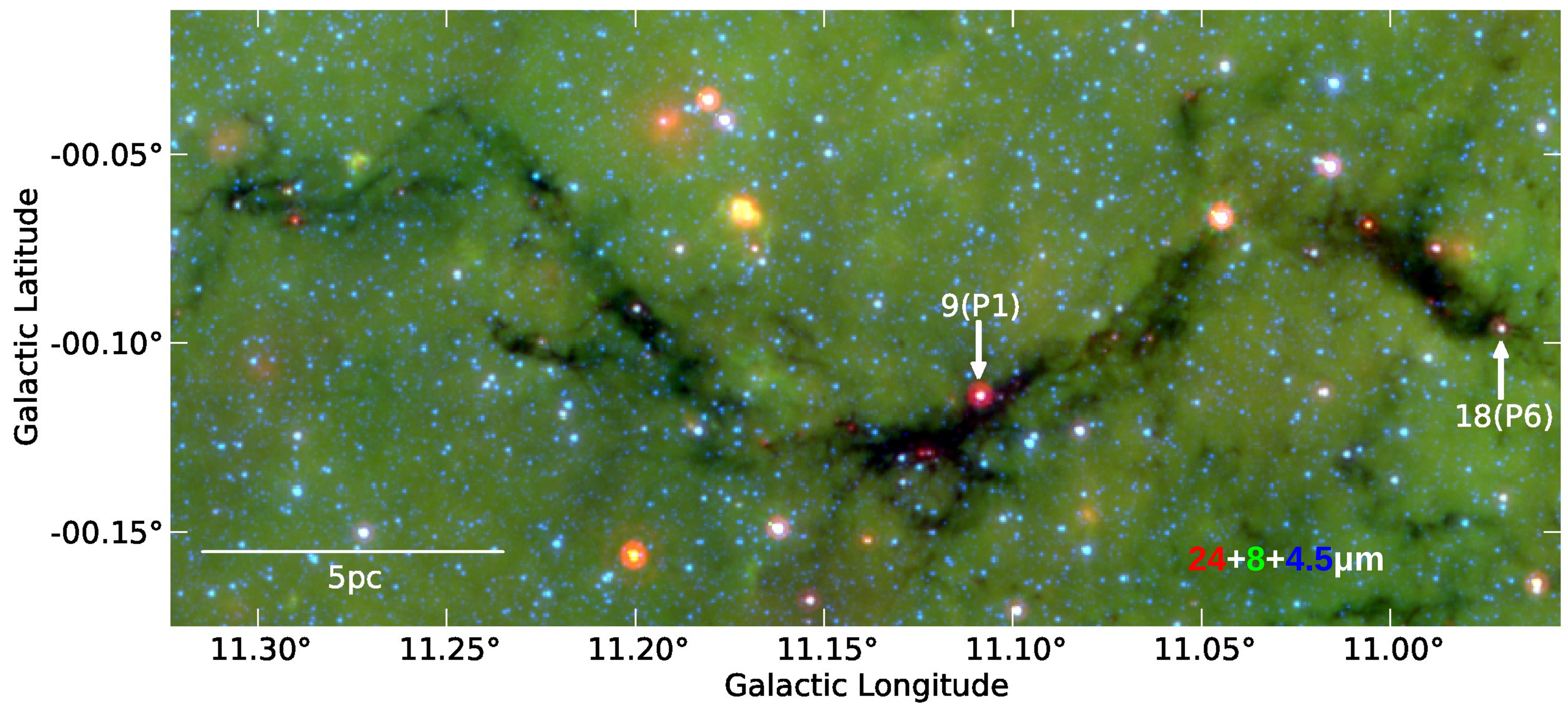
The Sequential Growth of Star Formation Seeds in the Galactic "Snake": Infrared Dark Cloud G11.11-0.12

