California, Riverside
Vanzella, Eros	INAF - Bologna Astronomical Observatory
Verhamme, Anne	Geneva University
Wise, John	Georgia Institute of Technology
Yajima, Hide	University of Edinburgh
Zackrisson, Erik	Department of Astronomy, Stockholm University

Abstracts

Lyman continuum escape and the local starburst population

Bergvall, N. (Uppsala U)

Studies of Lyman continuum leakage from local starburst galaxies can help us to constrain the conditions for leakage at high redshifts. So far, however, very few local leakers have been detected. We argue that the detection rate is strongly dependent on how the targets were selected and question the choice of extreme starbursts at the peak of their activity. Based on a statistical investigation of local starburst galaxies we also make an effort to constrain the fraction of local leakers and discuss how this could change with redshift.

A local clue to the reionization of the universe

Borthakur, S. (Johns Hopkins U), Heckman, T. (Johns Hopkins U), Leitherer, C. (STScI) and Overzier, R. (Observatorio Nacional Rio de Janeiro)

Identifying the population of galaxies that were responsible for the reionization of the universe is a long standing quest in astronomy. We present the first viable low-z candidate that has an escape fraction of ionizing flux of 40% – the largest ever detected. This detection confirms the existence of gaps in the neutral gas enveloping the starburst. Such gaps are believed to be an integral property of galaxies at the epoch of reionization. The candidate is a massive yet highly compact starburst and the gaps are most likely created by the unusually strong winds and intense ionizing radiation produced by this extreme starburst. Our study also validates the indirect technique of using the residual flux in saturated interstellar absorption lines for identifying such leaky galaxies. Since direct detection of ionizing flux is impossible at the epoch of reionization, this is a highly valuable technique for the next generation of studies.

Effects of stellar feedback and runaway OB stars on ionizing photon escape fraction

Cen, R. (Princeton U) and Kimm, T. (Princeton U)

We would like to present some recent research results on ionizing photon escape fraction for galaxies at the epoch of reionization. We will first present the first self-consistent supernova feedback model that can be used by all cosmological simulation practitioners. We will then discuss its effects, following by a separate physical effect due to runaway OB stars, on ionizing photon escape fraction. Implications on cosmological reionization are also discussed.

The power of panchromatic imaging: Intrinsic UV flux and its leakage from NGC 4214

Choi, Y. (U Washington), Fouesneau, M. (MPA, U Washington), Gordon, K. (STScI), Weisz, D. (UCSC), Dalcanton, J. (U Washington), Williams, B. (U Washington), Sandstrom, K. (U Arizona)

The HST multi-wavelength imaging from the near-UV to the near-IR allows us to measure the broad spectral energy distributions (SEDs) for ~36,000 resolved stars within the nearby starburst dwarf galaxy NGC 4214. We constrain the stellar parameters and the line-of-sight dust properties for individual stars within the galaxy by modeling these SEDs. Using the resulting dust extinction map, we infer the intrinsic UV flux from individual stars. We are able to estimate the escape fraction by comparing this intrinsic UV flux to the ionizing photon flux that is actually absorbed by the galaxy, derived based on the extinction-corrected Hα emission. Our preliminary result suggests that the escape fraction is about 10% for NGC 4214.

Not the usual suspects: Uncovering key contributors to cosmic reionization

Cooke, J. (Swinburne UT)

To-date, all spectroscopic efforts to directly measure the Lyman continuum escape fraction (f_{esc}) from high redshift galaxies have exclusively searched $z \sim 3 - 4$ Lyman break galaxies (LBGs). These searches have yielded mixed results and escape fractions that fall short of the contribution necessary to reionize the Universe. The problem with LBGs is that they are selected for their decrement in flux shortward of the Lyman limit as a historical means for efficient detection and thus provide poor 'high-f_{esc}' galaxy candidates. I will discuss our physically motivated technique that provides an accurate measure of the average f_{esc} for the LBG population (and explains trends for narrow-band f_{esc} imaging searches in Ly-α emitters). Our technique has also isolated a population of 'high-f_{esc}' galaxies, termed Lyman continuum galaxies (LCGs), that reside outside the conventional Lyman break color selection regime. I will present results of our Keck spectroscopic follow-up program of LCG candidates selected via deep, medium-band IR imaging and our ongoing spectroscopic program to directly quantify f_{esc} and nebular emission properties of $z \sim 3 - 4$ LCGs. These data, combined with those for LBGs, are providing a more complete census of high redshift galaxies and the ionizing photon budget in the early Universe.

The environment of CIV absorption systems in the post-reionization Universe: discovery of the galaxies that dominate the ionizing flux density at z ~ 6

Diaz, C. G. (Swinburne UT), Ryan-Weber, E. (Swinburne UT), Ouchi, M. (U Tokyo), Shimasaku, K. (U Tokyo), Koyama, Y. (NAOJ), Tran, K. (Texas A&M U)

Detection of high-ionization absorption systems after the epoch of reionization depends on the fluctuations of the ionizing flux density. Our search for galaxies in two fields with $z \sim 5.7$ CIV absorption systems shows that they are found in regions dominated by Lyman-α emitters (LAEs), which are younger, fainter, and lower mass systems than Lyman

break galaxies. The results imply that $z \sim 5.7$ CIV systems trace low- to intermediate-density environments and that faint galaxies are important sources of ionizing radiation. Moreover, the spectroscopic confirmation of LAE 103027+052419 at 212 h^{-1} physical kpc from the strongest CIV absorption system known at $z > 5.5$, is solid evidence for its association with a detectable star-forming galaxy. I will discuss evidence for an early ($z > 6$) production and distribution of metals, which supports the idea that a significant fraction of the metals in the intergalactic medium (IGM) was injected during a pre-galactic stage of galaxy formation by low-mass star-forming galaxies. Regardless the enrichment mechanism, LAE 103027 +052419 is most likely the dominant source of radiation that maintains the ionization state of the nearby CIV absorption system. Finally, OI absorption systems have been proposed as probes of the physical state of neutral filamentary over-densities in the later stages of the EoR. If this is the case, strong CIV absorption systems at $z \geq 5.7$ with no low ionization metal lines are the complement to OI absorption systems. It could be possible to combine low ionization and high ionization metal absorption lines to study the EoR, because OI systems are expected to trace the haloes of the galaxies that produced the cosmic reionization, whereas CIV systems seem to trace diffuse recently ionized IGM.

Escape fractions and supernova feeback in the epoch of reionisation

Duffy, A. (Swinburne UT), Wyithe, S. (U Melbourne), Mutch, S. (U Melbourne), Poole, G (U Melbourne)

We use high resolution simulations of cosmological volumes to model galaxy formation at high redshift, with the goal of studying the photon budget for reionization. We demonstrate that galaxy formation models that include a strong, thermally coupled, supernovae scheme reproduce current observations of star formation rates and specific star formation rates, both during and after the reionization era.

These models produce enough UV photons to sustain reionization at $z < 8$ ($z < 6$) through a significant population of faint, unobserved, galaxies for an assumed escape fraction of 20% (5%). We find that models with less efficient supernovae feedback can sustain reionization at $z < 6$ for escape fractions as low as 2% but at the expense of over-predicting current observations of the UV luminosity function.

Constraints on re-ionization at z ~ 8 using Lyman-α emitters

Faisst, A. (ETH Zürich), Capak, P. (Spitzer Science Center), Carollo, M. (ETH), Scarlata, C. (U Minnesota), Scoville, N. (Caltech)

In my talk I will focus on our empirical model (Faisst et al. 2014, arXiv:1402.3604) in which we combine the observed UV-continuum LFs (from literature) and the observed Lyman-α line LFs (from literature as well as from our unique limits at $z \sim 7.7$) between $z = 6$ and $z = 8$ in order to study the change in Ly-α transmission. We find a strong decrease of Ly-α transmission of a fac-

tor of ~4 within this redshift range, clearly tracing a rapid evolution of the properties in the early universe. Various models (e.g., Santos et al. 2004, McQuinn et al. 2007) allow us to translate this change in Ly-α transmission into a change in absolute fraction of neutral hydrogen that we find to be >60% at $z \sim 8$. Interestingly, this result seems to be at odds with current WMAP constraints on the optical depth. The interpretation of the Ly-α transmission leading to the above fraction of neutral hydrogen is, however, degenerated. Changing assumptions on Ly-α escape fraction and clumping factor, for example, can change the above conclusion and can make the actual re-ionization process shallower and therefore could resolve the tension with WMAP. It is thus important to break this degeneracies by using simulations and/or observations.

