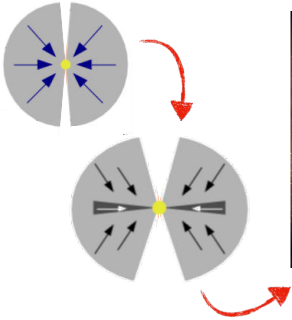
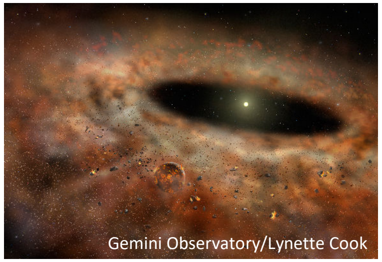
Studying disc-hosting young stars at high angular resolution

Motivation: **How do stars like our Sun and planetary systems like our own Solar System form?**
(It's one of the big "how did we get here?" questions humanity has pondered for millennia)

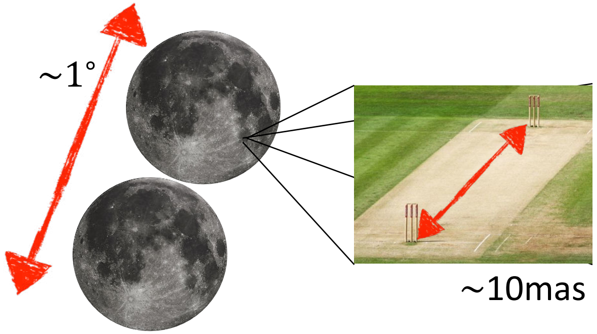


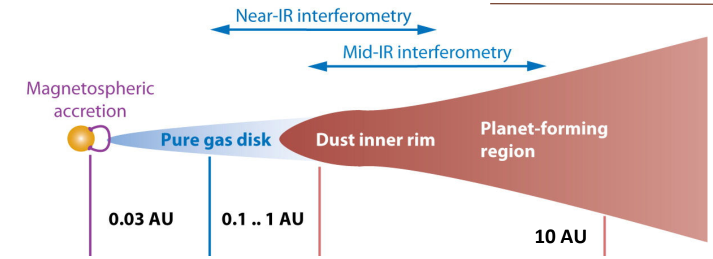


Gemini Observatory/Lynette Cook

We have a good idea already that **planets form in the disc-shaped reservoirs of gas and dust that exist around stars during their formation**. These structures form as a result of conservation of angular momentum during a star's gravitational collapse from its natal molecular cloud core: the originally centrally-focused spherical infall is directed onto a plane perpendicular to the rotation axis of the collapsing core.

As order-of-magnitude scales of inward orbital migration appears unlikely, most planets are expected to form within the inner few astronomical units (au) of their protoplanetary discs. The closest regions of star formation young enough (< 10 Myr) to retain a substantial disc-hosting population of young stars are > 120 pc away: **to look in detail at the main planet-forming disc regions, we need 1-10 milliarcsecond (mas) angular resolution**.
(That's roughly equivalent to being able to resolve a cricket pitch on the Moon!)





Dullemond & Monnier, (2010, ARA&A 48, 205)

Specifically, as the disc temperature on scales of tenths to a few au is expected to be $\sim500-1500$ K, we need to be able to obtain this angular resolution across near-infrared to mid-infrared wavelengths ($\sim1-3\ \mu$m). These disc regions are thus **only accessible using optical long baseline interferometry** (OLBI).

With OLBI, angular resolution increases with increasing separation between the telescopes in the interferometric array (i.e., the baseline length, B). We can obtain the required 1-10 mas angular resolution by using the world-leading OLBI facilities, the Very Large Telescope Interferometer (VLTI) and the Center for High Angular Resolution Astronomy (CHARA) Array.