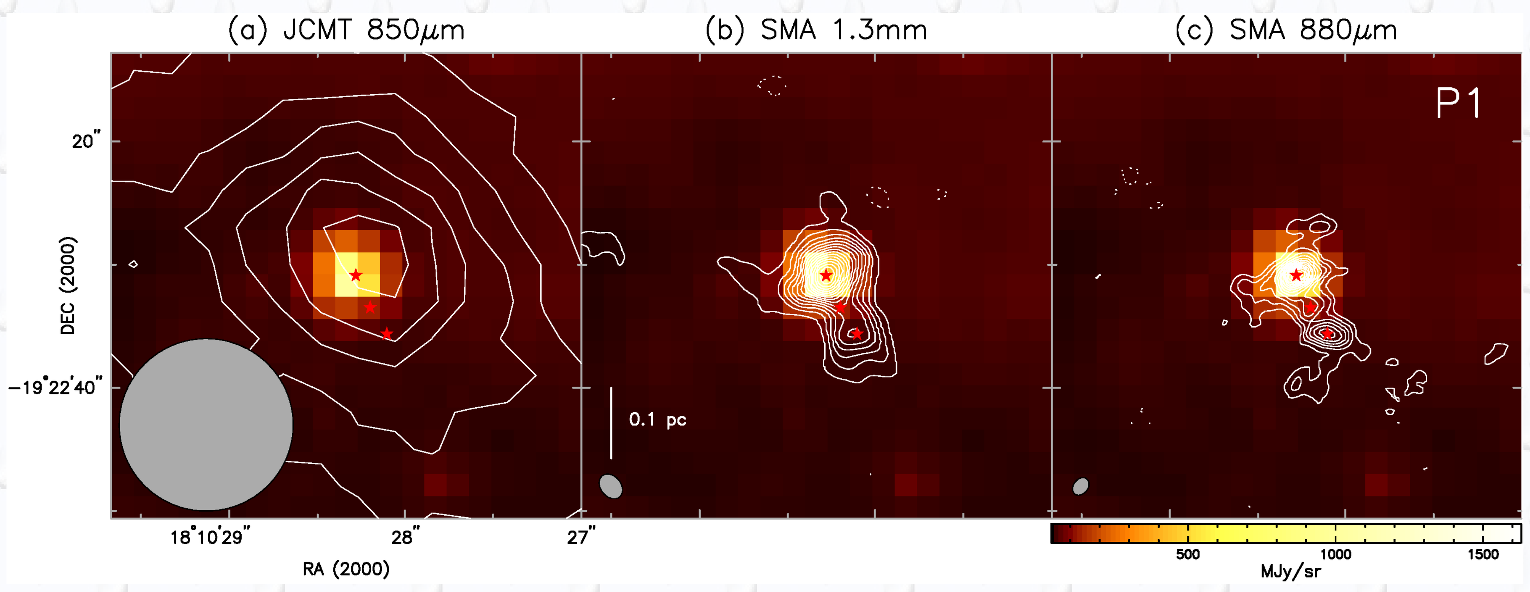
PPVI 2013 Heidelberg
Poster #1S025
Contact me at kwang@eso.org

Ke Wang (ESO), Qizhou Zhang (CfA), Leonardo Testi (ESO), Yuefang Wu, Huawei Zhang (PKU), Floris van der Tak (SRON), Friedrich Wyrowski (MPIfR), Thushara Pillai, Sean Carey (Caltech), Sarah Ragan, and Thomas Henning (MPIA)