Modeling infrared observations of high redshift galaxies to determine the escape fraction

Fernandez, E. (Kapteyn Astronomical Institute), Dole, H. (Institut d'Astrophysique Spatiale), Iliev, I. (U Sussex)

Going hand in hand in understanding reionization history is understand the escape fraction of ionizing radiation from galaxies at high redshifts. Unfortunately, constraining the escape fraction of high redshift galaxies is challenging, since the escape fraction can have complex dependencies on mass, redshift, the properties of the stars, and the internal structure of the galaxy. Therefore, instead of seeking the escape fraction of individual galaxies, we seek to understand the escape fraction from the global population. We discuss ways to link observations in the infrared, simulations, and analytical formalisms to constrain the global escape fractions of high redshift populations. This includes making use of the observations of cumulative light from reionization that may be observed in the cosmic infrared background, as well as theoretical modeling of individual galaxies.

Metal absorbers in inhomogeneous reionization models

Finlator, K. (DARK), Zackrisson, E. (U Stockholm)

The observed evolution of the cosmic star formation rate density can most easily be reconciled with the growth of the extragalactic ionizing background and the progress of cosmological reionization through an ionizing escape fraction that varies strongly with mass and weakly with redshift. I will begin by discussing how these pieces fit together within the framework of reionization simulations. Unfortunately, the star formation efficiency in faint systems is degenerate with the escape fraction, leading to a wide class of models that can match constraints. Observations of metal absorbers have the potential to break this degeneracy because the total mass of metals traces the total mass of massive stars formed, while the abundance ratios in different ions traces both the amplitude and the shape of the ionizing background. The interpretation is complicated, however, by the fact that new metals are formed and ejected as reionization proceeds. I will discuss how these factors interplay within the same simulations with a

view toward identifying observations that can be carried out using upcoming facilities.

A study of Lyman-α emission from low-redshift galaxies and its potential use as a tracer of Lyman continuum escape

Fleming, B. (U Colorado), McCandliss, S. (Johns Hopkins U)

Hydrogen Lyman-α has been suggested as a potential proxy for Lyman Continuum at high redshifts as it is the most prominent spectral line at the epoch of reionization. The hydrogen emission spectrum in a typical star-forming region is primarily the result of recombination following photoionization, therefore the number of LyC photons absorbed can be estimated from the hydrogen emission spectrum. The high resonant scattering cross section of the Lyman-α line along with its susceptibility to absorption by dust and velocity gradients add an additional level of escape complexity in comparison to the Lyman continuum. We present the results of a new Hubble Space Telescope – Advanced Camera for Surveys study of the Lyman-α emission from eleven $0.02 < z < 0.043$ star-forming galaxies. We show that diffuse Lyman-α emission is present in all eleven targets, however, on fine angular scales, especially in face-on spirals, emission is in close proximity to regions exhibiting continuum absorption, so the net Lyman-α flux can appear to be zero when averaged over large areas. We discuss the implications of using Lyman-α as a tracer of LyC emission and outline a potential strategy for using Lyman-α maps to guide Lyman Continuum observations in the local universe. We will also briefly discuss the Sub-Lyman-α Explorer (SubLymE); a proposed NASA Small Explorer mission to provide multi-color imaging in the 1020 – 1200 Å angstrom spectral window with 2 arc second resolution.

The escape of ionizing radidation from local starburst galaxies: revised Lyman continuum escape fractions for Tololo 1247-232 and Haro 11

Fremling, C. (U Stockholm), Zackrisson, E. (U Stockholm), Inoue, A. (Osaka Sangyo U)

We revisit the two local Lyman continuum leakers Haro 11 and Tol 1247-232. Both galaxies show measurable flux of ionizing photons at wavelengths below 900 Å in FUSE spectra. The ratio of the leaking <900 Å photons to the intrinsic production, i.e. the Lyman continuum escape fraction, has been previously estimated for both of these galaxies: ~2.4% for Tol 1247 (Leitet et al. 2013), and 3–10% for Haro 11 (Bergvall et al. 2006; Hayes et al. 2007; Leitet et al. 2011, 2013).

Here we present new escape fraction estimates, based on deriving the intrinsic Lyman continuum photon production from the total extinction-corrected Hα flux of the galaxies. Further, the total infrared luminosities of the galaxies are estimated, and used to correct the escape fraction estimates for dust absorption of the intrinsic Lyman continuum photons.

We find that our Hα and IR-based escape fraction estimates are quite different from previous results. For Tol 1247-232 we find that only a small fraction of the intrinsic Lyman continuum photons are absorbed by dust, resulting in an escape fraction of ~9%,

substantially higher than the previous estimate by Leitet et al. (2013). For Haro 11, on the other hand, we find that a substantial part of the intrinsic Lyman continuum photons are expected to be absorbed by dust, resulting in a final escape fraction of only ~0.8%, much lower than all previous estimates.

Cosmic Reionization on Computers

Gnedin, N. (Fermilab)

Cosmic Reionization On Computers (CROC) is a long-term program of numerical simulations of cosmic reionization. Its goal is to model fully self-consistently (albeit not necessarily from the first principles) all relevant physics, from radiative transfer to gas dynamics and star formation, in simulation volumes of up to 100 comoving Mpc, and with spatial resolution approaching 100 pc in physical units. We describe our numerical method, the design of simulations, the calibration of numerical parameters, and compare simulation results with the observational data.

Enabling radiative transfer on AMR grids in CRASH

Hariharan, N. (MPA), Graziani, L. (INAF), Ciardi, B. (MPA), Miniati, F. (ETH), Bungartz, H. J. (TUM)

We introduce a new version, CRASH-AMR of the cosmological Radiative Transfer (RT) code CRASH, enabled to use Adaptive Mesh Refinement grids (AMR). This new feature allows us to better resolve small scales in our radiative transfer simulations and to capture the ionization and temperature patterns in high density structures. We have tested the new release by performing the simulations established in the RT Code Comparison Project (RTCCP), finding an excellent agreement between the AMR and non-AMR version of CRASH. Additional simulations performed on realistic density fields obtained from the Santa Barbara project have shown different size and shape of the ionized regions as result of the increased resolutions. CRASH-AMR is hence able to provide a more accurate and detailed picture of the growth of HII regions and to allow simulations at much higher resolutions.

On the correction for the intergalactic attenuation of the direct Lyman continuum observation

Inoue, A. (Osaka Sangyo U)

The intergalactic attenuation against the Lyman continuum from galaxies must be corrected in order to estimate the escape fraction or emissivity of the continuum from direct observations. It has been made in a statistical way because of the lack of the information about the distribution of the intergalactic neutral hydrogen on the individual lines of sight for galaxies observed in their Lyman continuum. In this talk, I will present a latest one of this kind of model. In addition, I will also present a new way to obtain the information of the intergalactic hydrogen along the sight lines in a specific observing field. Finally, if possible, I may touch an attempt to make a simulation tailored to a specific observing field.

Constraints on LyC escape fraction from direct observations of z ~ 3 galaxies

Iwata, I. (Subaru Telescope)

We summarize constraints on LyC escape fraction for star-forming galaxies (Lyman break galaxies and Lyman-α emitting galaxies) at $z \sim 3$ based on Subaru / Suprime-Cam narrow-band imaging observations. The survey was conducted in the SSA22 field where a prominent proto-cluster at $z = 3.1$ has been identified. We will present our refined constraints on the average LyC escape fraction based on a sample of >300 star-forming galaxies. We will also compare our results with those by other authors at various redshifts and discuss a possible evolution of average LyC escape fraction. We will also present our plan to extend direct measurement of LyC escape fraction to higher redshifts using Subaru / Hyper Suprime-Cam.

