MeerKAT array (South Africa)

MALS
MeerKAT Absorption Line Survey

(https://mals.iucaa.in/)
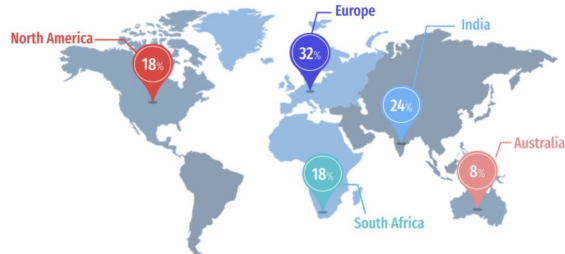
The MeerKAT Absorption Line Survey
## (cold atomic and molecular gas in and around galaxies)

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North America 18%
Europe 32%
India 24%
South Africa 18%
Australia 8%

Geographically distributed team of 37 scientists and engineers

MALS logo design: Lorena Fuentealba-Noterdaeme

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MeerKAT and MALS
(large survey project: 1655 hours)

MeerKAT array: most sensitive telescope at cm+ wavelengths
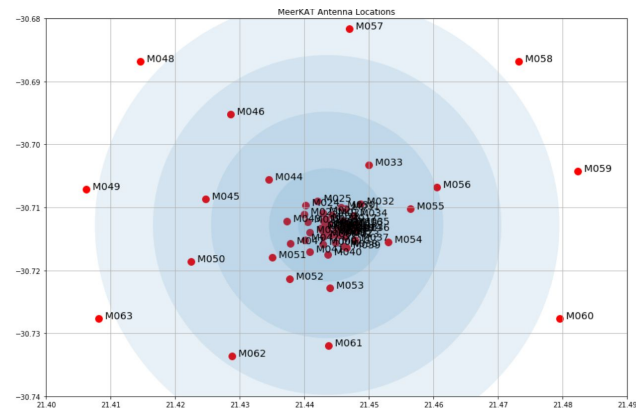
MeerKAT (South Africa) - SKA precursor in South Africa

Array layout: 64 offset Gregorian dishes (13.5 m)
Central concentration: 70% dishes (σ = 300m) + 30% dishes (σ = 2500m);
Baselines: 29 - 7700 m (8" synthesized beam at 1.4 GHz; robust = 0)
MeerKAT extension: +20 dishes - longest baseline 17 km

1. **L-band**: 900 - 1670 MHz (856 - 1712 MHz) ⇨ **HI 21cm: 0 < z < 0.57; OH 1667: 0 < z < 0.85**
2. **UHF-band**: 580 - 1015 MHz (544 - 1088 MHz) ⇨ **HI 21cm: 0.4 < z < 1.4; OH 1667: 0.64 < z < 1.87**
3. **Instantaneous BW**: 32K WB fine mode (8 sec integration implies ~1 TB / hr)

MALS consists of a maximum of 1655 hrs at L- and UHF-bands (~400 pointings)

1. 2017 - 2020: Commissioning and science verification.
2. June 2020: Survey started (~1250 hrs completed); goal to complete remaining by 2025 Q3.
3. L-band phase → Observations completed; 400 pointings (raw 500 TB) at IUCAA processed; science and DRs in progress.
4. U-band phase → 240 observed (raw 600 TB) at IUCAA processed. ~160 pointings (~400 hrs) remaining.

Total survey storage requirement - 8 PB (including public data releases)