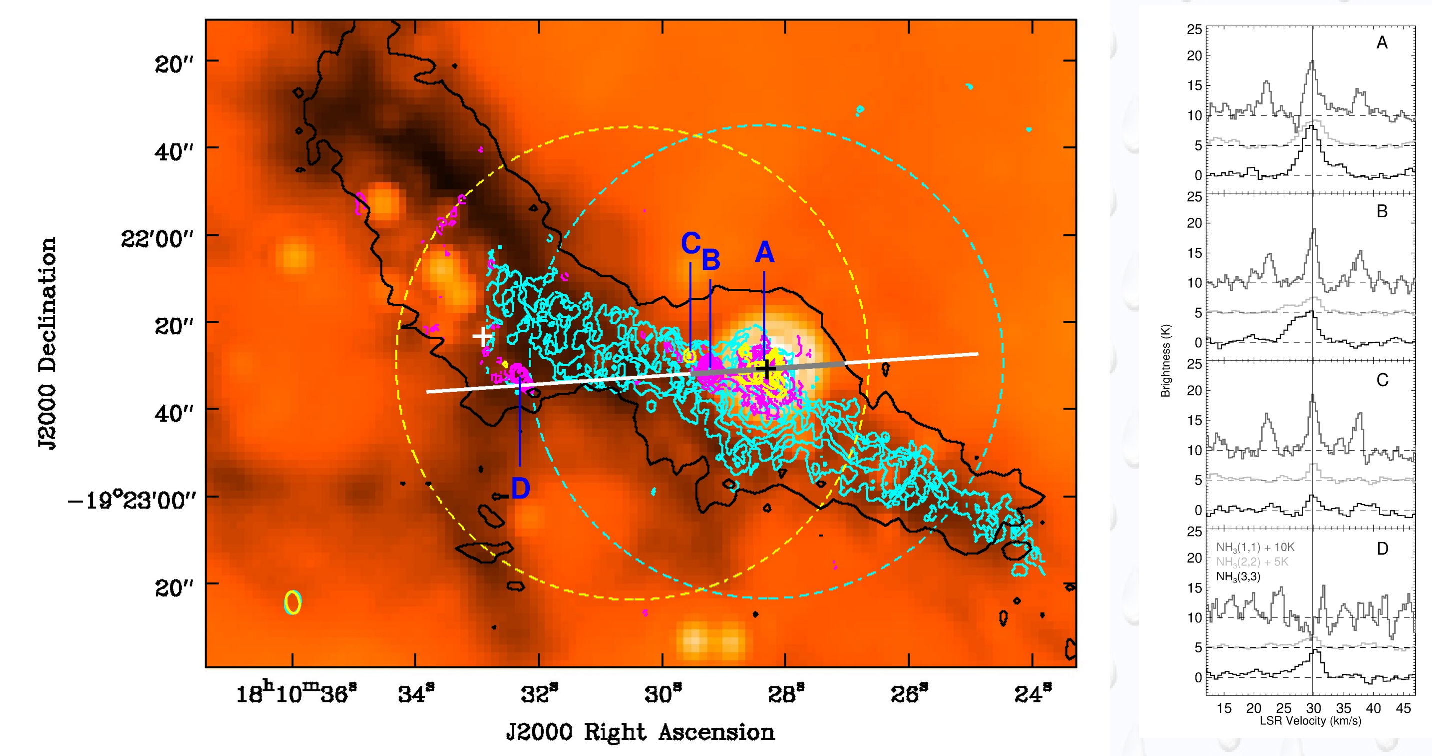
Abstract: *We present Submillimeter Array (SMA)* ***1.3 and 0.88 mm*** *broad band observations, and Very Large Array (VLA) observations in* ***NH_3 (J,K) = (1,1) up to (5,5)****, as well as H_2O and CH_3OH maser lines toward the two most massive molecular clumps in Infrared Dark Cloud (IRDC) G11.11-0.12, also known as the Snake nebula. The sensitive high-resolution images reveal hierarchical fragmentation from the ∼1pc clump scale down to ∼0.01pc condensation scale. At each fragmenting scale, the mass of the fragments is orders of magnitude larger than the Jeans mass. This is common to all four IRDC clumps we studied, suggesting that turbulence plays a dominant role in the initial stages of clustered star formation. Masers, shock heated NH_3 gas, and outflows indicate active ongoing star formation in some cores while no such signatures are found in others. Furthermore, chemical differentiation in cores reflects a sequential growth of these star formation seeds. The same applies to condensations and clumps. The mass function of the resolved condensations is consistent with a power law with an index of $\alpha = 2.0 \pm 0.2$ and a turnover at 2.7 $M_\odot$. Our combined SMA+VLA observations of several IRDC clumps have presented so far the deepest view of the early stages prior to the hot core phase, revealing snapshots of physical and chemical properties at various stages along an apparent evolutionary sequence, subject to further tests by detailed modelling.*

