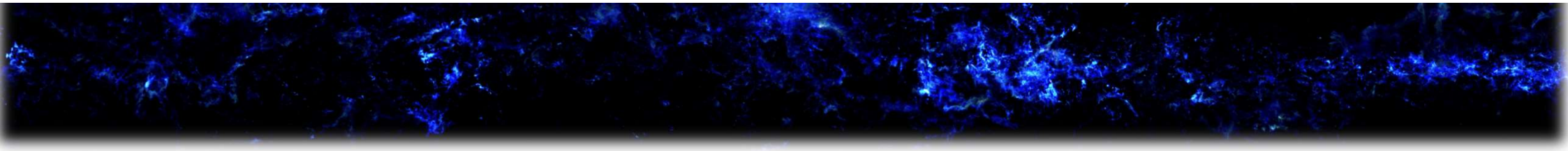

Millimeter & Submillimeter Wave Astronomy in China

Ji Yang
Purple Mountain Observatory, Chinese Academy of Sciences
Nanjing 210033
jiyang@pmo.ac.cn

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Outlines

- Several development phases of mm & submm astronomy in China
- Starting phase of millimeter-wave radio astronomy 1973-1982
- First mm-wave radio telescope in China 1982-1996
- Continued development of mm-wave radio astronomy: 1998-2010
- Application of Multibeam receiver and MWISP survey: 2011-2022
- Submillimeter astronomy efforts 1996-2022
- International collaborations in mm & submm astronomy: SMA, ALMA, Herschel, JCMT, NOEMA, EHT, and LCT

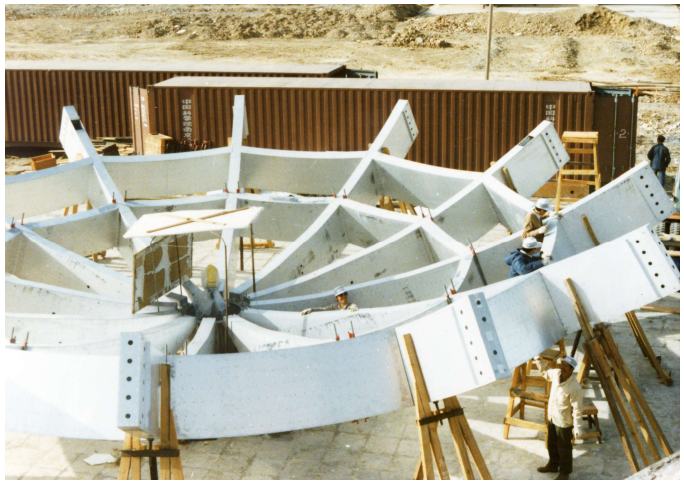
Starting phase of millimeter-wave radio astronomy 1973-1982

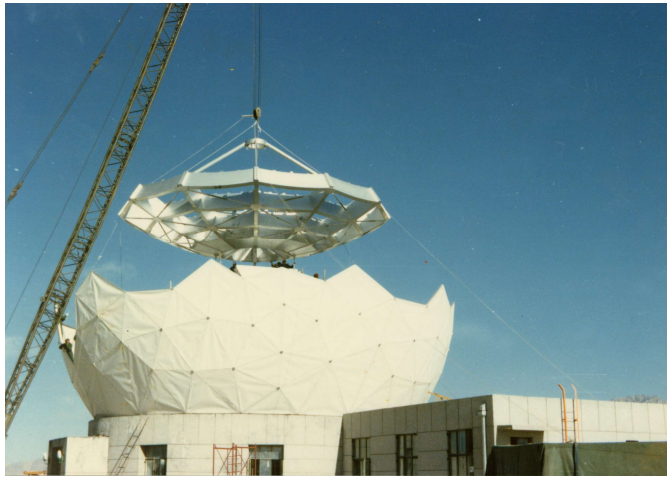
- The eight-year planning for astronomy
  - **The eight-year planning** (1973-1980) lead by CAS : (1) Identified molecular astronomy/mm-wave radio as an important new direction in radio astronomy; (2) To develop a 15m millimeter-wave radio telescope, a task assigned to Purple Mountain Observatory (PMO) to lead; (3) To initiate mm-wave radio astronomy research in CAS institutes and research/education in several universities (NJU, PKU, BNU).
- Conceptual study on 15m mm-wave telescope
  - **Studies on 15m telescope concept**, including optics, mechanics & receivers, jointly by CAS institutes and industrial sectors; **Surveys on mm-wave antenna and international consultations**.
  - Developments of mm-wave receivers at 8.6/4.1/3.2mm receivers by PMO, USTC, etc. .
- Site Surveys 1978-1981
  - **Site surveys around China**, especially west areas: Qinghai, Gansu, Xingjiang, Tibet.
  - Site adoption for **Delingha**, a site at 3200m a.s.l. : 1981 December & confirmed in 1982 March
- Targets for construction 1982
  - **Adopted ESSCO design** (13.7m or 45-feet, similar to FCARO 14m). Development jointly made among PMO, Nanjing Astronomical Instrument Factory, and ESSCO Company upon agreement.