Observational constraints of Lyman continuum leakage at redshift 4

Jones, T. (UCSB)

Our ability to detect ionizing Lyman continuum emission from galaxies at high redshift is fundamentally limited by absorption from the intervening intergalactic medium. An alternative approach is to measure the covering fraction of neutral hydrogen gas, i.e., the fraction of UV-luminous stars whose sightlines through the interstellar and circumgalactic media are optically thin to Lyman continuum radiation. Moderate resolution spectra of galaxies constrain the covering fraction and hence the Lyman continuum leakage via low-ionization metal transitions, and this technique can be applied at arbitrarily high redshifts provided the gas is modestly enriched (to ~1/20 solar metallicity). I will discuss results at $z = 2 - 4$ demonstrating that many UV-bright galaxies at these epochs have non-uniform covering fractions of neutral hydrogen, which may allow ionizing radiation to escape. The covering fraction is largely governed by outflows of cool gas driven by star formation feedback. Composite spectra as well as individual sources show demographic trends in the covering fraction, with typical galaxies having lower inferred covering fractions (hence higher ionizing escape fractions) at higher redshifts. Finally, I will discuss prospects for spatially resolved studies and for extending this work to higher redshifts.

Comparison of numerical and analytical methods for studying cosmic reionization

Kaurov, A. (U Chicago)

The methods for studying the epoch of cosmic reionization vary from full radiative transfer simulations to purely analytical models. While the numerical approaches are computationally expensive and are not suitable for generating many mock catalogues, the analytical methods are based on various assumptions and approximations. In this study, we perform a comparison of high resolution numerical simulations on an adaptive mesh with the most commonly used analytical models, including models of inhomogeneous reionization based on excursion set formalism. We examine which analytical approximations are valid and in what range of redshifts and scales. Subsequently, we discuss the limits of the analytical approach and the physical processes it fails to mimic. Our findings show that the analytical models typically have systematic discrepancy with numerical simulation; however, the combination of a few different analytical

methods can be well tuned to a particular numerical simulation. In conclusion, this combined approach can be used for describing the topology of ionization fields and for efficient generation of mock catalogs with similar statistical properties.

The role of environment in the near-zones of z ~ 7 QSOs

Keating, L. (U Cambridge), Haehnelt, M. (U Cambridge), Cantalupo, S. (UCSC)

The near-zones of bright high-redshift QSOs are a unique observational tool to study how reionization proceeds, as they allow us to push past the redshift at which, in general, the opacity in the Lyman-α forest becomes too large to extract detailed information. The brightness of the QSOs enables the taking of high-quality spectra, even at $z > 5$, and close to the QSO there is sufficient flux to study the ionization and thermal state of the IGM. Using zoomed-in initial conditions, I have resimulated the high-redshift IGM in a 40 Mpc/*h* radius around some of the most massive haloes in the Millennium simulation. I then post-process these hydrodynamical simulations with the 3D radiative transfer code RADAMESH to follow the progression of the ionization front after the QSO turns on. In this talk I will discuss the role environment plays in determining the shape of the ionization front and hence the size of the near-zone, by placing quasars of the same luminosity in a selection of haloes with different masses for a range of different initial neutral fractions. Based on the first full radiative transfer simulation of galaxy host haloes with masses as high as expected for the $z = 7.085$ QSO ULAS J1120+0641, I will critically assess the claim that the observed red damping wing in its spectrum suggests a substantial neutral fraction of the IGM at this redshift.

Variation in the escape fraction of ionizing photons from galaxies and the redshifted 21-cm power spectrum during reionization

Kim, H. (U Melbourne)

The observed power spectrum of redshifted 21-cm fluctuations is known to be sensitive to the astrophysical properties of the galaxies that drove reionization. Thus, detailed measurements of the 21-cm power spectrum and its evolution could lead to measurements of the properties of early galaxies that are otherwise inaccessible. We use a model for reionization which combines the hierarchical galaxy formation model GALFORM implemented within the Millennium-II dark matter simulation, with a semi-numerical scheme to describe the resulting ionization structure. Using this model, we study the effect of mass and redshift-dependent escape fractions of ionizing radiation on the ability of forthcoming experiments to constrain galaxy formation via the redshifted 21-cm power spectrum.

A new look at diffuse ionized gas in dwarf galaxies

Lee, J. (STScI)

I will present new results on diffuse Hα emission in the outskirts of nearby dwarf galaxies, which illustrate the propagation of Lyman continuum photons into the halos, and potentially out into the IGM. The results are

based on observations with the Magellan Maryland Tunable Filter, and are 8–10 times more sensitive in surface brightness than previous standard narrowband imaging.

Pushing the Cosmic Origins Spectrograph to the Lyman Limit

Leitherer, C. (STScI)

One of the major goals in cosmology is to understand how galaxies interact with the surrounding intergalactic medium (IGM). Studies of the circumgalactic medium provide insight into the escape of material and ionizing radiation from the host galaxy and the infall of matter from the IGM. These processes are intimately related and are ultimately responsible for the evolution of galaxies with redshift on the one hand, and for the cosmic reionization on the other. I will report on very recent results obtained with HST's Cosmic Origin Spectrograph in an attempt to constrain the mass outflow rates and Lyman radiation escape fraction in local Lyman-break analogs and star-forming galaxies. We have detections as well as significant upper limits in our sample. I will discuss the implications in the context of the properties of the ISM, star formation, and galaxy evolution and highlight similarities with galaxies at high redshift.

Escape of ionizing radiation from star formation selected galaxies at redshift 2.2

Melinder, J. (U Stockholm), Guaita, L. (Osservatorio di Monte Porzio), Östlin, G. (U Stockholm), Hayes, M. (U Stockholm), Murphy, D. (U Católica de Chile), Francke, H. (Joint ALMA Office)

The escape fraction of ionizing radiation (Lyman Continuum, or LyC radiation) in the high redshift universe is one of the most important quantities for studying the largely uncharted epoch of reionization, but also the most poorly constrained. At high redshifts ($z > 3$) galaxies that leak LyC radiation can be detected by using Lyman break selected galaxies, but this is not possible at lower redshifts. The Hα line is observable out to $z = 2.6$ in the near-infrared part of the spectrum, providing a redshift window that matches near-ultraviolet (NUV) HST imaging of LyC radiation, as well as ground based Lyman alpha (Ly-α) studies. Contrary to higher redshifts, the intergalactic medium is still largely transparent to ionizing photons at this redshift, and the usage of Hα mitigates the uncertainties from stellar models inherent in methods using the rest frame NUV continuum to estimate the intrinsic production of LyC photons.

Since the past few years, we are conducting the TRIDENT survey and perform ground based narrow band Ly-α and Hα imaging in fields with existing/planned HST UV imaging sensitive to LyC at $z = 2 – 2.6$. The use of narrow band imaging means that sources fainter than continuum selected methods can be probed, and the limits can be further improved by stacking the UV data.

We will present the first results from survey of star-forming galaxies behind Abell 1689, where we combine Hα narrow band imaging with deep HST NUV imaging to measure the escape of ionizing photons at $z \sim 2.2$ for the first time. The data have been obtained at the SOAR telescope with the SPARTAN instrument and covers approximately 10 sq.

arcmin (all of the HST/UVIS observation of the field is covered).

New analysis of LyC leaking z ~ 3 galaxies in the SSA22 field

Micheva, G. (Subaru Telescope), Iwata, I. (Subaru Telescope), Inoue, A. (Osaka Sangyo U)

We present the results of a Subaru Suprime-Cam deep imaging narrow-band observations of the SSA22 proto-cluster at $z \sim 3$. New analysis has increased the sample size to 38 objects with detections of ionizing flux in our specially designed narrow-band filter. Complementary FOCAS, LRIS, and VIMOS spectroscopic observations have been used to verify the redshift for a number of objects. If the redshift information is correct, approximately 20 objects are new LyC candidates. A number of objects show an apparent spatial offset between the ionizing and non-ionizing UV flux. We refine our analysis of these systems by comparing the Subaru data to high-resolution HST data in an attempt to reconcile the object colors with stellar population models. Some objects have very strong LyC flux, which may suggest a very metal-poor or even metal-free stellar population. We investigate the relationship between LyC leakage and other properties of the sample galaxies such as multi-band colors, luminosities, and morphologies to discuss the nature of the LyC galaxies.

Escape fraction of ionizing photons from high-redshift galaxies from reionization models

Mitra, S. (U of Western Cape)

The escape fraction, f_{esc}, of ionizing photons from high-redshift galaxies is a key parameter to understand cosmic reionization and star formation history. Yet, in spite of many efforts, it remains largely uncertain. We propose a novel, semi-empirical approach based on a simultaneous match of the most recently determined luminosity functions of galaxies in the redshift range $6 \leq z \leq 10$ with reionization models constrained by a large variety of experimental data. From this procedure, we obtain the evolution of the best-fitting values of f_{esc} along with their 2σ limits. We find that, averaged over the galaxy population, (i) the escape fraction increases from $f_{esc} = 0.068$ at $z = 6$ to $f_{esc} = 0.179$ at $z = 8$ and (ii) at $z = 10$ we can only put a lower limit of $f_{esc} > 0.146$. Thus, although errors are large, there is an indication of a 2.6 times increase of the average escape fraction from $z = 6$ to 8, which might partially release the 'starving reionization' problem.