# MALS primary objective: evolution of cold gas in and around galaxies
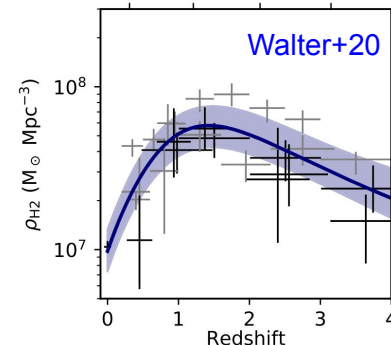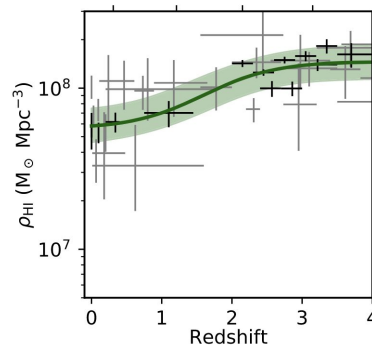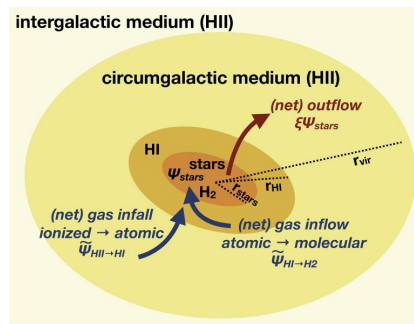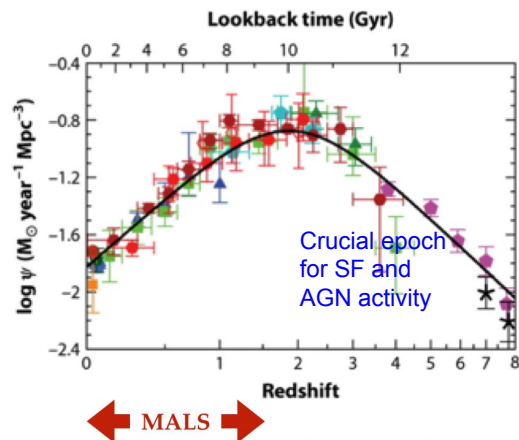
Compared to star formation rate density, little evolution in atomic gas.
How does the cold atomic and (diffuse) molecular gas evolve (on the pathway to H_2 and stars) ?

Cold gas accompanied by dust:need a dust-unbiased census of cold gas

Absorption lines as probe of gas in distant galaxies

Damped Lya absorber; N(HI)>2x10²⁰

DLAs trace bulk of HI at high-z
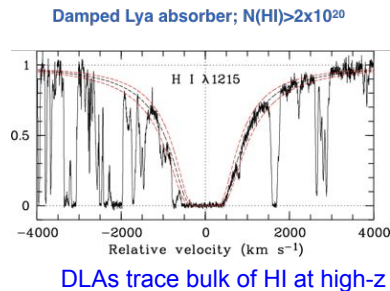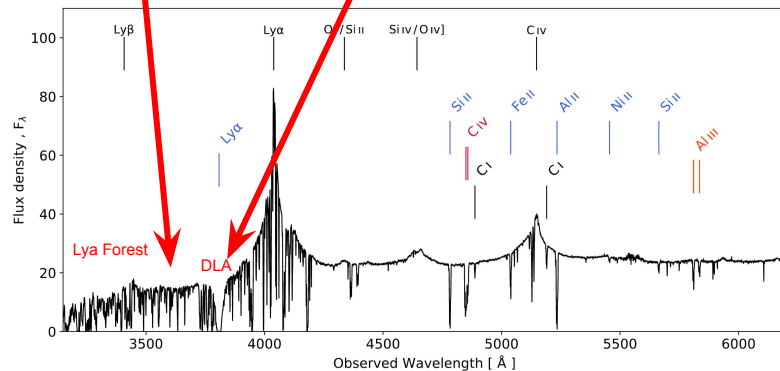
Gas **associated** with AGN and **intervening** galaxies.

Incidence i.e., no. of absorbers per unit comoving path length

$$\ell_{21} = \sum_{i=1}^{N_{abs}} \frac{1}{\Delta X(\mathcal{T}_i)}, \quad \Delta X(\mathcal{T}_j) = \sum_k g(\mathcal{T}_j, z_k) \frac{(1+z)^2}{\sqrt{(\Omega_m(1+z)^3 + \Omega_\Lambda)}} \Delta z_k.$$

Depends on the cross-section; luminosity unbiased probe. Complementary to emission line studies.

A powerful probe of gas in a wide range of environments but not dust-unbiased at optical/ultraviolet wavelengths

MALS : for CNM ΔX ~ 10³⁻⁴ (10-100 times larger than existing surveys; seamless coverage up to z~1.4)

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MALS footprint
(Multiwavelength synergies)