First mm-wave radio telescope in China 1982-1996

- Construction of telescope and Qinghai Station 1982-1983
  - Project started in 1982 and site development by PMO
  - Antenna fabrication by Nanjing Astronomical Factory, supervised by ESSCO company
  - Servo system referred from FCRAO design, and control software from NARO 12m system
  - Antenna Installed in 1986
- Receiver developments by PMO 1982-1996
  - 1.3cm receiver application 1986-1990
  - 3mm receiver 1990-1996, in collaboration with MPIfR & institutes in China
  - Spectrometers backends: AOS, filterbank, SAW, etc.. Some collaboration was with CSIRO for AOS
- System acceptance by CAS 1996
- Observational studies on molecular astronomy within the period
  - Starting from early 1980s, a number of research activities on molecular astronomy were made by sharing world telescopes: e.g., CO survey and galactic distribution, in collaboration with NRAO 12m; NH_3 studies of Rho Oph with Bonn 100m telescope, in collaboration with MPIfR; CO observations at Nagoya Univ 4m & NRO 45m/NMA, etc..
  - Water maser surveys with newly installed PMO-13.7m telescope.
  - Solar system and Ozone observations with PMO-13.7m telescope.

Construction of PMO-13.7m mm-wave antenna (1986)





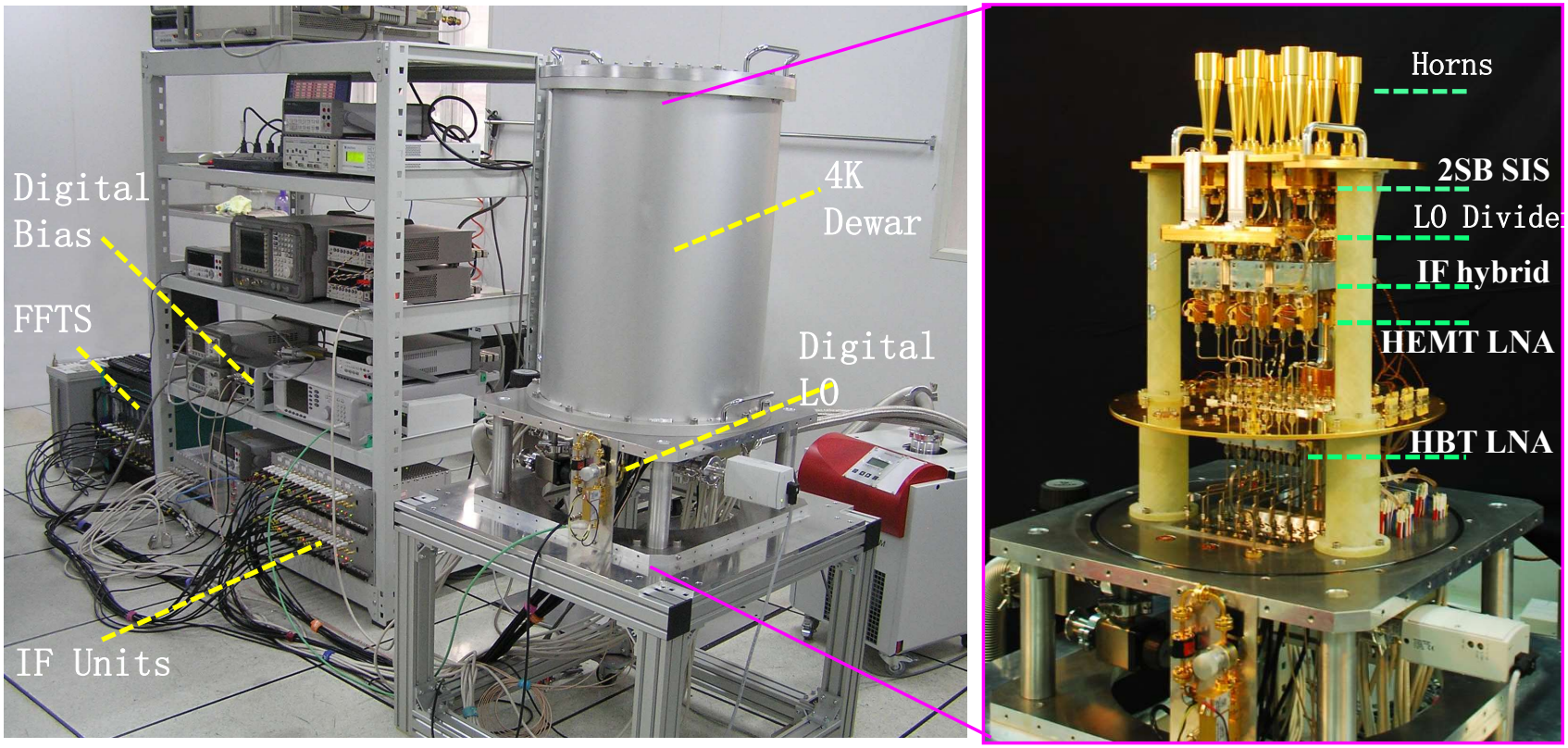
Photos from PMO archive

Continued development of mm-wave radio astronomy 1998-2010

- Application of SIS receiver 1998
  - The tunerless 85-115 GHz receiver, in collaboration with NRO, and installed into the telescope in 1998
- 3mm multi-line system 2012
  - A scheme to receive $^{12}CO/^{13}CO/C^{18}O$ lines using two side bands by one receiver, applied in 2002