Gerard Hudepohl / atacamaphoto.com

4 telescopes (each 1.8 or 8m); $B_{\max} = 130\ \mathrm{m}$

$$\theta \propto {}^{\lambda}/_{B_{\max}}$$


Eric Simison, Sea West Enterprises

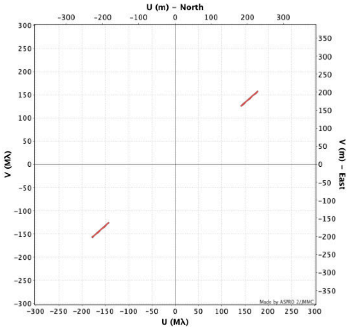
6 telescopes (each 1m); $B_{\max} = 330\ \mathrm{m}$

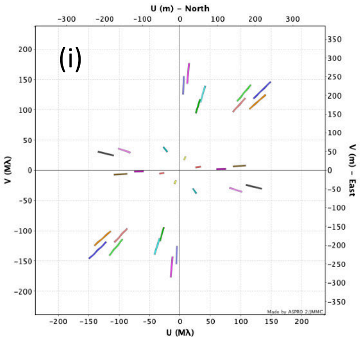
Interferometers do not take an image of the sky. Instead, they only sample a portion of the image plane. The uv-plane below shows the sky-coverage afforded by a pair of telescopes.

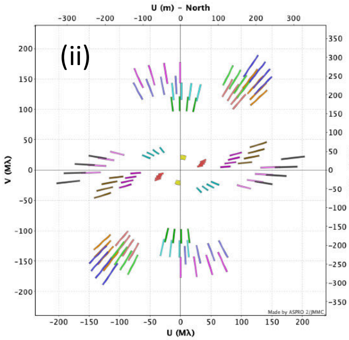
Image plane sampling is optimised using:

(i) a greater number of telescopes with non-redundant baseline lengths;

(ii) repeating an observation over the course of the night to make use of the sky's rotation overhead.







Until 2016, the number of young stars observable with OLBI was very low, mainly due to the limited flux sensitivity of existing instruments. Moreover, sufficiently sensitive instruments only used 2 or 3 telescopes. New instruments using all 4 VLTI telescopes or all 6 CHARA telescopes have since been successfully commissioned, including our own MIRC-X upgrades at CHARA...

Our MIRC-X (Michigan InfraRed Combiner-eXeter) upgrades:

- **Sensitivity improvements**:
  1. installed the revolutionary, sub-electron noise and fast-frame rate C-RED ONE camera (Gach et al. 2016, SPIE 9909, 13);
  2. redesigned the photometric channels used by the first-generation six-telescope combiner, MIRC;

→ Provides fringe tracking for other CHARA instruments, allowing longer on-sky integrations (& increasing their limiting mag).

- **Increased wavelength range**;

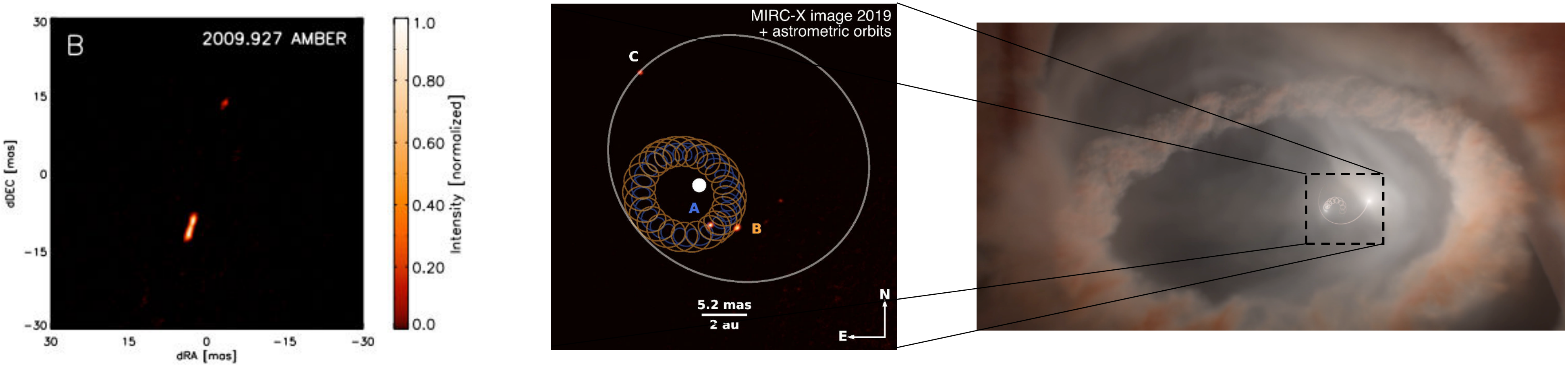
- **Enabled polarization observations** through the installation of a half wave plate for each beam and a Wollaston prism to measure the full Stokes parameters;

Further info: Anugu et al. (2020, arXiv:2007.12320); Kraus et al. (2018, SPIE 10701, 23); Anugu et al. (2018, SPIE 10701, 24).