Clump | ***Core*** | ***Condensation***

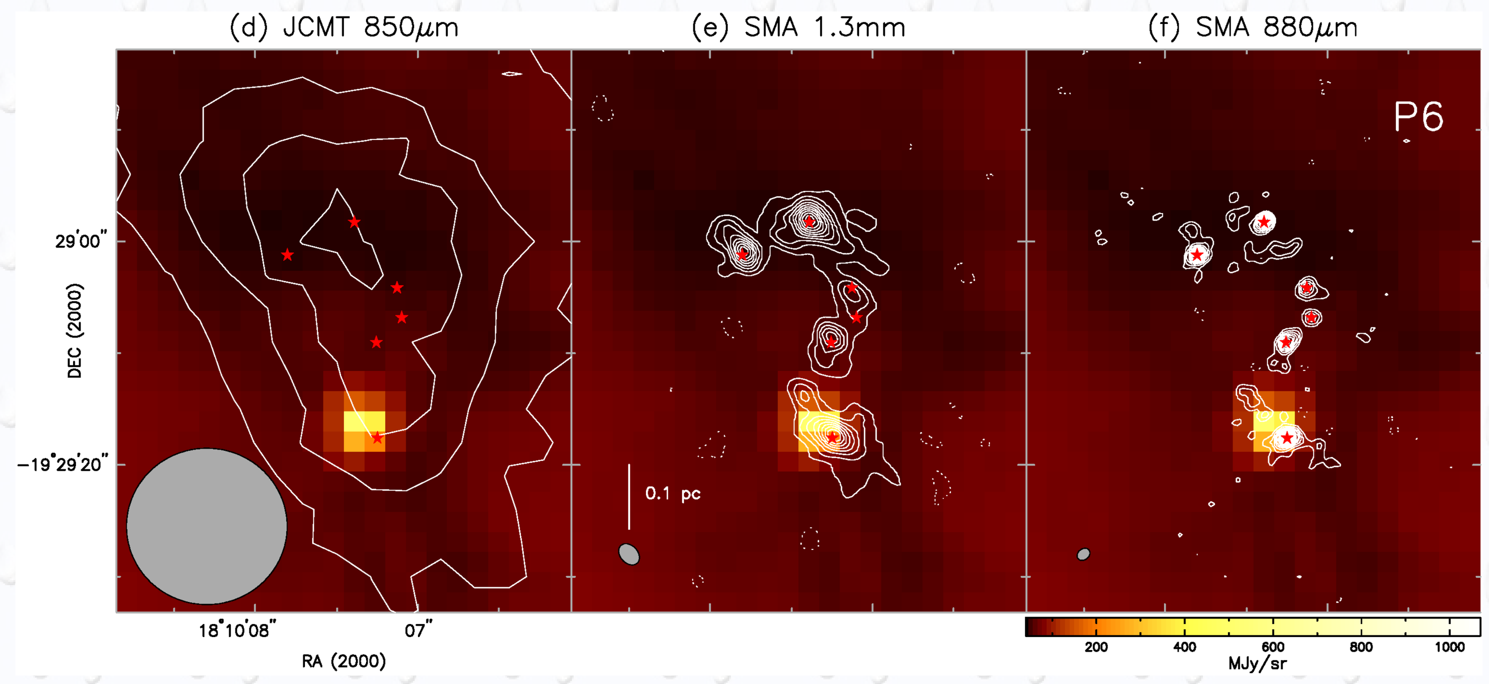


Up: *Hierarchical structures of clump P1 resolved in mm/submm emission (contours) at various resolutions (ellipses). The background is Spitzer 8 μm image. From left to right, clump (~1 pc, ~10^3 $M_\odot$), core (~0.1 pc, fraction of 10^2 $M_\odot$), and condensation (~0.01 pc, fraction of 10 $M_\odot$) are best seen, respectively. Red stars mark major condensations identified from the SMA 880 μm image.*