A critical test of LyC leakage in star-forming galaxies at z ~ 3

Mostardi Rehagen, R. (UCLA), Shapley, A. (UCLA), Steidel, C. (Caltech), Nestor, D. (UCLA)

We present results from a survey for $z \sim 2.85$ Lyman-Continuum (LyC) emission in the HS1549+1933 field and place constraints on the amount of ionizing radiation escaping from star-forming galaxies. Using a custom narrowband filter (NB3420) tuned to wavelengths just below the Lyman limit at $z \geqq 2.82$, we probe the LyC spectral region of 49 Lyman break galaxies (LBGs) and 91 Lyman-α emitters (LAEs) spectroscopically confirmed at $z \geqq 2.82$. Four LBGs and seven

LAEs are detected in NB3420. We observe that many LyC-detected galaxies exhibit spatial offsets between their LyC and non-ionizing UV emission and are characterized by extremely blue NB3420-V colors, corresponding to low ratios of non-ionizing to ionizing radiation that are in tension with current stellar population synthesis models.
To look deeper into the intriguing questions raised by these observations, we also present preliminary results from follow-up HST imaging obtained in this field. With high-resolution photometry in rest-frame U, V, J, and H, we aim to study the kiloparsec-scale structure of the LyC emitters, constrain the redshifts and stellar populations of individual subcomponents of each galaxy, and determine whether the offsets and blue colors of the LyC-emitters are merely a result of foreground contamination or are indicative of physical processes relevant to the role of star-forming galaxies in reionization.

Constraints on Lyman continuum optical depth from Ly-α, C II, and C II*

Oey, M. S. (U Michigan), Jaskot, A. (U Michigan)

We present a unified interpretation of the Lyman-α, C II, and C II* spectral lines in terms of optical depth and line-of-sight geometry for Lyman-α emitters (LAEs). For Lyman-continuum emitters (LCEs), Ly-α will be optically thin, which can be inferred from its line profile and escape fraction. The relative absorption and emission strengths of C II and C II*, respectively, constrain the orientation of low optical depth regions relative to our line of sight. These diagnostics are consistent with HST COS observations of four, extreme Green Pea galaxies at $z \sim 0.1$, confirming that objects with extreme [O III]/[O II] ratios are often likely to be LCEs.

Modelling of HST/COS Lyman-α spectra of low-z LyC leakers

Orlitova, I. (Astronomical Institute ASCR), Verhamme, A. (Geneva U), Schaerer, D. (Geneva U)

I will present our search for low-redshift LyC leakers based on their Lyman-α spectra, and possible applications to the high-redshift universe. We apply numerical Lyman-α transfer models to fit the observed profiles. From the best fits, we put constraints on the neutral hydrogen column densities and dust amounts, as well as the outflow velocities affecting the ISM, and evaluate thus the possibility of LyC escape.
In parallel, we measure the Ly-α spectral profile parameters (peak positions, broadening) and search for the LyC leaking signatures as predicted by Verhamme et al. (2014). We confront them with independent leakage indicators such as the saturation of the low-ionisation-state absorption lines, and the [OIII]/[OII] line ratios. Among the ~50 nearby galaxies with Lyman-α spectra available through the HST/COS archive, we find most favourable conditions for LyC leakage in Green Peas and compact dwarf galaxies. I will discuss the connections to high-redshift sources.

The escape fraction of ionizing photons from the first billion years simulation

Paardekooper, J.-P. (MPE), Khochfar, S. (Royal Observatory Edinburgh), Dalla Vecchia, C. (IAC)

One of the main challenges in determining the escape fraction of ionizing radiation, both in observations and simulations, is obtaining large samples of galaxies. Using the results from the First Billion Years project, a high-resolution cosmological galaxy formation simulation suite that we post-processed with detailed radiative transfer simulations, we were able to determine the escape fraction in a sample of more than 57,000 haloes between redshift 26 and 6. In addition to studying how the escape fraction depends on the properties of the halo in which the galaxies are forming, our very large sample allows us to study the variation of the escape

fraction in galaxies forming in haloes with similar properties. I will show which physical processes drive the escape of ionizing radiation from the first galaxies and the consequences for the contribution of galaxies to reionization.

The cross-power spectrum between 21cm emission and galaxies in hierarchical galaxy formation models

Park, J. (U Melbourne), Wyithe, S. (U Melbourne), Lacey, C. (Durham U)

The correlation between 21cm fluctuations and galaxies is sensitive to the astrophysical properties of the galaxies that drove reionization. I will present the evolution of the cross-power spectrum between 21cm emission and galaxies using the hierarchical galaxy formation model GALFORM implemented within the Millennium-II dark matter simulation, with a semi-numerical scheme to describe the resulting ionization structure. Our work find that the feature in the cross-power spectrum corresponding to the size of ionized regions is significantly affected by supernovae feedback. I will also present predicted observational uncertainties of the cross-correlation coefficient based on specifications of the Murchison Widefield Array (MWA) combined with galaxy surveys.

Messy Lyman-α emitters at $z \sim 3$ as likely sites of Lyman continuum leakage

Rauch, M. (Carnegie Observatories)

Ultra-deep spectroscopic surveys for Lyman-α emitters at $z \sim 3$ keep turning up sources that show unusually high equivalent widths for Lyman-α, anisotropic and spatially highly extended emission, and morphologically disturbed and apparently very blue stellar populations, i.e., conditions that are likely to be conducive to the enhanced production and escape of ionizing photons. While these sources are generally too faint to detect a leaking Lyman continuum directly, they are quite common, and may represent an increasing fraction of the galaxy population toward higher redshift.

Lyman continuum leakage in dwarf star-forming galaxies at $z \sim 1.2$

Rutkowski, M. (U Minnesota), Scarlata, C. (U Minnesota), Malkan, M. (UCLA)

We present results of a direct search for leaking Lyman Continuum from low-mass ($\sim 10^8$ $M_\odot$) star-forming galaxies at $0.95<z<1.5$ in the CANDELS fields (COSMOS, GOODS-South & North, and AEGIS). We study a well-defined flux-limited sample of about 2000 galaxies, spectroscopically identified by the Hα emission observed in WFC3

grism spectroscopy. The combination of deep GALEX UV data for this field and the Hα luminosity allow us to measure for the first time the absolute escape fraction of LyC photons for galaxies at this redshift. Furthermore, the sample includes approximately 400 sub-M* strong Hα emitters; such dwarf SFGs are thought to be the analogs of the sources that reionized the universe. The results of a stacking analysis of the GALEX data confirms an unambiguous detection of FUV flux – indicative of leaking LyC in AGN at this redshift. A similar stacking analysis of these deep GALEX data also reveals a marginal detection of FUV flux in low-mass strong Hα emitters. We discuss the implications of these measurements for the role low-mass galaxies serve in the cosmic reionization of the neutral hydrogen in the high-redshift universe.

Deep HST searches for Lyman continuum from galaxies at z ~ 2 – 3

Siana, B. (UC Riverside)

Our group has been conducting several HST searches of leaking Lyman continuum from faint galaxies at $2.4 < z < 3.2$. Using the same data, we have also been quantifying the amount of star formation in low luminosity galaxies at these epochs. Together, these two measurements greatly constrain the contribution of star-forming galaxies to the ionizing background at its peak epoch. I will review our studies and compare to recent results. In particular, I will emphasize the importance in using strong lensing to measure escaping Lyman continuum.