Current MIRC-X capabilities		(vs old MIRC)
Visibility precision	0.5%	--
Closure phase precision	0.5°	--
Limiting H-band correlated magnitude	≈ 8.2	6.5
Waveband range	J+H	H
Spectral resolution ($R = {}^{\Delta\lambda}/_{\lambda}$)	50, 190 or 1035	50

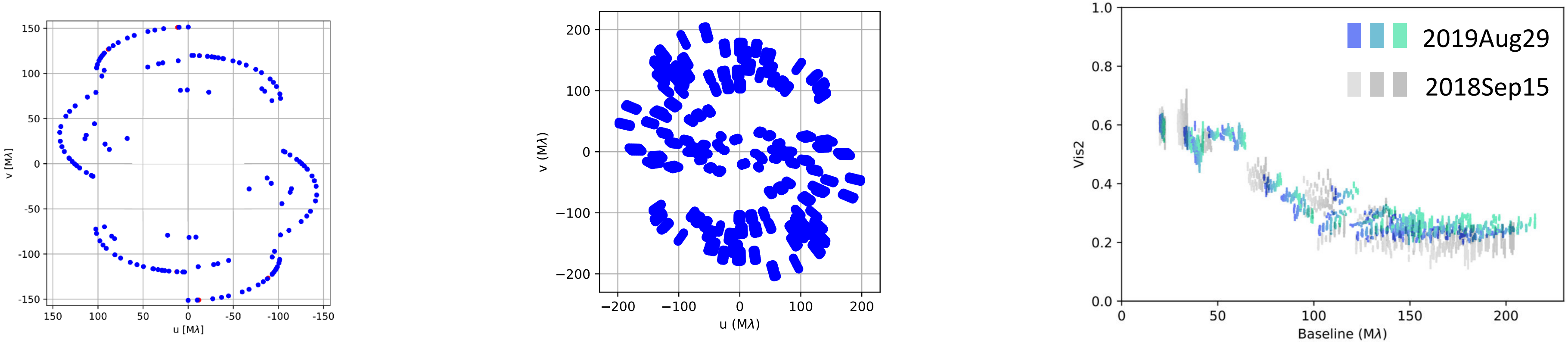
The MIRC-X team celebrate successful instrument commissioning (**left to right**: Benjamin Setterholm, John Monnier, Stefan Kraus, Narsi Anugu, Claire Davies & Tyler Gardner. **Not present**: J-B le Bouquin, Jacob Ennis, Aaron Labdon & Cyprien Lanthermann).

Science highlight #1: Marginally spatially resolved circum-primary and circum-secondary discs (25 and 24 $R_\odot$, respectively) of the protoplanetary disc-hosting triple system, GW Ori, for the first time (Kraus et al. 2020, Science 369, 1233).



Left: attempt to resolve the three young stars in GW Ori with VLTI/AMBER; **Middle**: what has been possible with the new MIRC-X instrument. The astrometric orbit fit of the primary (A), secondary (B), and tertiary (C) components is overlaid. These data were combined with 10+ years of multi-instrument, multi-wavelength data to study the full system, including the disc (Kraus et al. 2020, Science 369, 1233). **Right**: artistic impression of the stellar motions and the tilted inner ring of dust which has been torn apart from the warped outer disc regions (ESO/Exeter/Kraus et al./L. Calçada).

Science highlight #2: Image-plane sampling that took years with CHARA's 3-telescope beam combiner can now be far-exceeded in just a single night with MIRC-X, opening up the time domain for imaging studies of protoplanetary discs!



Left: uv-plane coverage obtained for protoplanetary disc hosting star, RY Tau, using the CLIMB, 3-telescope combiner at CHARA between 2010Sep and 2012Nov (Davies et al. 2020, ApJ 897, 31). **Middle**: uv-plane coverage obtained for the same object with MIRC-X on 2018Oct25 (Davies et al. *in prep*). **Right**: squared visibilities obtained for RY Tau on 2018Sep15 (grey data) and 2019Aug29 (blue/green data) highlighting changes in the disc structure on scales of tenths to a few au (Davies et al. *in prep*).