MALS footprint - overlap with multi-wavelength photometry and spectroscopy
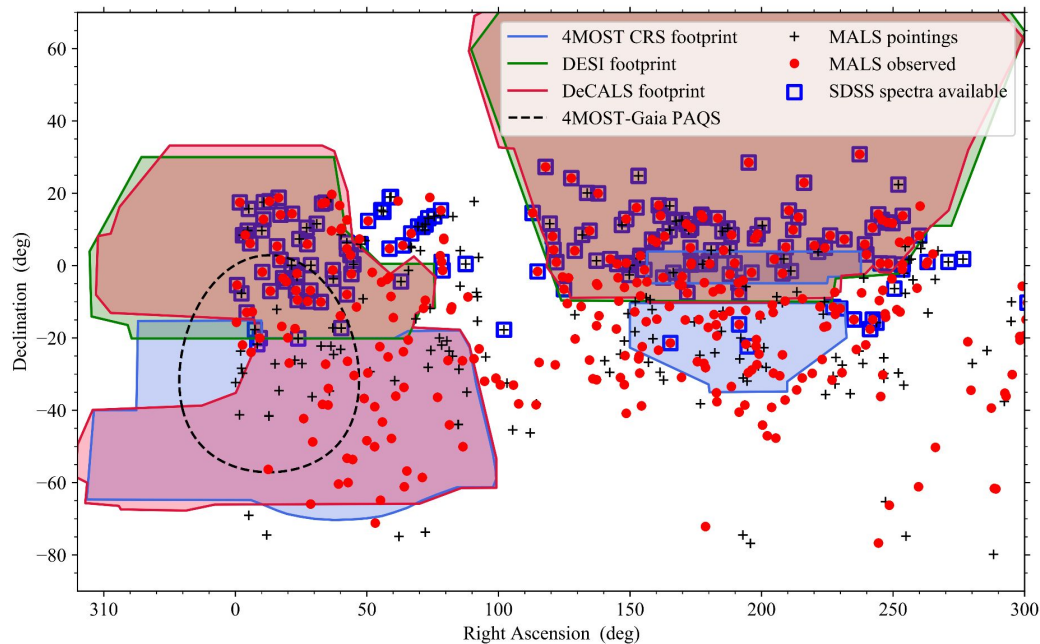
Partnership with large IFU surveys for optical spectroscopy:
1. DESI (Petitjean/Yeche): ~50,000 (secondary targets)
2. 4MOST S6/PAQS (Merloni/Krogager): ~200,000 spectra

Pool of 650 pointings (**flexibility**): ~400 pointings for L/U-bands.

MALS data challenge
(Wide range of spectral line and continuum science)

MALS data processing challenge

- Data transfer: shipped from SARAO, South Africa: LTO7 (1.7 PB).
- Data products:
  - Calibrated visibilities (another 1.7 PB)
  - Spectral line cubes (32K x 3k x 3k):
    - 1 PB (chunks of 100 GB) -> a few million images and 10 million spectral chunks.
    - 6 million core hours (3 years)
- Multi-layered storage: 4 PB (Fast DDN) + 2 PB Disks + 2 PB tapes) -> 8 PB (maximum; to support full survey)
  - Currently: 4 PB Fast DDN + 2 PB disk + 1.2 PB tapes
- Compute: VROOM: 26 nodes

DATA PROCESSING JOURNEY
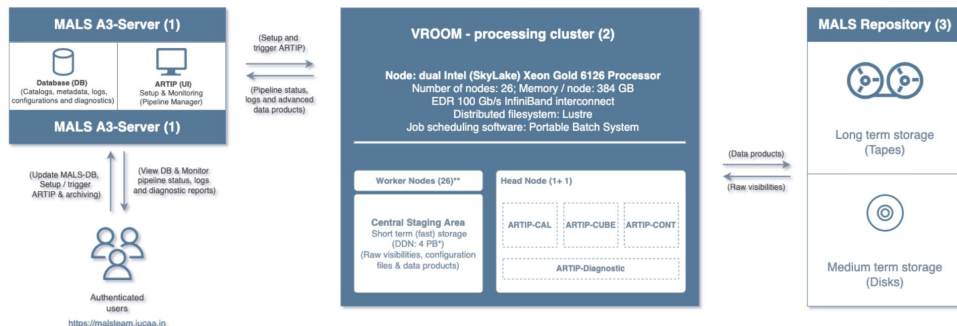
TECHNOLOGY STACK

Custom code + (experimental) CASA tools
to correct for direction dependent effects

Details and tech-stack described in Gupta+, 2021, ApJ, 907, 11 (also https://mals.iucaa.in/)

MALS science and data release(s)

