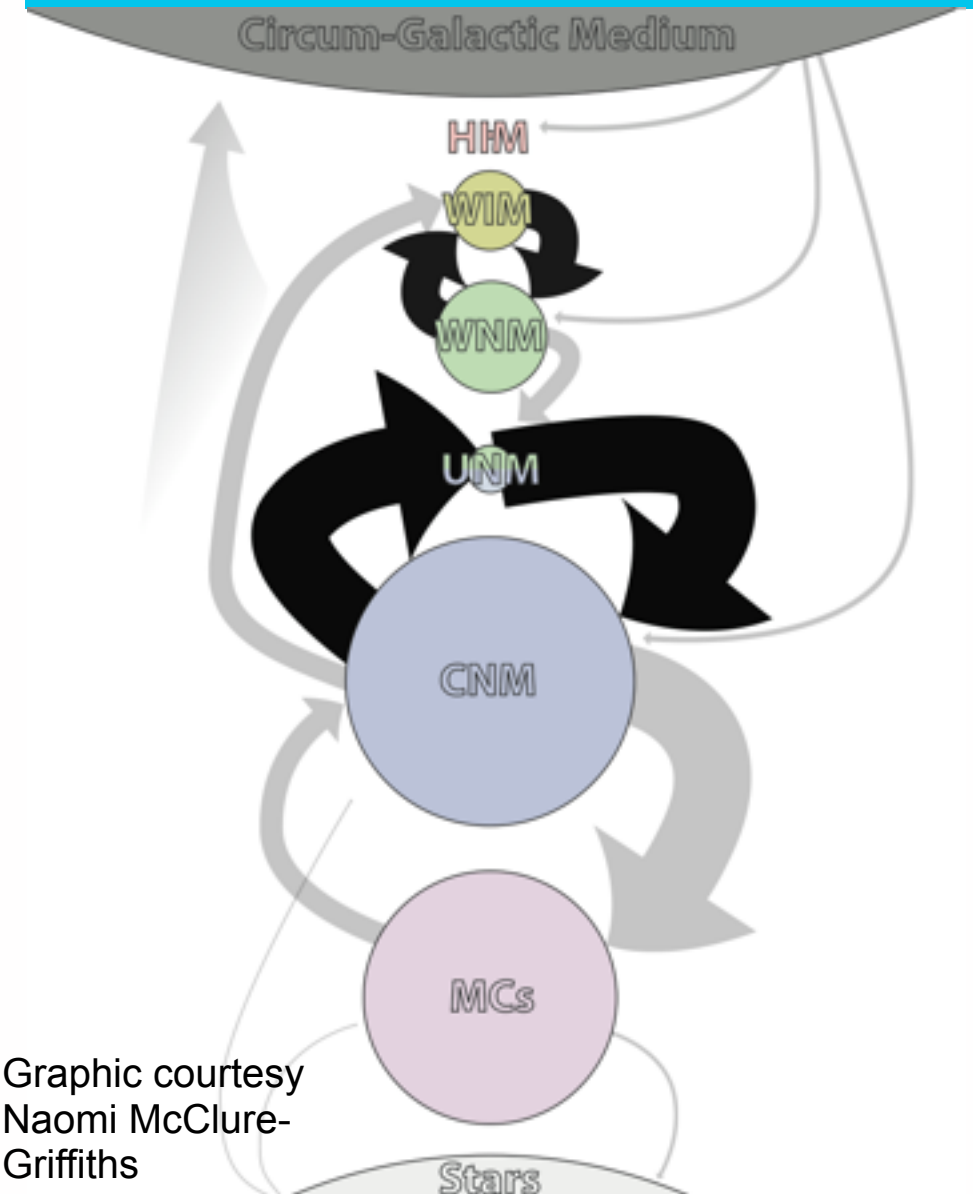
University of Hertfordshire

Milky Way SKA: the ISM, star formation and stellar evolution with the SKA

Mark Thompson, Grazia Umana, Naomi McClure-Griffiths, Laurent Loinard, Gary Fuller, Guillem Anglada, Sergio Molinari, Raymond Oonk and the Our Galaxy SWG

Uncovering the ecology of baryons



Graphic courtesy Naomi McClure-Griffiths

How do galaxies work?

What is the flow of material from & to the Circum-Galactic Medium, the Interstellar Medium and stars?

What powers the ionisation of the Warm Ionised Medium?

How do molecular clouds form?