Investigating the ionizing escaping radiation at high redshift (z > 3)

Vanzella, E. (INAF)

The direct observation of Lyman continuum leakage is still challenging, especially at high redshift where it is strongly limited by the severe IGM attenuation. Indirect methods are needed to set constraints to the escape fraction of ionizing photons close and during the Reionization epoch ($z > 6$). A clear observational picture on how the ionizing radiation escapes from high-redshift sources, how it is spatially distributed and how it relates to the other galaxy/AGN physical properties is still missing. However, recent progress has been made on this topic. I will report on a study of relatively bright $L \geqq$ L* LyC emitter candidates at $z \geqq 3$ by looking at their ionizing and non-ionizing regimes exploiting the GOODS/CANDELS surveys and spectroscopic campaigns at VLT/LBT. The invstigation of very faint $L \ll$ L* luminosities can be performed through strong lensing magnification. In this regard, the discovery of faint $L < 0.1$L*, low mass, and very blue ($\beta < -2.5$) star-forming galaxies at $z \sim 6.0 – 6.5$ in the Frontier Fields galaxy clusters will be also reported and their (possible) ionizing nature discussed.

On the use of Lyman-α to detect Lyman continuum leaking galaxies

Verhamme, A. (Geneva U), Orlitova, I. (Astronomical Institute ASCR), Schaerer, D. (Geneva U), Hayes, M. (Stockholm U)

We propose to infer ionising continuum leaking properties of galaxies by looking at their Lyman-α line profiles. We carried out

Lyman-α radiation transfer calculations in two models of HII regions which are porous to ionizing continuum escape: 1) the so-called "density bounded" media, in which massive stars produce enough ionizing photons to keep the surrounding interstellar medium transparent to the ionizing continuum, i.e almost totally ionized, and 2) "riddled ionization-bounded" media, surrounded by neutral interstellar medium, but with holes, i.e. with a covering factor lower than unity. The Lyman-α spectra emergent from these configurations have distinctive features: 1) a "classical" asymmetric redshifted profile in the first case, but with a small shift of the maximum of the profile compare to the systemic redshift (V_{peak} < 150 km/s); 2) a main peak at the systemic redshift in the second case (V_{peak} = 0 km/s), with, as a consequence, a non-zero Lyman-α flux bluewards the systemic redshift. Assuming that in a galaxy leaking ionising photons, the Lyman-α component emerging from the leaking star cluster(s) dominates the total Lyman-α spectrum, the Lyman-α shape may be used as a pre-selection tool to detect Lyman continuum (LyC) leaking galaxies, in objects with well determined systemic redshift, and high spectral resolution Lyman-α spectra (R ≧ 4000). The examination of a sample of 10 local starbursts with high resolution HST-COS Lyman-α spectra and known in the literature as LyC leakers or leaking candidates, corroborates our predictions.

Propelling reionization with the faintest galaxies

Wise, J. (Georgia Institute of Technology)

I will present results from a suite of cosmological radiation hydrodynamics simulations that focus on the transition from the first stars to the first galaxies. Each simulation captures the radiative and chemical feedback from ~300 first stars, leading to the formation of a 10^9 solar mass dwarf galaxy at z = 7 that has a stellar population with a tight metallicity distribution function centered at 0.01 of solar metallicity. This agrees with the observed luminosity-metallicity relation in local dwarf galaxies. I will also demonstrate that these faintest galaxies are the primary driver of the reionization of the universe, only to be suppressed by photo-heating at later times, perhaps evolving into a subset of dwarf galaxies in the local universe.

The escape of ionizing photons from Lyman-α emitters at the epoch of reionization

Yajima, H. (U Edinburgh)

A large number of high-redshift galaxies have been discovered via their narrow-band Lyman-α line or broad-band continuum colors in recent years. The nature of the escaping process of photons from these early galaxies is crucial to understanding galaxy evolution and the cosmic reionization. Here, we investigate the escape of Lyman-α, ionizing photons and non-ionizing UV-continuum from galaxies by combining a cosmological hydrodynamic simulation with three-dimensional multi-wavelength radiative transfer calculations. We find that the escape fraction of these different photons shows a complex dependence on redshift and galaxy properties: the escape fraction of Lyman-α and non-ionizing UV continuum

photons appear to evolve with redshift, and they show similar, weak correlations with galaxy properties such as mass, star formation, metallicity, and dust content, while the escape fraction of ionizing photons remains roughly constant at ~0.2 from $z \sim 0 - 10$, and it shows the weak mass dependence. In addition, we find a relation between the emergent Lyman-α luminosity and the ionizing photon emissivity of Lyman-α emitters (LAEs). By combining this relation with the observed luminosity functions of LAEs at different redshifts, we estimate the contribution from LAEs to the cosmic reionization. Our result suggests that ionizing photons from LAEs alone are not sufficient to ionize IGM at $z > 6$, but they can maintain the ionization of IGM at $z \sim 0 - 6$.

Probing Lyman continuum leakage from galaxies in the reionization epoch

Zackrisson, E. (Stockholm U), Inoue, A. (Osaka Sangyo U), Jensen, H. (Stockholm U)

If galaxies are to explain the reionization of the Universe, these objects must have been leaking Lyman continuum (LyC) radiation into the intergalactic medium at $z > 6$. How does one demonstrate that this really happened? The escaping LyC radiation can be measured directly for galaxies at lower redshifts, but the opacity of the intergalactic medium precludes such measurements throughout the actual reionization epoch. In a recent paper (Zackrisson et al. 2013, ApJ, 777, 39), we argue that since LyC leakage leaves tell-tale signatures in the spectra of galaxies at non-ionizing wavelengths, spectroscopy with the upcoming James Webb Space Telescope should be able to provide indirect constraints on the LyC escape fractions of individual objects up to $z \sim 9$.

Social Programme

Conference dinner

The conference dinner will take place at the restaurant Hasselbacken (see Figures 1 and 2) on Thursday, August 14 at 6 p.m. The restaurant is situated on the green island Djurgården, home of the Royal National City Park and many of Stockholm's top museums and attractions. The islands Skeppsholmen and Gamla Stan are just a short boat trip away. You will have the chance to visit the open-air museum Skansen just next door after dinner, as it is open until 10 p.m.

The dinner is free of charge. Accompanying persons pay around 620 SEK, children under 13 pay only a small sum. If you have not registered for the dinner, or forgot to mention food allergies or that you prefer a vegetarian dinner, please talk to the LOC as soon as possible.

Figure 1 Location of the Restaurant Hasselbacken

Figure 2 Close-up view of the restaurant location

Meeting place & time: 6:00 p.m. inside the Restaurant Hasselbacken

How to get there from Albanova: Bus 44 (*Skansen*) goes directly from *Ruddammen* to *Skansen* on Djurgården. The bus stop closest to the restaurant is *Gröna Lund*. You can find travel information (including Djurgården ferry) on the SL website.

Excursion

We offer a small excursion during the evening of Friday, August 15th.

Rooftop tour

"Things may be different in other parts of the world, but in Stockholm people hardly ever live in a little house of their own on top of a roof. But Karlsson does. He is a very small, very round, and very self- possessed gentleman—and he can fly!"

— "Karlsson on the roof" by Astrid Lindgren

If you ever wanted to feel like Karlsson on the roof, then this tour is for you! Get a bird's eye view of Stockholm from the rooftops of the city. You will walk along the rooftops of some of the city's most historical buildings and learn about Stockholm's history during this guided climbing/sightseeing tour. You can find more information on the organizer's website.

Figure 3 Meeting place for the rooftop tour

Meeting place & time: ~6:45 p.m. at the statue of Birger Jarl, right at the center of Birger Jarls Torg on the small city island Riddarholmen (see Figure 3).

How to get there from AlbaNova: T-Bana (subway) from *Tekniska högskolan* to *Gamla Stan*, from there it is a short walk of about 6 minutes to the statue of Birger Jarl. You can find travel information on the SL website.

Duration: ca. 75 min.

Price: 595 SEK per person (incl. VAT). Payment method: in cash at the registration (August 13).

Important: Read the safety rules before you register!

(in short: >150cm/4.86ft, <120kg, no drugs or alcohol, no high heels, no cardiovascular problems, no fear of heights or tendency to faint)

Travel Information

From the airport

Figure 4 Location of the Stockholm Arlanda airport

Figure 5 Map of the Stockholm Arlanda airport

The main airport is Stockholm Arlanda, located around 40 km north of Stockholm and around 30 km south of Uppsala. There are several ways to go from Arlanda airport to the city center, in order of increasing complexity:

- Arlanda Express: the airport train is with 20 minutes the fastest connection between Arlanda and the central station, with no stop in between. It departs every 15 minutes. A one-way ticket costs 260 SEK, a return ticket 490 SEK. In August, tickets are significantly

cheaper when several people travel together. You can easily find the train station at Arlanda, as it is well signposted.