  - Novel control system based on multi-task/shared memory framework with real-time modules
- Improving 13.7m telescope 1998-2010
  - **Improve antenna accuracy**: surface accuracy to 70 micron level by photogrammetric measurements and pre-adjustment techniques; adjusted radome ventilation; thermal analysis and insulations of antenna;
  - **Improving pointing:** to 3-5" rms by improving mechanics, upgrade the servo system, real-time meteorological parameters, new switching electronics, accurate solar system ephemeris, and new pointing models;
  - **Improving alignment:** 3D measurement of receiver beam pattern and laser-assisted alignment scheme ;
  - **Application of digital technologies to the receiving system:** DC bias, digital LO, digital spectrometer based on high-speed ADC and FPGA.
  - **Comprehensive testing utilities and metrological routines**.
- Development of 3x3 multibeam receiver with sideband separation mixers 2007-2010, PMO
  - 2SB scheme, ^{12}CO in USB & $^{13}CO/C^{18}O$ in LSB
  - Full digital system: digital DC bias, digital LO, and FPGA spectrometers;
  - Newly developed On-The-Fly observing scheme and reduction pipelines.

The Superconducting Spectroscopic Array (SSAR 2010-)

An array receiver of 3x3 pixels, based on superconducting SIS mixing and sideband separation (2SB) technologies, operates over 85-116 GHz with fully digital tuning LO, bias, and FFT spectroscopic analysis based on high-speed ADC and FPGA.



Noise Temperature 60 K (SSB) Image Rejection Ratio 10 dB

Shan, W.-L. et al. 2012, IEEE Trans. THz Sci & Tech., 2, 593.