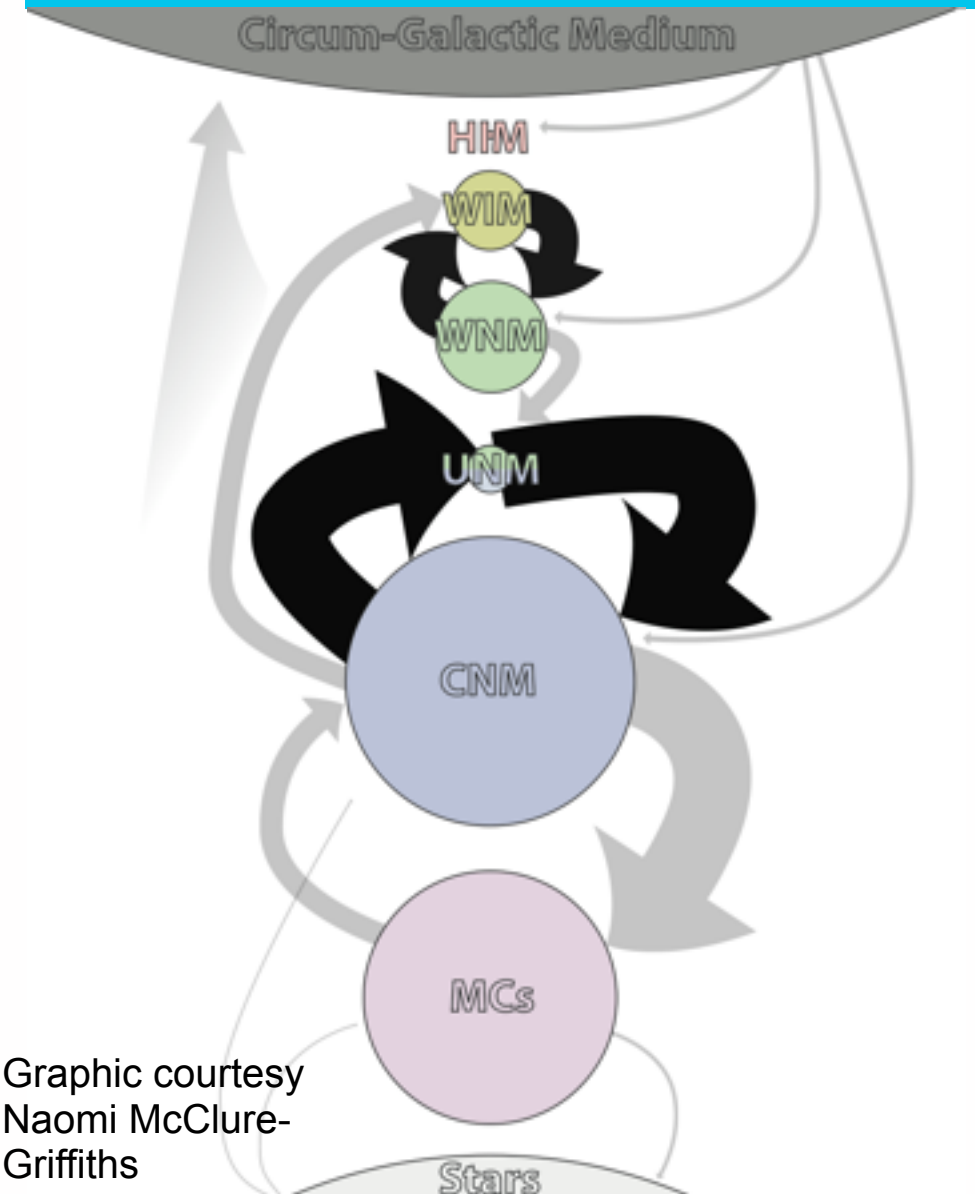
What is the relation between molecular clouds and star formation “laws”?

How do stars drive turbulence & energy into the ISM?

What can the structure of stellar clusters tell us about star formation?

What is the SNR/PNe formation rate in the Milky Way?

The SKA puts it all together



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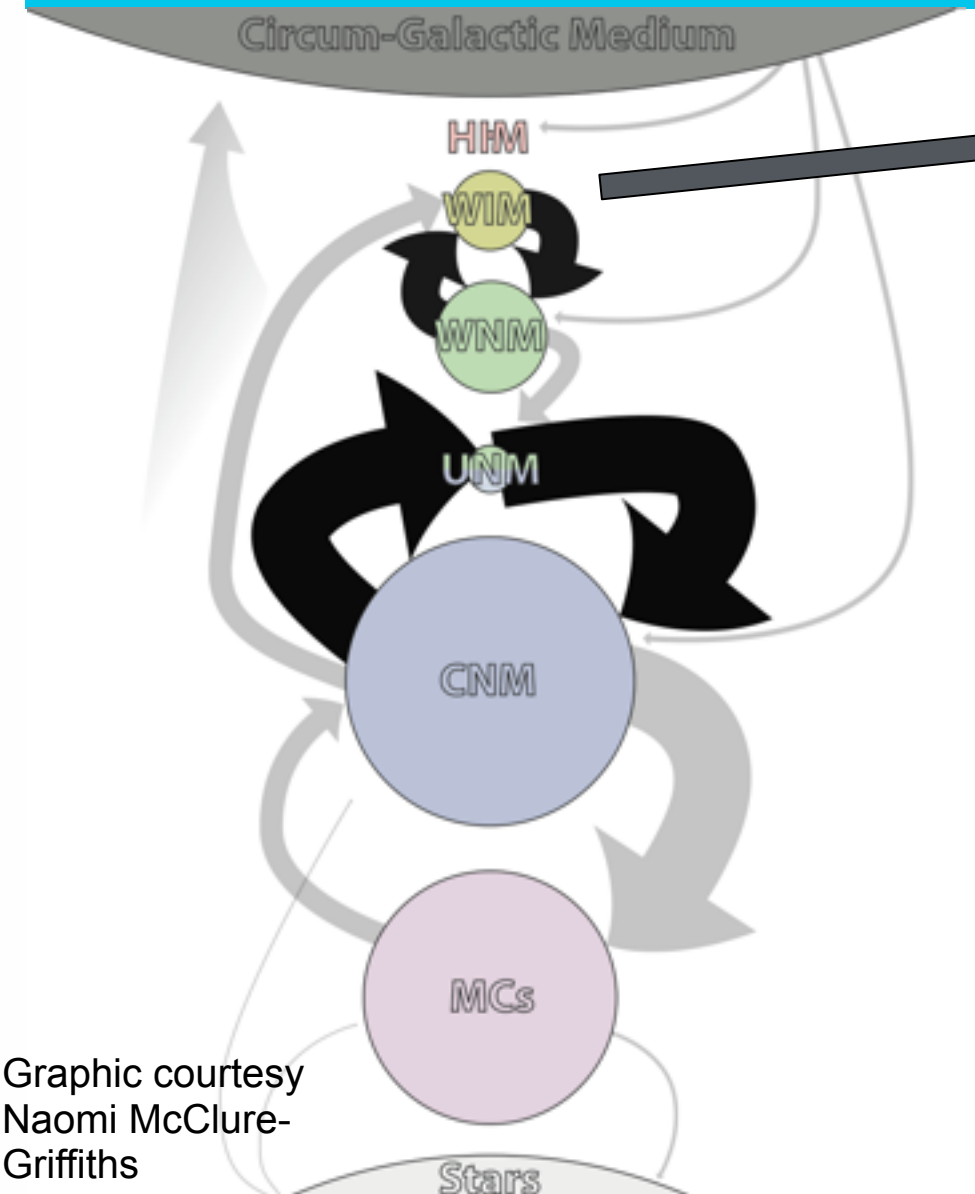