- Flygbussarna: the airport coaches depart every 10 minutes just outside the terminals 2, 4 and 5 and it takes about 40 minutes to reach the city centre. A ticket costs 105 SEK. The Flygbussarna also connects the other two airports of Stockholm, Bromma and Skavsta, with the city centre (75 resp. 139 SEK).

- Taxi: This is the most expensive option due to the relatively large distance between the airport and and the city center. If you choose this option, ask for a fixed price, which is available from the major taxi companies (Taxi 020, Taxi Kurir, Taxi Stockholm, Taxi Solna). The price is then around 500 SEK.

- Pendeltåg: the commuter train takes you in 38 minutes to the city center. The train station Arlanda C is located in SkyCity between Terminals 4 and 5. This option makes sense if your hotel is located near a Pendeltåg station of line J38 Uppsala-Älvsjö, or if you want to use public transport during your stay in Stockholm and need to avoid extra costs. Ticket information and fares are detailed below in the Public Transport section. To enter or leave Arlanda airport by Pendeltåg, you need to pay an extra fee of 75 SEK.

- Bus/Pendeltåg: If you really need to save money and want to avoid the 75 SEK fee for leaving Arlanda by Pendeltåg, you can take Bus 583 to Märsta station and from there the Pendeltåg J36. This way it takes about one hour to reach the city centre. Ticket information and fares are detailed below in the Public Transport section. As it is not possible to purchase tickets onboard regular buses, you first have to go to the entrance of the Pendeltåg station in SkyCity to purchase a ticket. Bus 583 departs just outside Terminals 2, 4, 5 and SkyCity.

Public Transport

Detailed information about the public transport system can be found on the SL website, and about the tickets here. Before you can use the public transport, you need to purchase a ticket at one of the ticket offices at commuter rail stations (Pendeltåg), SL centers and ticket agents like Pressbyrån, Seven-Eleven and certain supermarkets. If you arrive at Arlanda and want to use the Pendeltåg, you can buy it directly at the entrance to the Pendeltåg. The SL center or Pressbyrån at Stockholm Central (the central station) would be another possibility to purchase a ticket shortly after your arrival. If you stay in Stockholm for less than 72 hours, you can buy a single use travel card for 24 or 72 hours (115 resp 230 SEK). For most other ticket options you have to purchase an SL Access card for 20 SEK. The SL access card then has to be charged

with a ticket (e.g., 7-day travel card for 300 SEK) which can be done at the previously mentioned places or at one of the self- service ticket machines at subway and train stations. The SL access card can be re-used at your next visit to Stockholm.

It is not possible to purchase tickets onboard busses!

With the travel card you can use the subway (Tunnelbana), the commuter train (Pendeltåg), busses, tram, the Djurgården ferry as well as the regional trains Roslagsbanan, Saltsjöbanan, Lidingöbanan, Tvärbanan and Nockebybanan to travel throughout the county of Stockholm. However, to enter or leave Arlanda airport by pendeltåg, you need to pay an extra fee of 75 SEK. Please use http://sl.se/en to plan your trip.

Getting to AlbaNova

The easiest way to go to AlbaNova is by public transport. The bus stop of the bus lines 43 and 44 Ruddammen is just outside the building. Leave the bus at the last stop Ruddammen, walk a

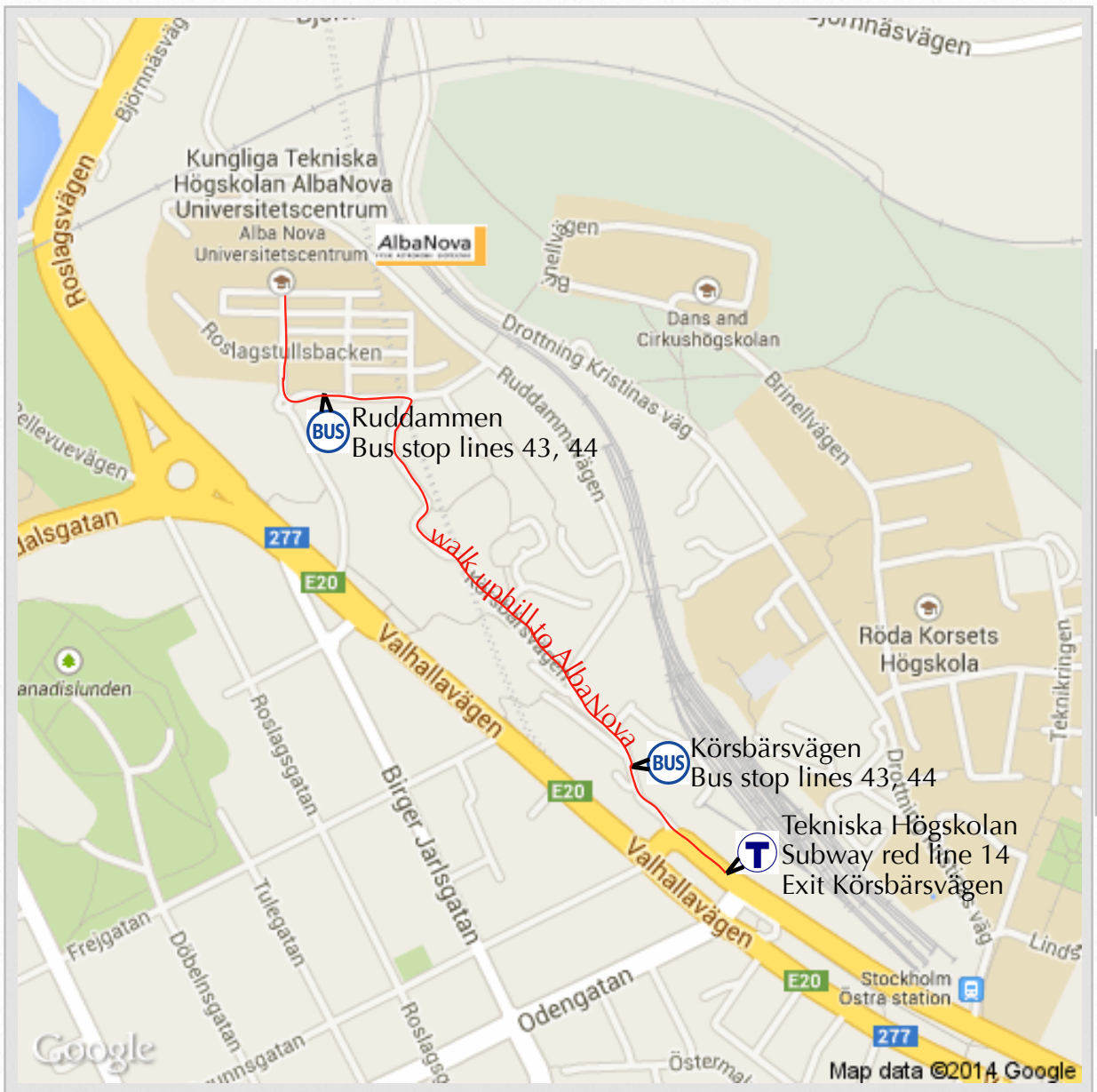

Figure 6 Getting to AlbaNova

The AlbaNova building

few meters in the travel direction of the bus, turn right at the roundabout and go straight until you hit the AlbaNova building.

The closest subway station is Tekniska Högskolan (red line 14 in the direction of Mörby Centrum, if you come from the city centre). Take the exit to Körsbärsvägen. You can walk up the hill to AlbaNova (approx. 10 minutes) or take bus 43 or 44 from the bus stop located about 150m from the subway exit. Figure 6 shows the mentioned subway and bus stops as well as the shortest walk up the hill from the subway.

If you stay at one of the suggested hotels, you can walk to AlbaNova within about 5-25 minutes.

Local Information

Lunch options near AlbaNova

Most restaurants in Stockholm serve lunch between around 11a.m. and 2p.m. If they have a special lunch menu, it is advertised as “Dagens lunch” or “Dagens rätt” for a special price. In many restaurants this includes bread, simple salad like coleslaw, water and coffee. Many of the restaurants shown in Figure 7 offer lunch for take-away. Traditional Swedish food is called “husmanskost” and is usually rich in meat, fish, dairy and eggs. Typical Swedish vegetables are root vegetables. There are usually little or no vegetarian or vegan options at Swedish restaurants, but generally people are helpful in identifying ingredients and offering alternatives. In Sweden, gluten and lactose intolerance awareness is high.