Where to point? → centered at AGN brighter than 200mJy

~400 pointings each at L- (56 mins / pointing) **and UHF** (120 mins / pointing) ➡ ~15 uJy/ beam
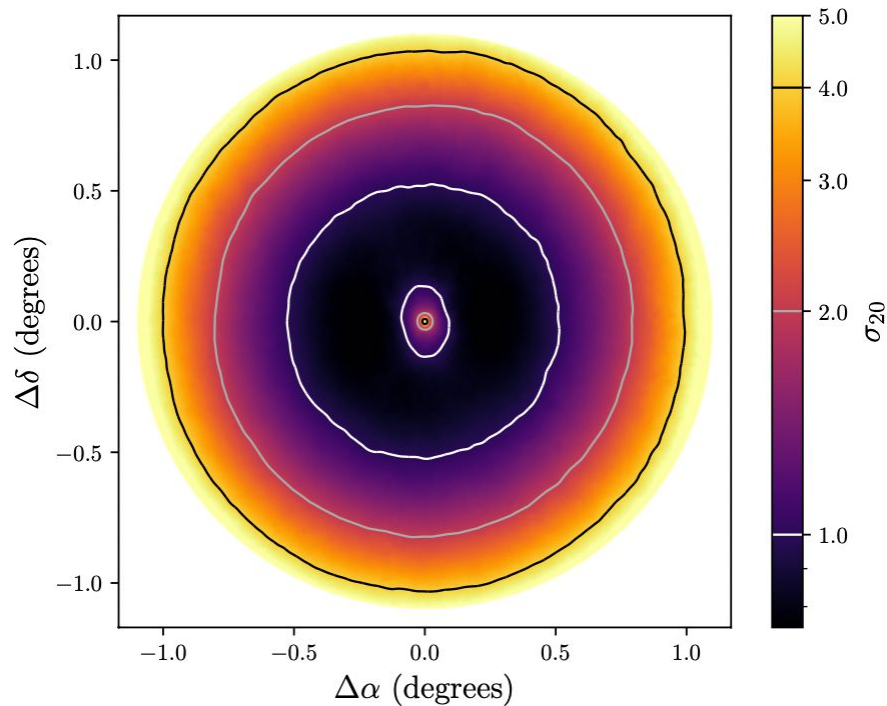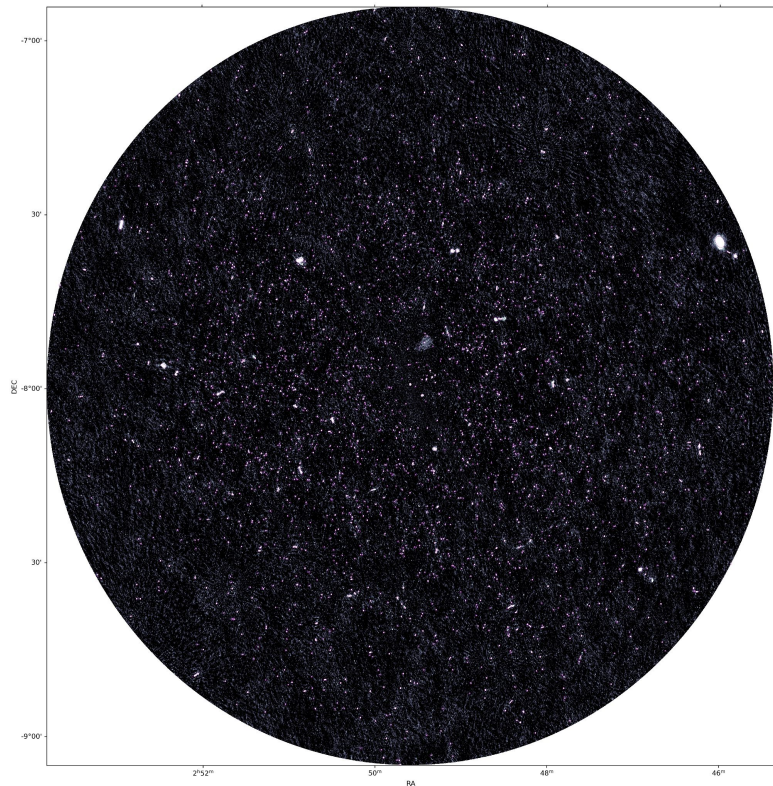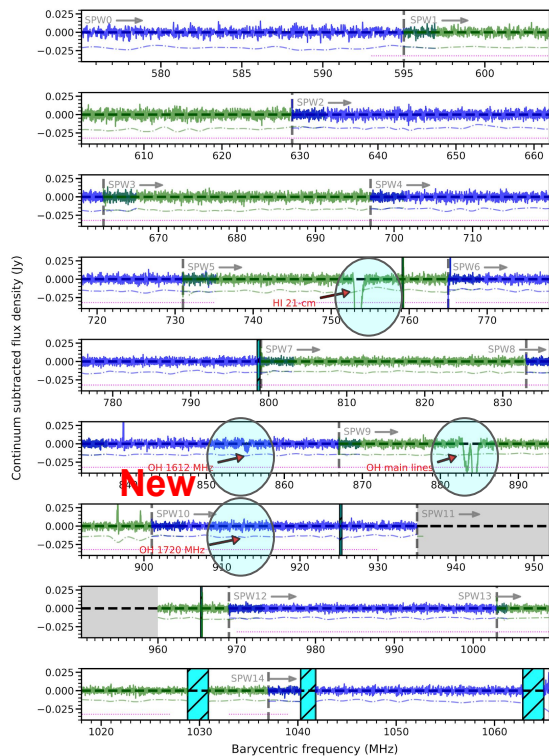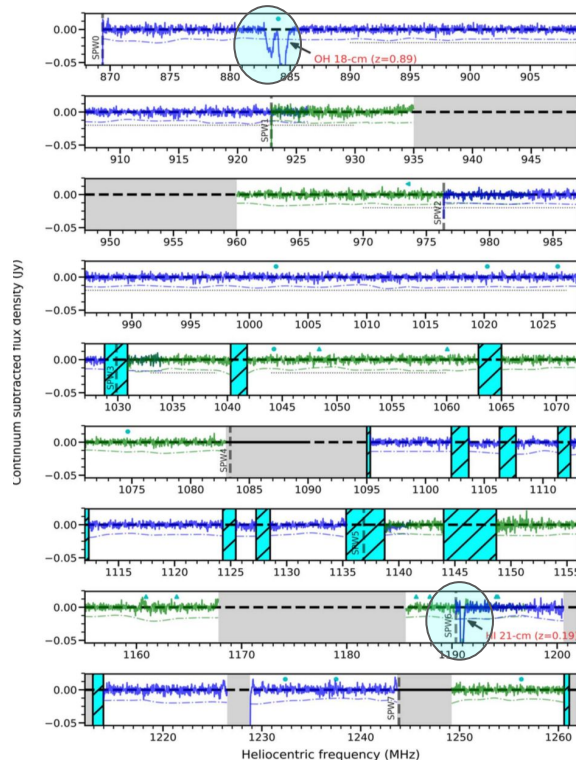