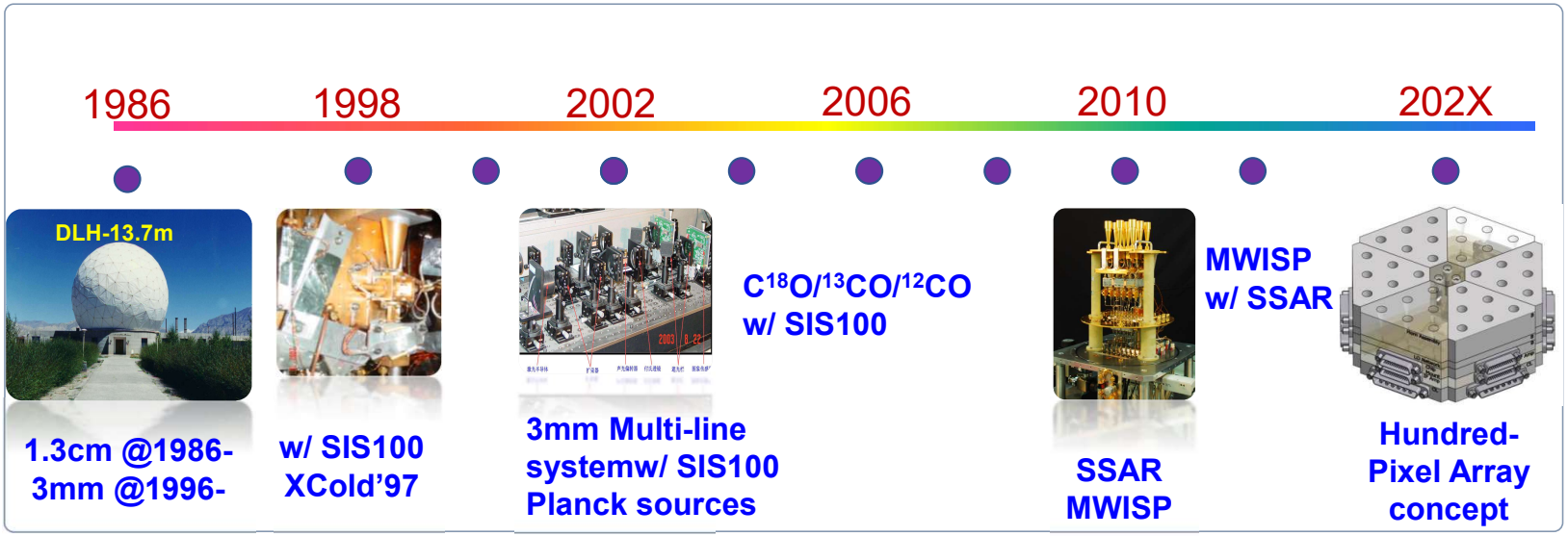
Application of SSAR and MWISP survey 2011-2022

- The Milky Way Imaging Scroll Painting (MWISP) project
  - Discovery of new molecular clouds, and study on large-scale physics and chemistry;
  - Statistic distribution of dense cores within each cloud complex;
  - Dynamical processes involved in star forming processes, such as infall , and outflow motions, dynamic expansions;
  - New components and sub-structures of our Milky Way galaxy as well as its motions;
  - Interactions between molecular clouds and other galactic processes, such as SNR & cosmic rays sources.

- Key technical parameters
  - Sky coverage: L=0 ~ +250deg, B= +/- 10deg
  - Resolution: 50-55 arcsec
  - Line probes: ^{12}CO/^{13}CO/C^{18}O (J=1-0)
  - Spectrometers: 18x1GHz, spectral resolution 61 kHz (= 0.17 km s^{-1} @ 110 GHz)
  - Sensitivities: 0.5 K for ^{12}CO and 0.25K for ^{13}CO/C^{18}O
  - Data managements: acquisition, reduction, quality control, & database storage;

- Phase I survey: B = +/- 5deg from 2001 to 2011.