Below: *NH_3* ***(1,1)***, ***(2,2)*** *and* ***(3,3)*** *line emission shown in cyan, yellow and pink contours respectively. Dashed circles represent VLA primary beams. The black contour outlines dense gas traced by JCMT 850 μm emission which matches well with the NH_3 emission and the background Spitzer 24 μm extinction. Crosses mark H_2O masers, the grey line denotes SiO (5-4) outflow and the white line is its extension. The right panel plots NH_3 spectra from representative emission peaks which are aligned on the outflow pathway. Note the blue-shifted line wings in (3,3) induced by the outflow.*

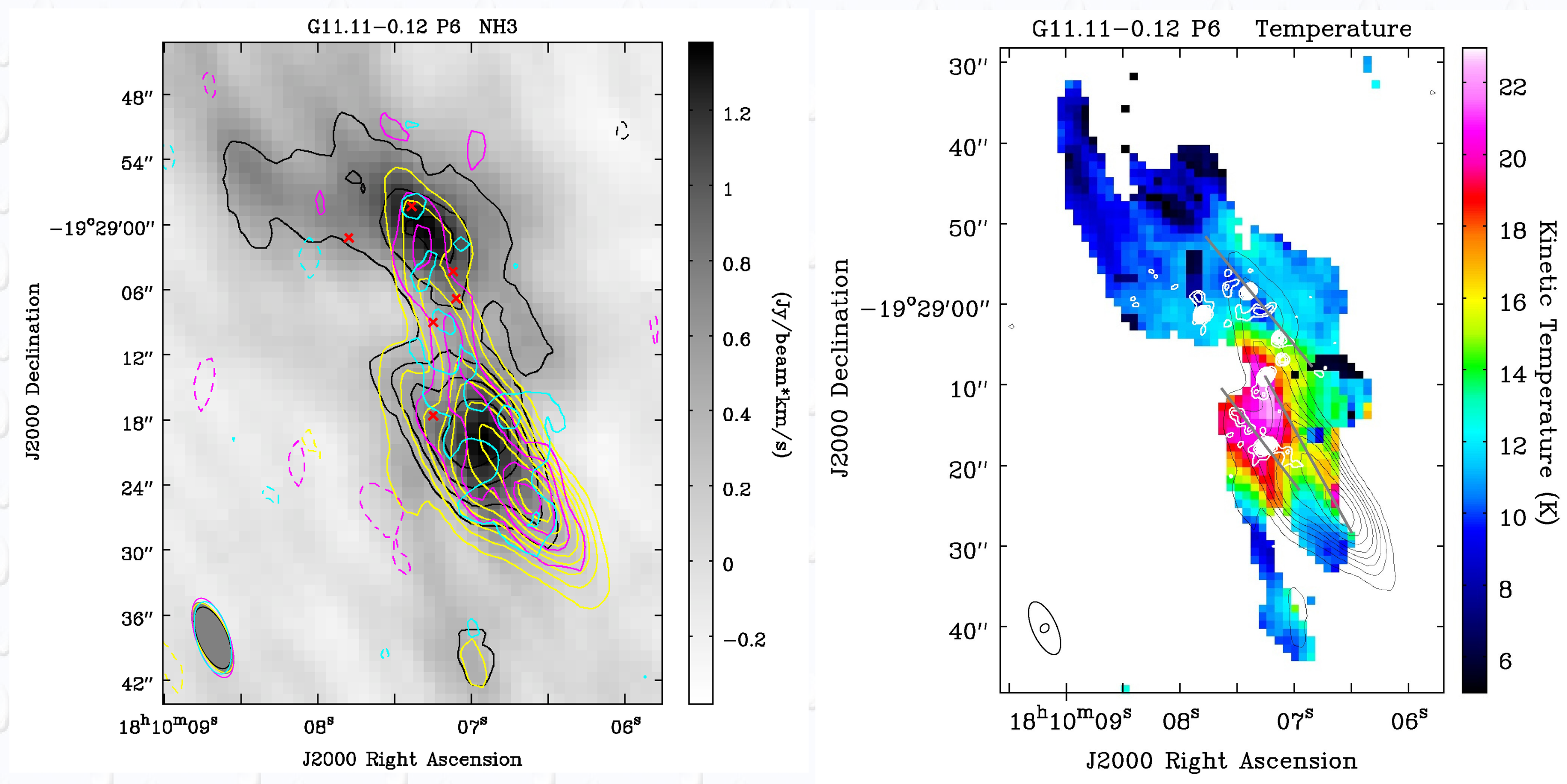


Clump | ***Core*** | ***Condensation***

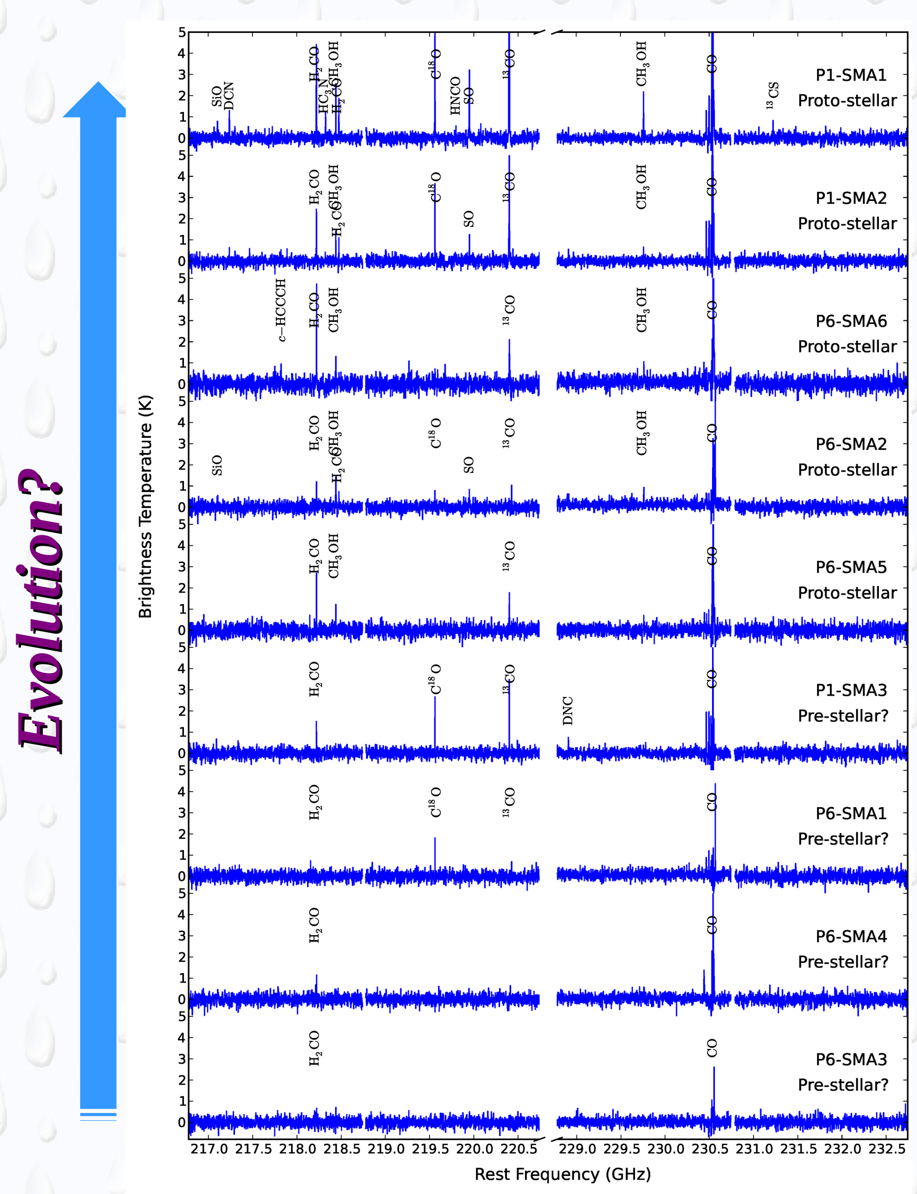


Up: *Hierarchical structures of clump P6. Symbols are the same as for P1.*

Below: *NH_3* ***(1,1)***, ***(2,2)***, ***(3,3)***, ***(4,4)*** *and* ***(5,5)*** *line emission plotted in grey scale, black, yellow, pink, and cyan contours respectively. Red crosses mark major condensations identified from the SMA 880 μm image. The right panel shows kinetic temperature derived from para-NH_3, overlaid with SMA 880 μm contours (white) and NH_3 (3,3) contours (black). The grey lines denote CH_3OH (4-3) outflows. Note the spatial correlation between outflows and ortho-NH_3 (3,3).*