Median rms map of all 391 pointings (Wagenveld+24)

~4000 sources per pointings: few million sources (AGN and SF galaxies) over a kilo degree square !
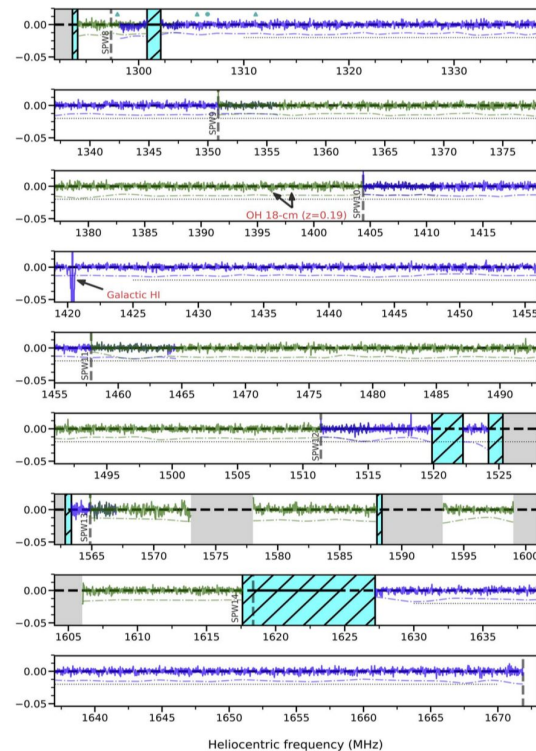
MALS science verification (detailed view of PKS1830-211)

FIRST MEERKAT SPECTRA

UHF-band (580 - 1015 MHz; Combes+21, A&A, 648, 116)