Thermal continuum from HII regions
Radio Recombination Lines

Graphic courtesy
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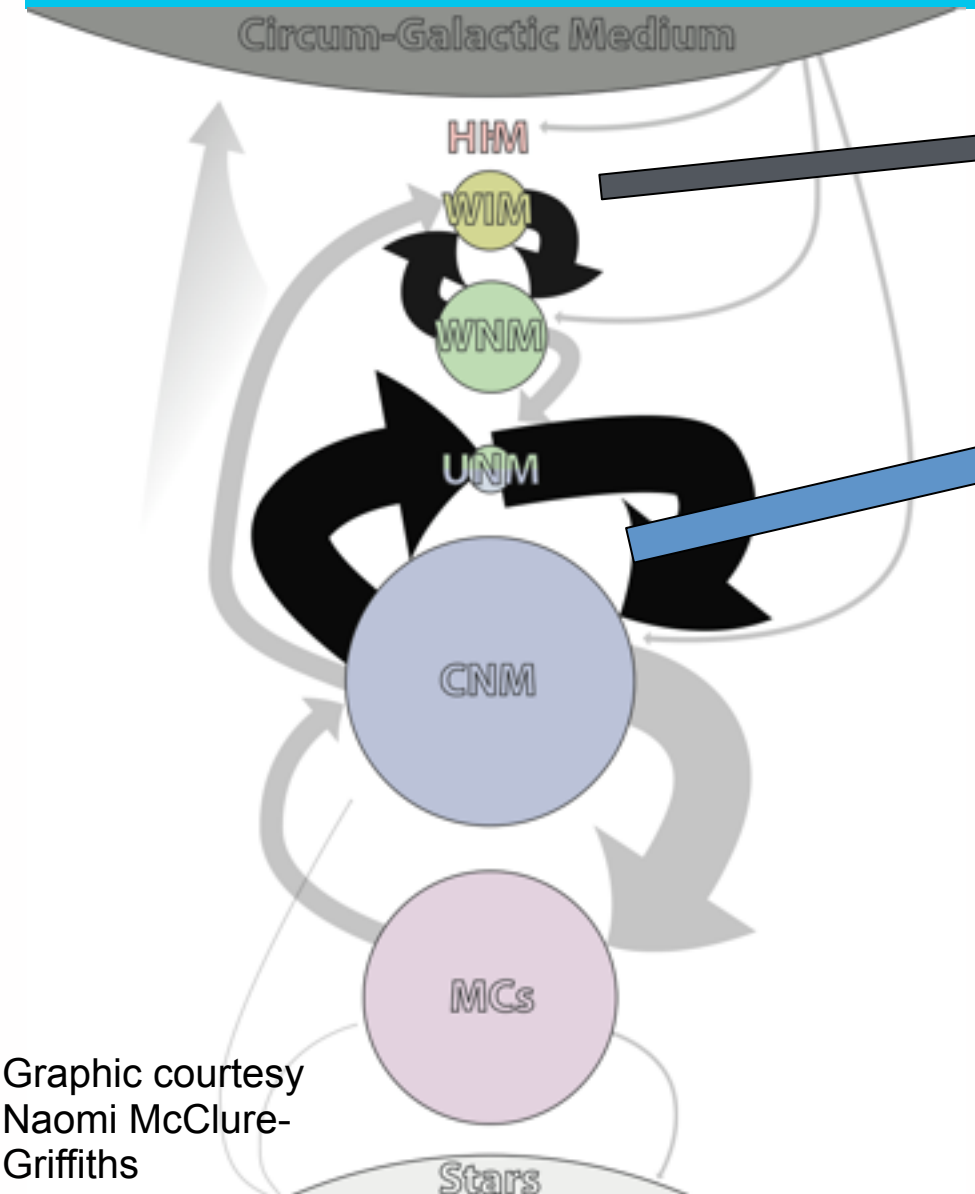

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HI emission
HI absorption
HI tomography