Right: *SMA 230 GHz spectra extracted from major cores, plotted in order of inverse evolution. The brightness temperature has been corrected for primary beam attenuation. Detected molecules are labelled. The evolutionary sequence is inferred based on line features and star formation signatures including outflows, masers and luminosity. These spectra provide an ideal data set for chemical modelling.*



Key references:

Wang et al. 2012, ApJ, 745, L30
Wang et al. 2011, ApJ, 735, 64
Wang et al. 2009, A&A, 507, 369
Zhang & Wang et al. 2011, ApJ, 733, 26
Zhang et al. 2009, ApJ, 696, 268
(Paper reporting G11.11-0.12 will be submitted soon. Stay tuned!)

Summary: *We study the fragmentation of two massive (~10^3 $M_\odot$), relatively low-luminosity (<~10^3 $L_\odot$), and dense (~8×10^4 cm^{-3}) molecular clumps P1 and P6, the most likely sites of high-mass star formation in the IRDC G11.11-0.12, using high resolution SMA and VLA observations. The achieved mass sensitivity is better than the Jeans mass, and our main findings are:*

- *The clump fragmentation is consistent with a cylindrical collapse, but the fragment masses are much larger than the relevant thermal Jeans masses. This is the same as what we have found in IRDC clumps G28.34-P1 and G30.88-C2, suggesting that turbulence dominated fragmentation is common in the initial stages of massive star formation.*
- *Star formation is ongoing in 5 of the 12 identified cores, producing outflow shocks that have enriched ortho-NH_3. The discovery of a collimated east-west outflow in P1, together with previous studies, points to an outflow-disk system in a possible proto-binary which deserves further study with better resolution.*
- *With a detection limit of 1-3.5 $M_\odot$, we identify 23 condensations that are subject to form individual stars or a small stellar system. The mass spectrum of these condensations is consistent with a power law with a slope $\alpha = 2.0 \pm 0.2$ and a turnover at 2.7 $M_\odot$ condensation mass. Future deep ALMA images with improved resolving power toward all the six clumps in the Snake nebula will reveal a complete census of individual condensations for a robust study of CMF.*
- *Chemical differentiation reflects a sequential growth of the cores. This also applies to smaller scales down to condensations, and to larger scales up to clumps. Accordingly, an evolutionary sequence is inferred for cores and clumps respectively. The hierarchical fragmentation leads to seeds of star formation grow inhomogeneously, also in a hierarchical way.*