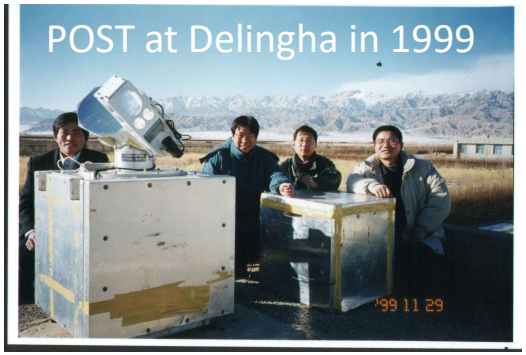
Mm-wave developments and application to astronomy



- With just the single mm-wave antenna, efforts have been made to improve the system, to upgrade receiver /backends, and to adopt new observing schemes in a continuous way, leading to a better observing performance of the whole system.
- Focusing on some dedicated sciences: large-scale survey of galactic molecular clouds with highest sensitivity; systematic investigation of methanol masers along the galactic plane; mapping Planck cold clumps, and deep line integration toward nearby galaxies.

Submillimeter astronomy efforts 1996-present

- Site testing in west part of China for future mm & submm 1993- present
  - A joint site survey in west China organized by East Asian institutes 1993
  - Continued measurements of site conditions in west China for future submm telescopes, 60m , CMB , etc., using radiometer & FTS.
- The Portable Submillimeter Telescope (POST) experiments 1996-2004
  - Developed in collaboration with NAOJ, the 30cm telescope was the first professional instrument for submm observations and site measurements in China.
  - First NbN SIS mixer application, experimental observations in Qinghai & Tibet
- The KOSMA move to Tibet 2010-
  - Agreement between Koln Univ and NAOC on the KOSMA move to Tibet 2009
  - Telescope move (2010), new radome construction, testing and CCOSMA re-commissioning, science observations
- Feasibility study on 5m Dome A THz telescope (DATE5) 2008-2016 (CCAA collaboration)
  - Pre-HEAT: a 661 GHz radiometer for opacity measurements at Dome A
  - FTS: a broadband spectral measurement for THz atm windows at Dome A
  - International collaboration in Pre-HEAT & FTS, 5m Dome A THz Explorer (DATE5) feasibility study, and R&Ds for THz detectors.
- THz R&Ds (very recent)
  - Several institutes launched astronomy-related THz R&Ds: mixer, broadband detector arrays, THz sources, and other devices. Application of THz receiving modules at CSST.



Involvement into international mm & submm programs: SMA, ALMA, Herschel， JCMT, NOEMA/MRT, EHT, and LCT

- Chinese institutes and scientists have been actively involved in many international mm & submm facilities and/or programs, including SMA, ALMA, Herschel, JCMT, NOEMA/MRT, EHT, and LCT.
- **Collaboration for SMA** in SIS Rx development & array commissioning (2000-2004) ; shared use (NJU & CfA).
- Involved **in joint R&D activities of ALMA band 4/8 receivers** through ALMA-J (2002-); Active use through international applications, collaborative programs, and archival data.
- NAOC joint **Herschel/SPIRE collaboration** (2009-); PMO, together with other institutes, shared telescope time at IRAM package (2017-) .
- Since 2015, China joint the **shared operation of JCMT** through East Asian Observatory (EAO) . A large number of users participated the legacy programs and PI programs.
- Shanghai Normal University (ShNU) joint **the relocation and operation of LCT** in Chile, a 10m submm telescope, through contract with Caltch and UdeC in 2017.
- Researchers from several institutes joint the international **EHT collaboration**.

Mm & submm astronomy in China - A brief summary

- Millimeter astronomy in China began in 1973， for the purpose to catch up the newly merged direction of molecular astronomy.
- A 13.7m telescope was built during 1982-1996, making it possible to do mm-wave observation from Qinghai-Tibet plateau.
- Observational studies on molecular clouds, interstellar masers, star formation, galactic structures started from early 1980s by sharing the international mm-wave telescopes.
- The telescope have been improved continuously and facilitated advanced instruments for dedicated millimeter sciences, and began to make significant contribution on CO-related subjects.
- R&D, experimental observations and site evaluations for submm using small-scale telescope and instruments, such as POST（1996-), CCOSMA in west China, and Pre-HEAT/FTS at Dome A （2008-).
- A number of collaborations in mm & submm regime with international projects have been made, including SMA, ALMA, Herschel， JCMT, NOEMA/MRT, EHT, and LCT. Chinese institutes became a major partner in JCMT and LCT.
- After nearly 50 yrs of development, China has become an active player in international mm & submm astronomy.