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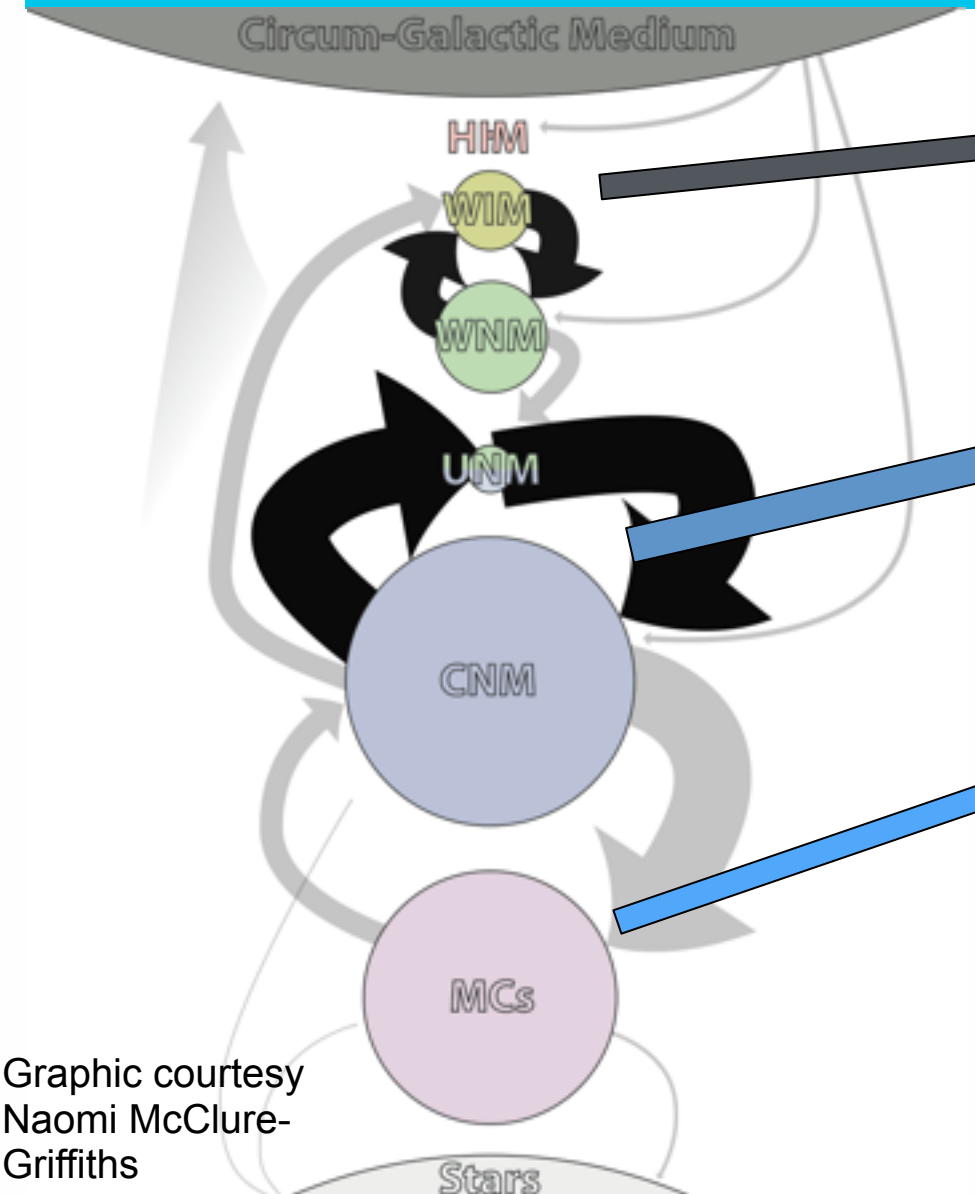

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Thermal OH - CO dark gas

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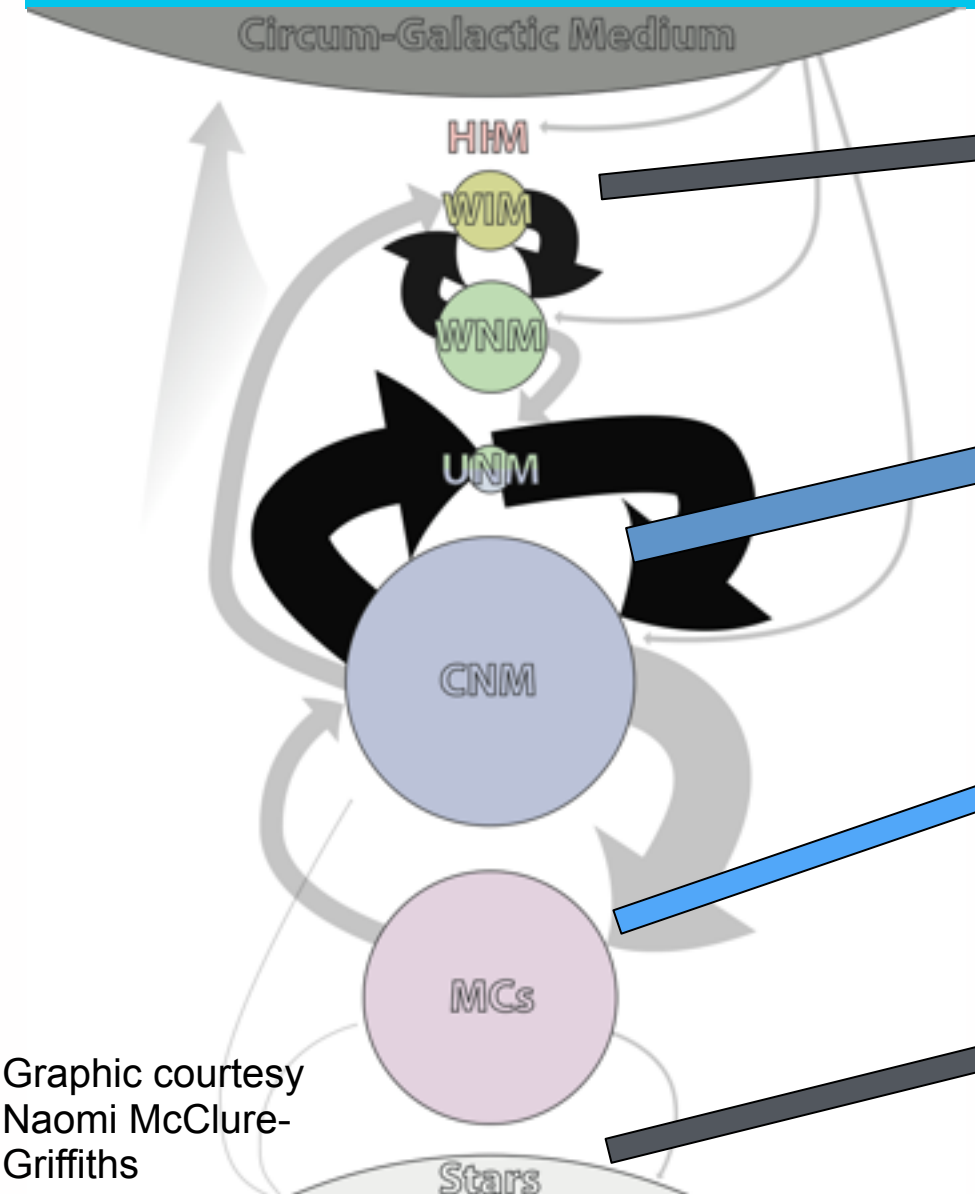