Around the exits of the subway station *Tekniska Högskolan* on Valhallavägen there are several small lunch places (e.g., Pizza, Sushi, Fast food). They are not shown on the map. There is a small ICA supermarket on Birger Jarlsgatan 122, in case you need to buy something or want to prepare your own lunch. They have a small salad bar. Two more supermarkets (ICA and Coop) and a small health food store (Ortagubben, no lunch option) are located somewhat further away on Odengatan between Valhallavägen and Sveavägen.

1. Restaurang Entré

Roslagstullbacken 21. The AlbaNova cantine, located in the 3rd floor. They serve three different dishes (meat, fish, veg) including bread, drink, salad and coffee for SEK 89. They also sell sandwiches, packaged salads (SEK 65), salad from the salad bar (small: SEK 25, large: SEK 45; on most days this is the only vegan option), cakes, ice-cream and bottled drinks. No cash, credit card only.

2. Värdshuset Kräftan

Roslagsvägen 101. Lunch restaurant on one of Stockholm University’s campuses. Nicely located close to the lake Brunnsviken. They offer a lunch buffet for SEK 105 (meat, fish, veg, vegetarian or vegan soup and stew, salad buffet, bread).

3. Tullfritt Grill

Valhallavägen 11. Fastfood. Offers Hamburgers, Hotdogs, Swedish tunnbröd-rulle etc.

4. Phi-Phi Island

Birger Jarlsgatan 121. Thai restaurant. They offer a variety of dishes for around SEK 140 – SEK 200.

5. Don Corleone

Birger Jarlsgatan 115A. Pizzeria. Lunch from SEK 70.

6. Prime Burger Company

Birger Jarlsgatan 101. American. Meals from ~SEK 80.

7. Due Fratelli

Birger Jarlsgatan 95.Italian Restaurant. Lunch SEK 89.

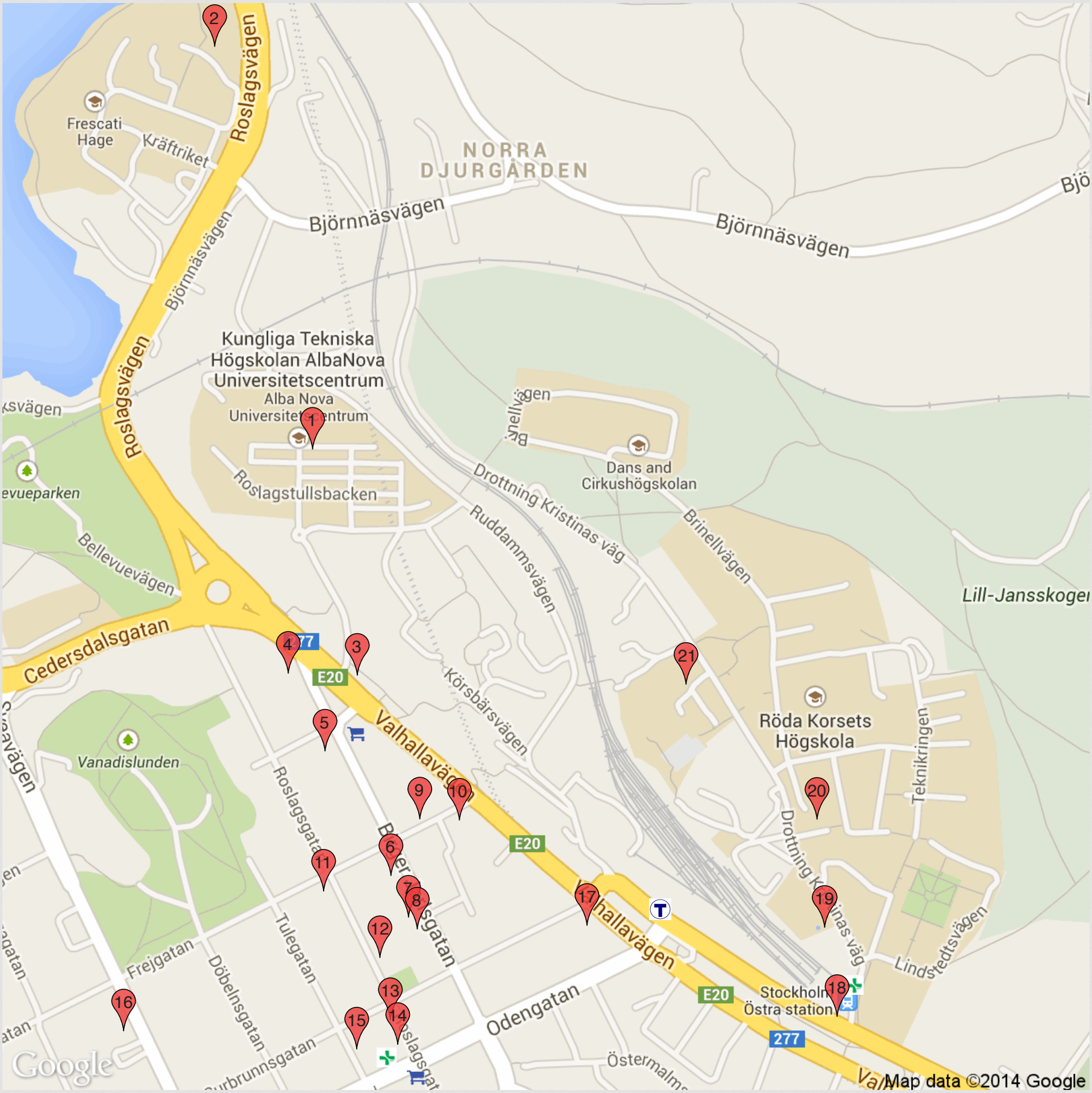

Figure 7 Map of restaurants near AlbaNova (Map data ©2014 Google)

8. Ramen Ki-Mama
Birger Jarlsgatan 93. Japanese. Meals from ~ SEK 115.

9. SushiZen
Frejgatan 6. Sushi. Lunch from SEK 75.

10. Indian Town
Frejgatan 3. Indian Restaurant.

11. Sibiriens Soppkök
Roslagsgatan 25. Soups. Lunch around SEK 70 – SEK 150.

12. Motwalls
Roslagsgatan 20. Swedish Specialties. Lunch around SEK 100 – SEK 200.

13. Bollywood
Roslagsgatan 9. Indian Restaurant. Lunch around SEK 90.

14. Restaurang Dagobert
Roslagsgatan 7. Restaurant and Pizzeria. Lunch from SEK 79.

15. Restaurang Tulegården
Tulegatan 22. Swedish. Lunch SEK 85. One vegetarian option per week for SEK 98.

16. Kokyo
Sveavägen 105. Chinese and Japanese. Meals around SEK 100 – SEK 160. Many vegetarian/vegan dishes.

17. Restaurang Cypern
Valhallavägen 50. Greek restaurant. Lunch SEK 85.

18. Östra Station Järnvägsrestaurangen
Valhallavägen 77. Swedish. Lunch SEK 92. No vegetarian option.

19. Restaurang Nymble
Drottning Kristinas Väg 15, 2nd floor. Student cantine on KTH campus. Lunch SEK 75.

20. Syster & Bror
Drottning Kristinas Väg 24. Restaurant on KTH campus. Lunch SEK 85.

21. Restaurang Q
Osquldas väg 4. Restaurant on KTH campus. Lunch SEK 68. Vegetarian-friendly.

Restaurants in central Stockholm

Figure 8 shows some suggestions for restaurants at various locations in central Stockholm. The choice in restaurants is quite large as any place serving alcohol has to have a proper kitchen, so basically any pub or bar is also a restaurant.

Stockholm has a good selection of restaurants, both serving Swedish and international food. Traditional Swedish cuisine offers both a lot of fish and meat (pork, beef, but also meat from reindeer and moose/elk).

There are many small cheap places serving pizza, kebab or sushi, but they will often have limited seating (mostly take away).