L-band (900 - 1670 MHz; Gupta+21, ApJ, 907, 11)

z= 2.51 quasar (**strong gravitationally lensed**) sight line intercepted by two absorbers at z = 0.19 and 0.89.
z = 0.89 is rich in molecules and dust ($N(H_2) \sim 10^{22}$ cm^{-2} ; more than 60 molecular species detected - Muller+11,14, Tercero+20)
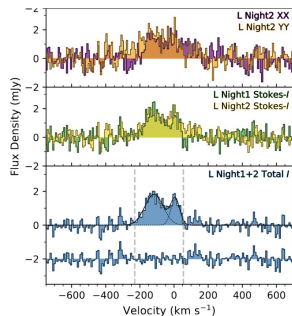
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MALS
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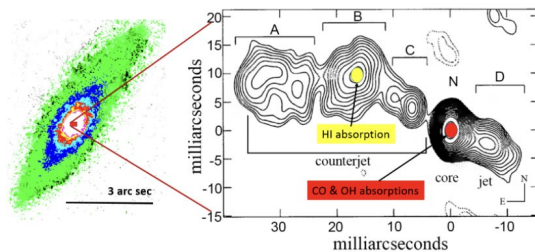*https://mals.iucaa.in/*

(1) Highest redshift detection of satellite lines; previous at z=0.25. 1712 MHz line most luminous till date: 6100 $L_\odot$
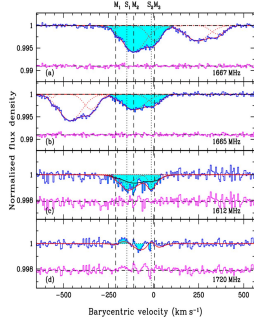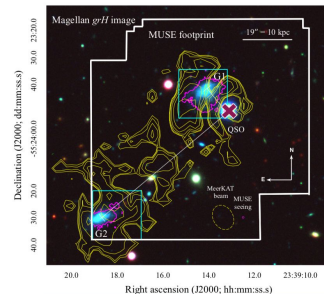

(2) First unambiguous detection of Hydrogen radio recombination lines in the distant universe.
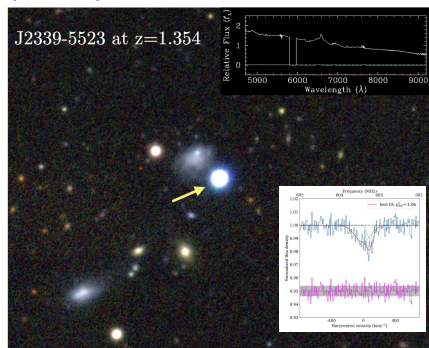

(3) Variability in HI absorption lines revealing the parsec structure in the gas associated with a distant galaxy.
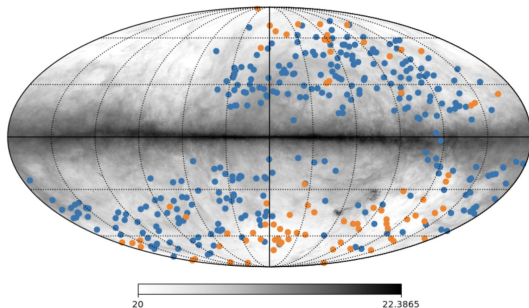

(4) Revealing origin of absorbing gas detected in the ultraviolet spectroscopy with the HST.

(5) Detection of a rare intriguing case of HI absorber at z~1.3 with no counterpart in optical spectrum.

(6) Census of cold gas in MW Galactic halo - towards a framework to interpret **extragalactic** HI / OH absorption.