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HI emission
HI absorption
HI tomography

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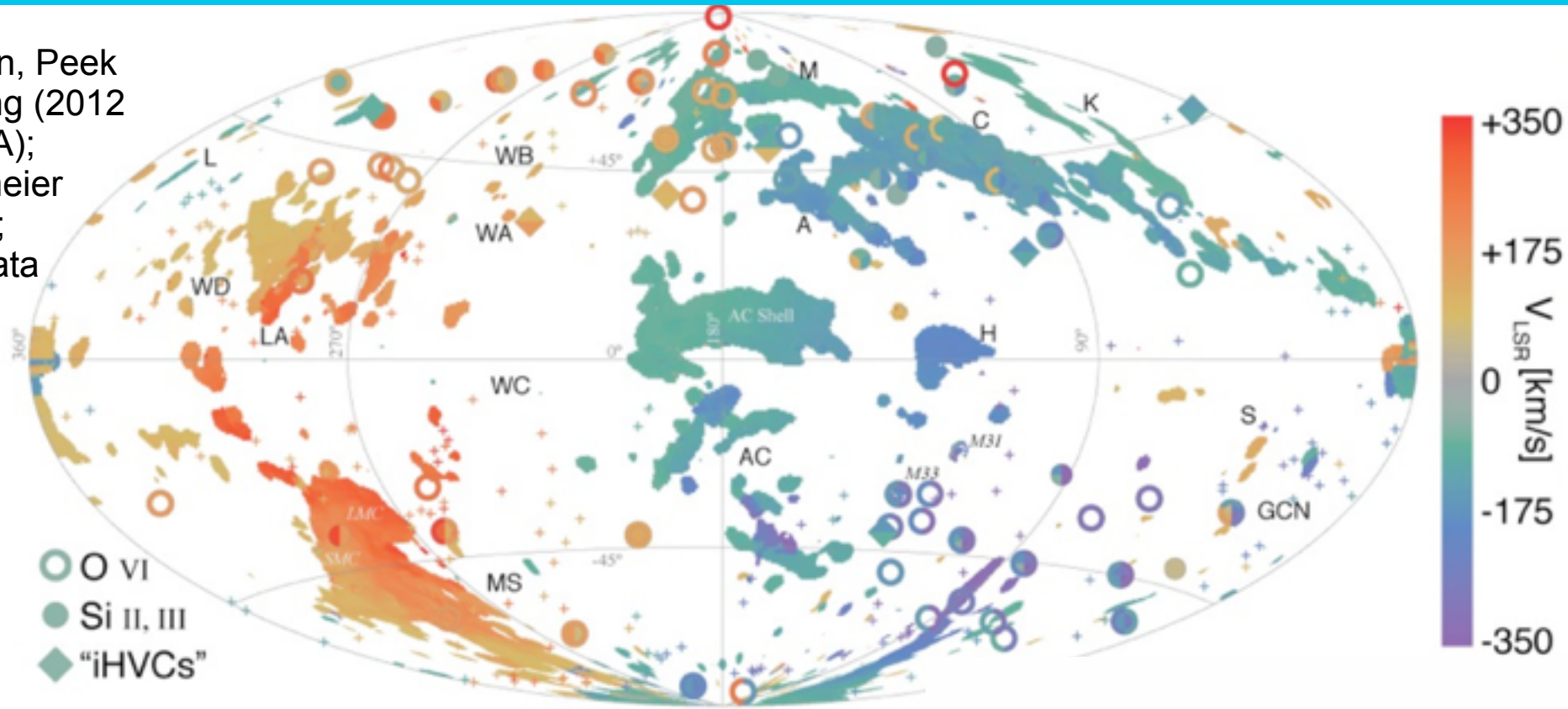
Thermal OH - CO dark gas

Thermal continuum from jets & winds
VLBI Tomography of young clusters
Stellar Radio HR diagram