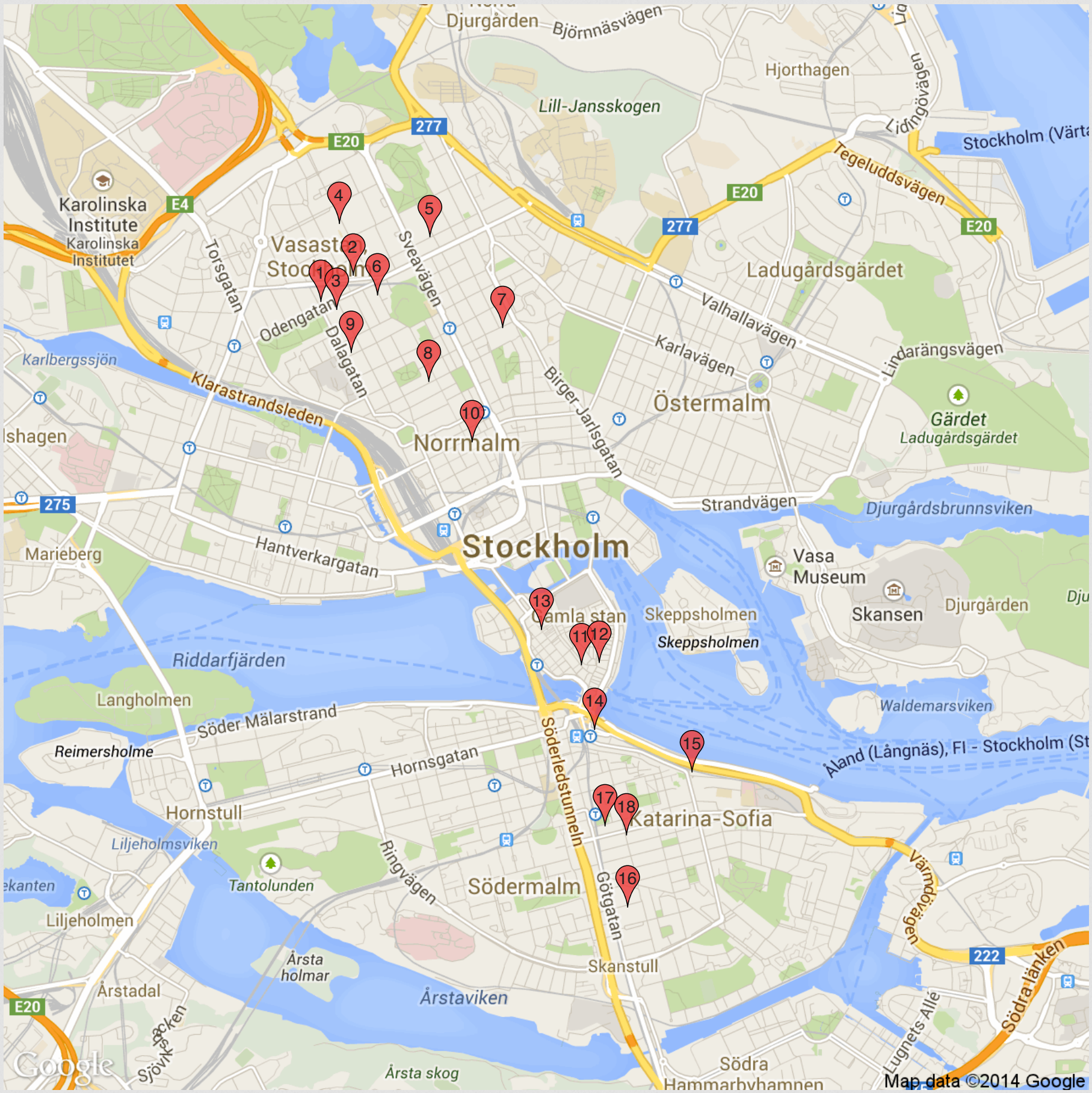

Figure 8 Restaurants in central Stockholm (Map data ©2014 Google)

1. Tennstopet

Dalagatan 50 (Subway Odenplan). Traditional Swedish food. Has a restaurant and bar part, you can eat in both.

2. Tranan

Karlbergsvägen 14 (Subway Odenplan). Traditional Swedish food. Popular place, may be difficult to get places for large groups. Bar in the basement.

3. Ristorante Pompei

Odengatan 83 (Subway Odenplan). Fairly standard Italian restaurant in a convenient location.

4. Cliff Barnes Restaurang

Norrtullsgatan 45 (Subway Odenplan). Swedish/International. Popular among students. Becomes bar/club later in the evening.

5. Andalucía

Surbrunnsgatan 37 (Subway Odenplan). Spanish. Friendly place, sometimes with live music.

6. Vasa's Bar & Matsal

Norrtullsgatan 15 (Subway Odenplan). Swedish. Bar/restaurant with no frills.

7. Café Piastowska

Tegnérgatan 5 (Subway Rådmansgatan). Polish restaurant, run by a Polish family. Very friendly, with a large basement.

8. Restaurang Jai Thai

Kammakargatan 44 (Subway Rådmansgatan, Hötorget). Thai restaurant, formerly known as Sabai-Sabai. Recommended by Lonely Planet.

9. O'Mamma Mia

Kungstensgatan 62 (Subway Odenplan, Rådmansgata, S:t Eriksplan). Pizzeria. They have a separate vegan menu with a large variety of vegan pizzas and some mexican dishes.

10. Voltaire Restaurang

Hötorget 13 (Subway Hötorget). Health food. Restaurant in the basement of PUB, Stockholm´s oldest department store. Offers a variety of raw vegan, vegan, vegetarian and seafood dishes, smoothies and green smoothies. Attached is a health food market. Open Mon-Fri 10-19, Sat 10-18, Sun 11-17.

11. Ardbeg Embassy

Västerlånggatan 68 (Subway Gamla Stan). Swedish. Good place for reindeer and moose. Restaurant in the back of a bar with whiskeys and Swedish beers.

12. Den Gyldene Freden

Österlånggatan 51 (Subway Gamla Stan). Swedish. Old traditional restaurant dating back to 1722 with medieval cellars. Expensive.

13. Hermitage

Stora Nygatan 11 (Subway Gamla Stan). Vegetarian. All-you-can-eat buffet for SEK 110 including salads, several warm dishes, bread, water, tea. Usually everything except one warm dish and one salad or so is vegan. Omnivores generally like it, too.

14. Gondolen

Stadsgården 6 (Subway Slussen). Swedish/French restaurant with a spectacular view, located 33m above the water at Katarinahissen. Expensive.

15. Hermans

Fjällgatan 23B (Subway Slussen, Medborgarplatsen). Vegetarian restaurant with a spectacular view over Stockholm. All-you-can-eat vegetarian buffet including bread, water, coffee and tea. During summer they may have barbecue in the garden. Most dishes are vegan. They also have great raw vegan desserts.

16. Pelikan

Blekingegatan 40 (Subway Skanstull, Medborgarplatsen). Traditional Swedish large beer hall.

17. Kvarnen

Tjärhovsgatan 4 (Subway Medborgarplatsen). Traditional Swedish large beer hall.

18. Soldaten Svejk

Östgötagatan 35 (Subway Medborgarplatsen). Czech. Popular place to go for beer and Schnitzel, and they also offer vegetarian alternatives.

Sightseeing in Stockholm

The Stockholm Visitor Center provides information about interesting sights, activities, restaurants etc. in Stockholm. A travel guide in pdf format is also available from them.

Useful apps

- Swedavia: Swedish Airports Flight manager and travel planner for flights from/to Swedish airports, including check-in function. Free.
- City Maps 2Go: Detailed offline maps. Useful anywhere, not just in Stockholm
- Stockholm 3D: Free offline map with 2D and 3D view and points of interest.
- Res i STHLM: Free journey planner for Stockholm public transport (SL).

Money

The official currency is the Swedish Krona (SEK).
1 EUR = 9.12351 SEK
1 US$ = 6.71039 SEK
1 GBP = 11.4219 SEK (Jun 24, 2014)

Almost anything can be paid by credit card, so you do not necessarily have to change money. Some places, like the AlbaNova cantine, only accept credit cards and no cash. Very few places accept cash only (e.g., street food, public toilets).

If you use a foreign credit card to buy something, you might be asked to show your passport. What they are looking for is the personal number. At less touristy places people might be a bit

puzzled if you do not have a personal number, but it is usually sufficient to show them your date of birth on your passport.

Internet

Eduroam is available at all University campuses in Stockholm, at Arlanda airport and various other locations. At AlbaNova we will give every participant access to the local wireless network. Most hotels offer free wireless access.

Should you in addition need an internet connection on the way or the possibility to make phone calls, several providers offer pre-paid cards ("Kontantkort"). They are sold, e.g., at Pressbyrån.