(7) MALS data releases publicly available

Already available at https://mals.iucaa.in/
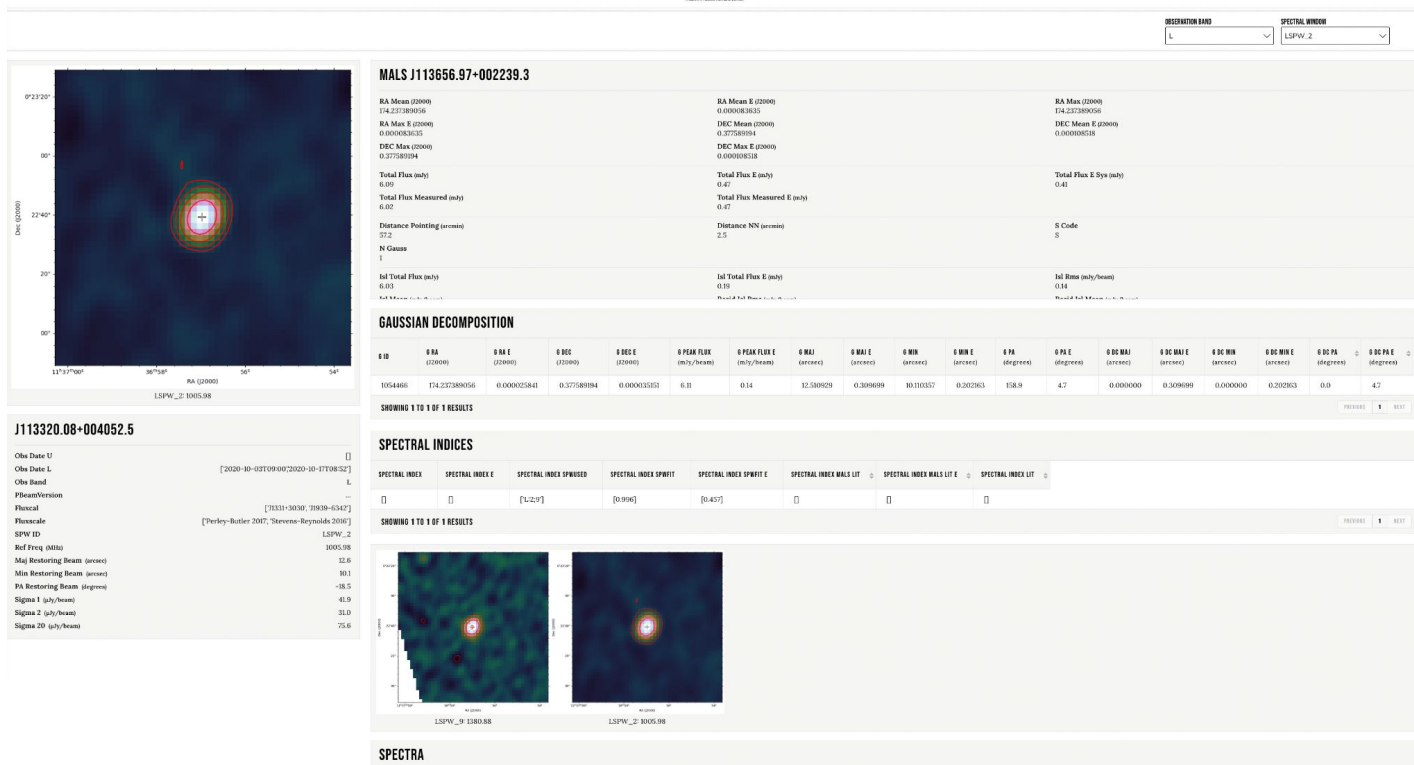1. DR1: L-band continuum
2. DR2: L-band (wideband continuum)

Coming soon …
3. DR3: Galactic HI and OH
4. DR4: L-band extragalactic HI
5. DRX: UHF-band continuum
6. …..

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MALS Data Releases - https://mals.iucaa.in/

Explore region of interest and bulk downloads

Summary

1. Absorption lines a powerful tool to study gas in and around galaxies
2. MALS (dust-unbiased view) - <u>associated</u> (AGNs) and <u>intervening</u> (normal galaxies) absorbers
   a. large survey project (1655 hours) at MeerKAT to obtain most sensitive spectra ever taken
   b. characterize the distribution of cold atomic (HI 21-cm) and molecular gas (OH 18-cm) in and around galaxies
3. Cold gas accompanied by metals and dust (need dust-unbiased approach but synergies with multi-wavelength surveys for ISM physics - **SDSS, DESI, 4MOST**)
   a. Survey footprint based on strong MIR selected AGNs (fainter / dust-unbiased) at the pointing center and numerous off-axis sources (serendipitous)
   b. Multiwavelength spectroscopy to characterize physical conditions in the absorbing gas
4. Survey well underway: ~400 pointings at L- and UHF

Absorption line ($\Delta X \sim 10^{3-4}$) + a competitive HI emission (few thousand galaxies) and continuum survey (few million sources) providing a comprehensive view of cold gas in various environments (including the Milky Way) at $z<2$.

All the data products will be released to the community

Thanks to SARAO engineers and commissioning teams for all the hard work towards making the MeerKAT telescope ….. NRAO CASA group for excellent software …. IUCAA computing team for keeping everything running !