Graphic courtesy Naomi McClure-Griffiths

Gas accretion via HVCs

Putman, Peek & Joung (2012 ARA&A); Westmeier (2007); LAB data

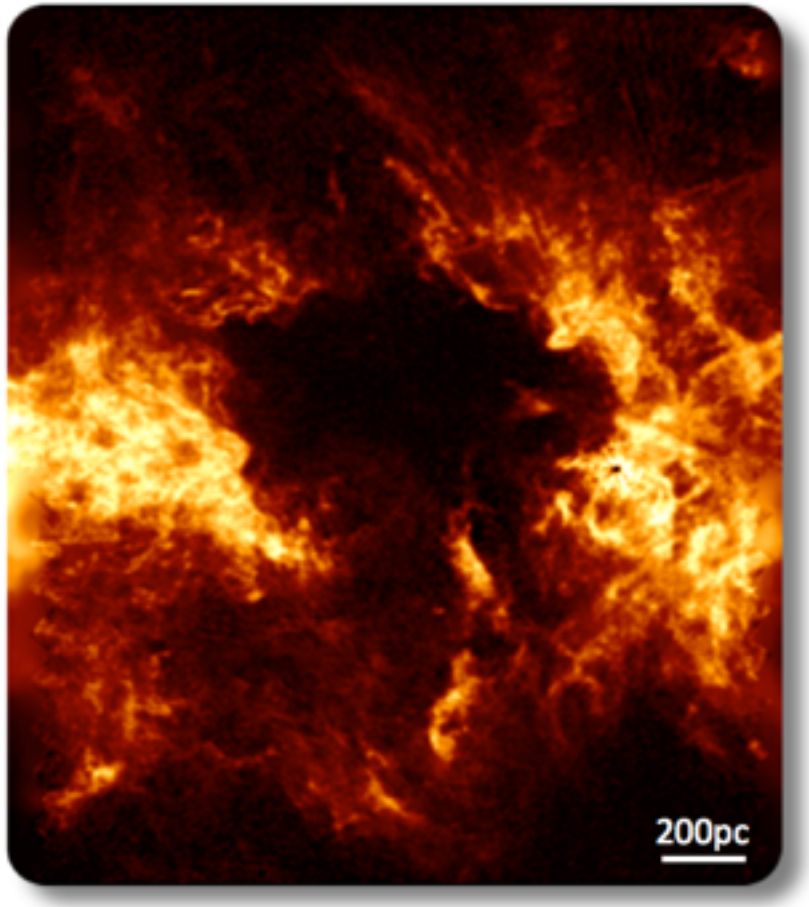


Large undetected reservoir of low column density gas (<10^{18} cm^{-2})

Combined with large area UV absorption spectroscopy, SKA will be able to detect and map the cold & warm gas reservoir

Gas outflow from galaxies

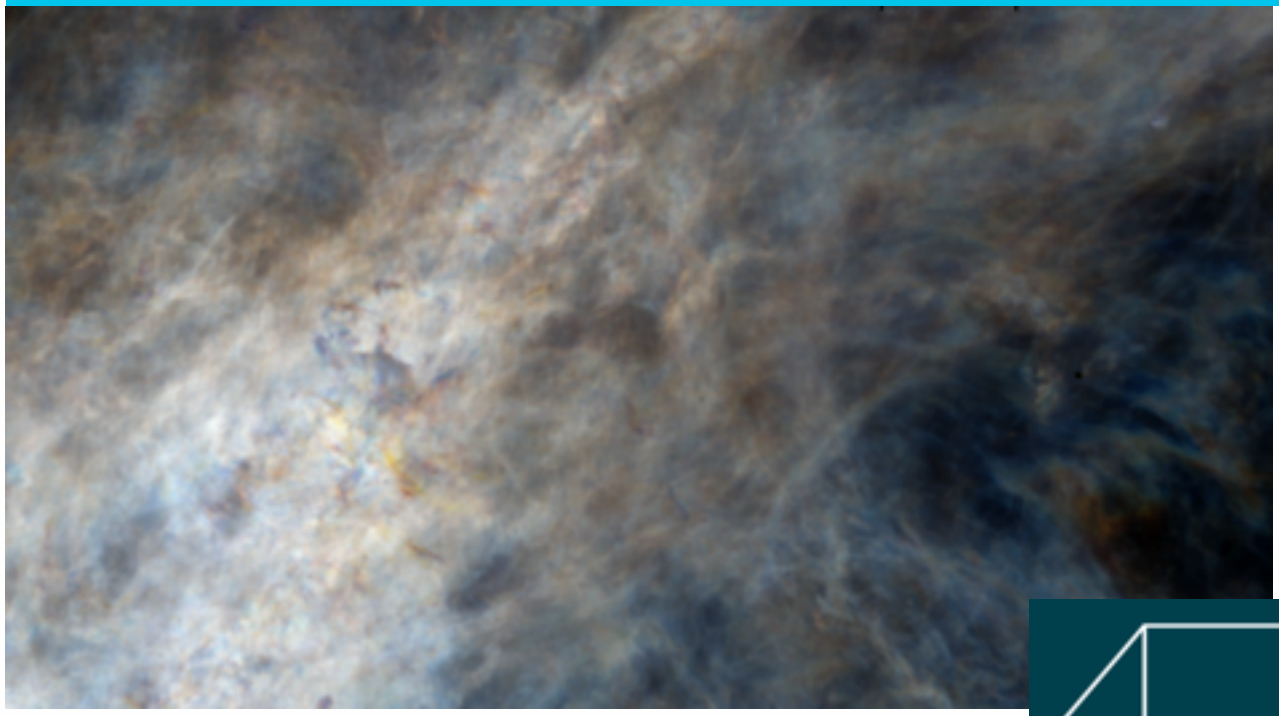
M82. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



MW GSH277+00+36: McClure-Griffiths et al. (2003)

Parsec-scale resolution of multiphase gas in outflows & lower halo

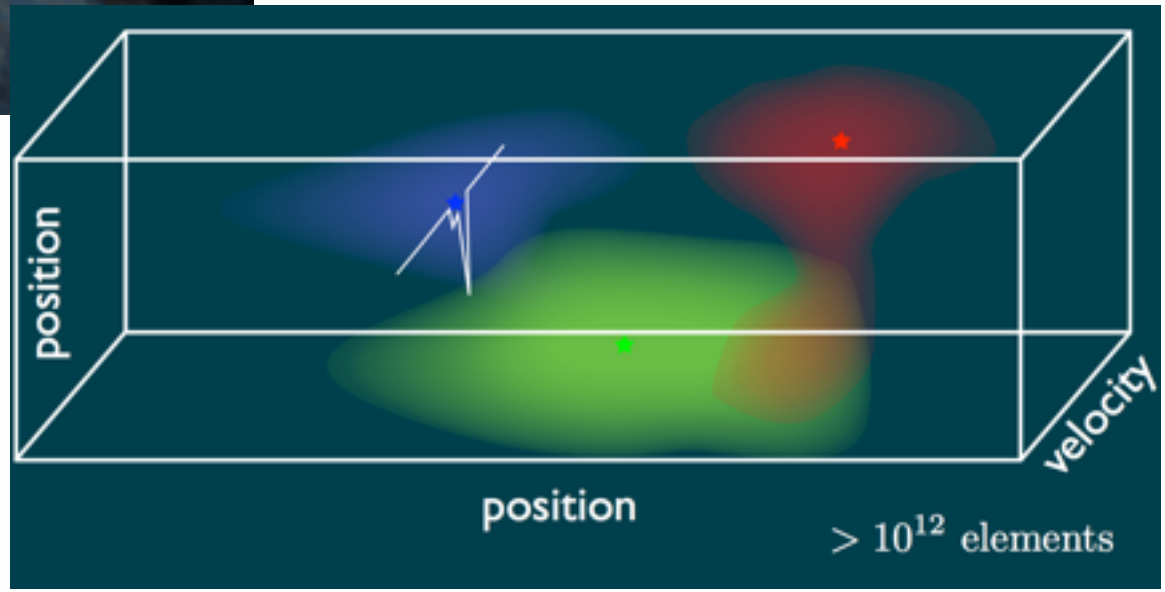
Cold gas via HISA/HINSA & tomography



Column density via self absorption

Spin temperature via absorption from background continuum sources

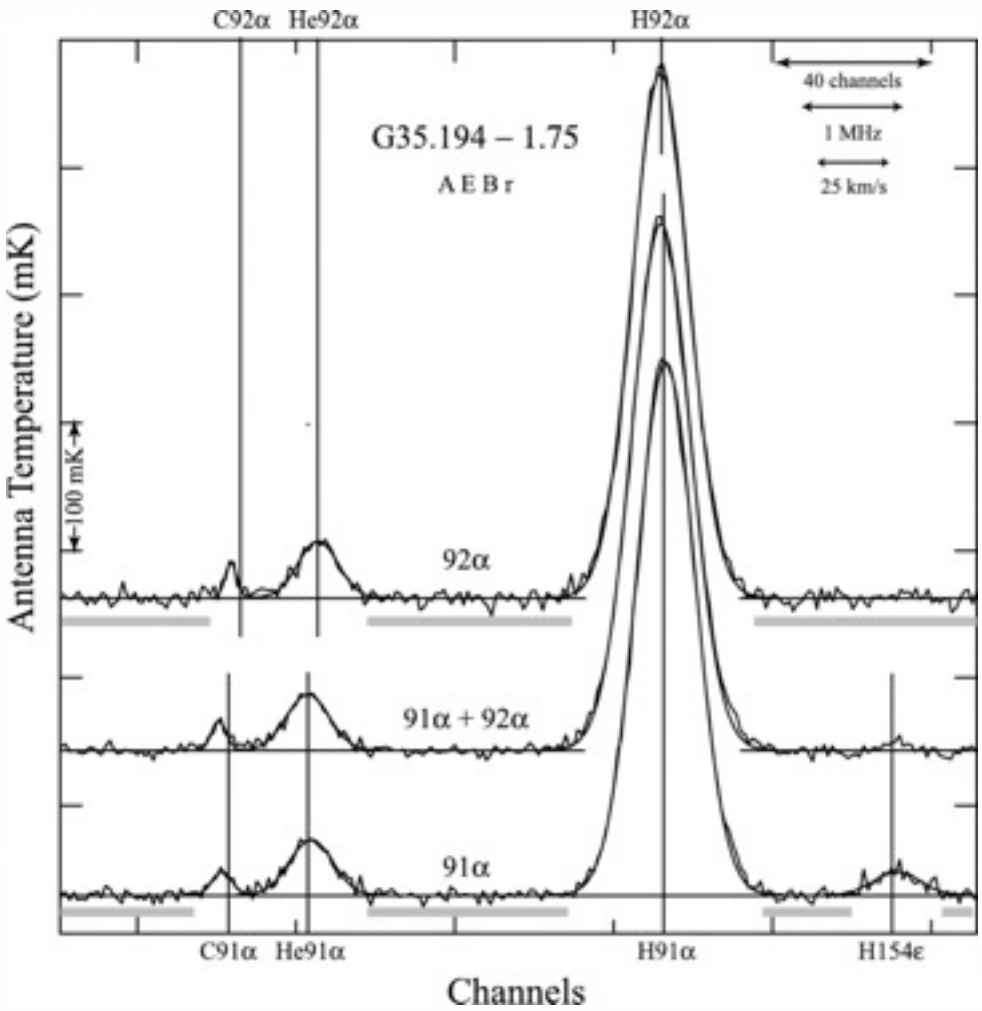
Map flows of HI onto molecular clouds



Combine kinetic information from SKA HI survey with GAIA/LSST extinction maps

Coupled dust/gas 4D kinetic tomography!

The ionised medium with RRLs



SKA will be a recombination line mapping machine:

Can simultaneously map 50 Hα (+ Heα + Cα RRLs) in Band 2 and 25 in Band 5

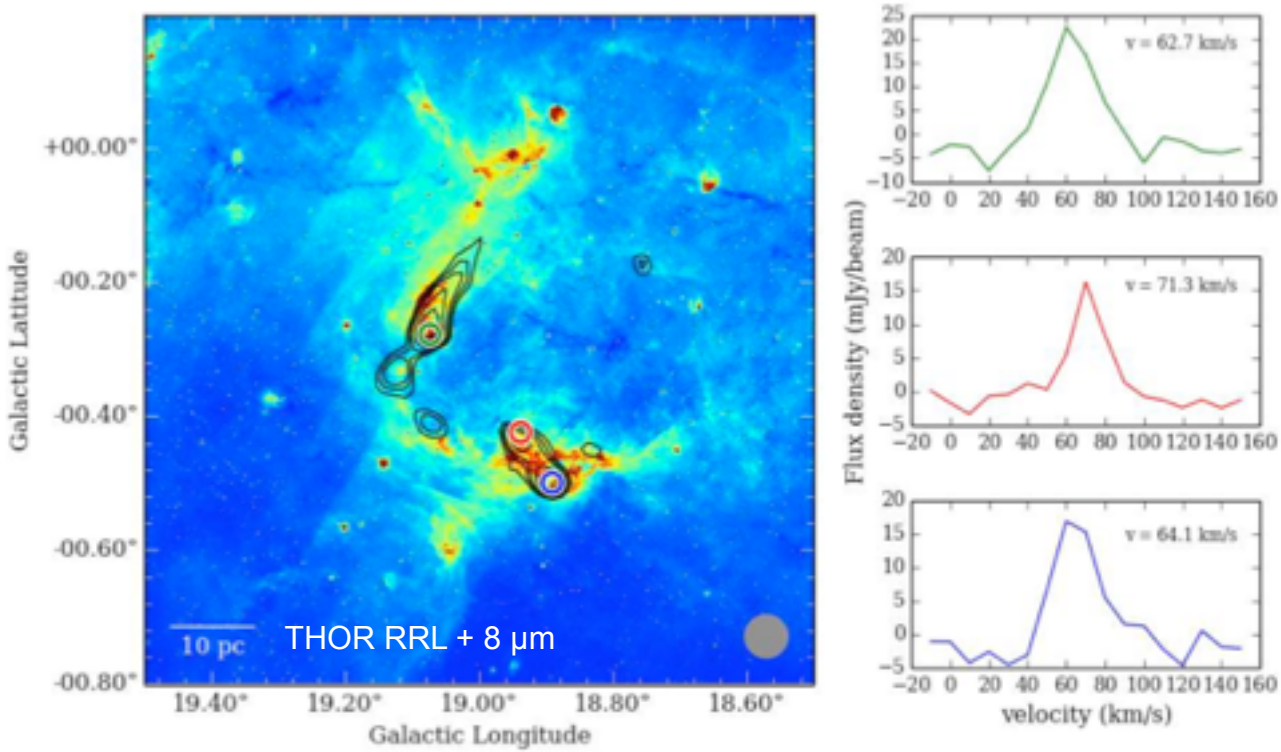
Band 2 **RRL** mapping speed of SKA1-mid comparable to VLA *continuum* mapping speed

SKA-Low unique probe of diffuse ISM via low frequency Carbon lines

Broad frequency coverage traces different electron densities

Multiple lines from multiple atoms allows metallicity, abundance, radiation field to be measured

A Band 2 RRL diffuse ISM survey



THOR detects RRLs toward bright continuum (> 70 mJy)

But in high densities & with pressure broadened lines

For diffuse unbroadened gas need to trace n_e~100 cm^{-3}

Needs ~1 hour/pointing for SKA1-mid w/ line stacking

Fully commensal with HI survey ~300 hours for entire Plane

Out of the box early science towards individual HIIs (~150 hours to map top 12 HIIs)

(THOR - The HI, OH, Recombination Line Survey of the Milky Way, Bihr et al 2015)

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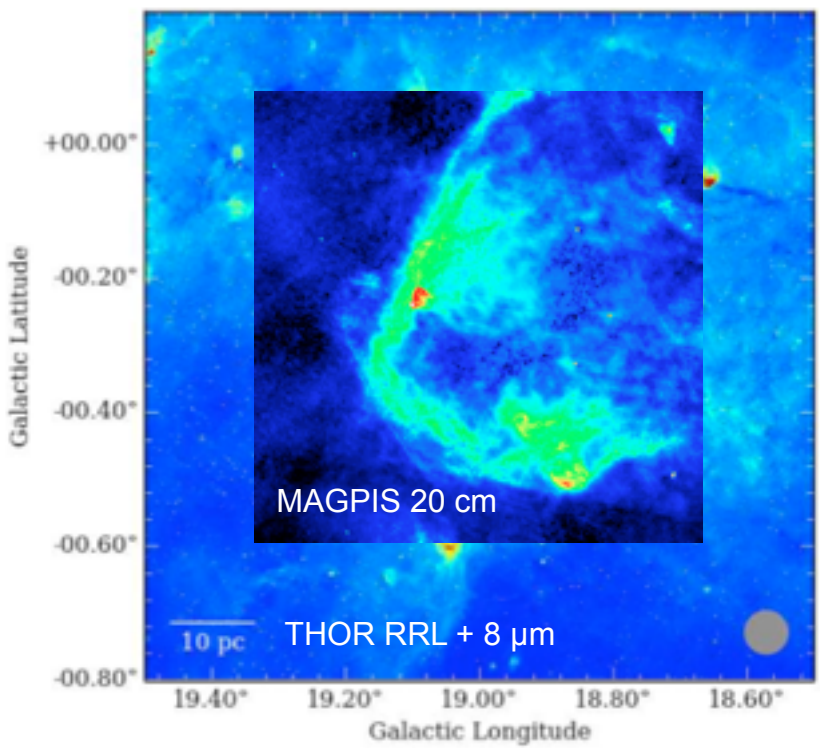

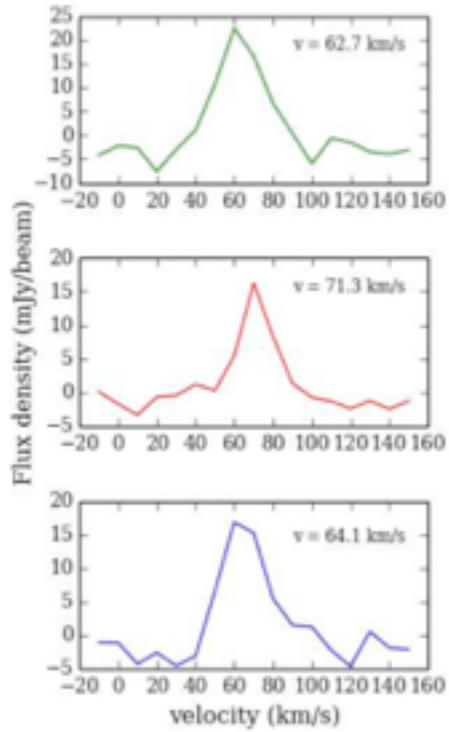

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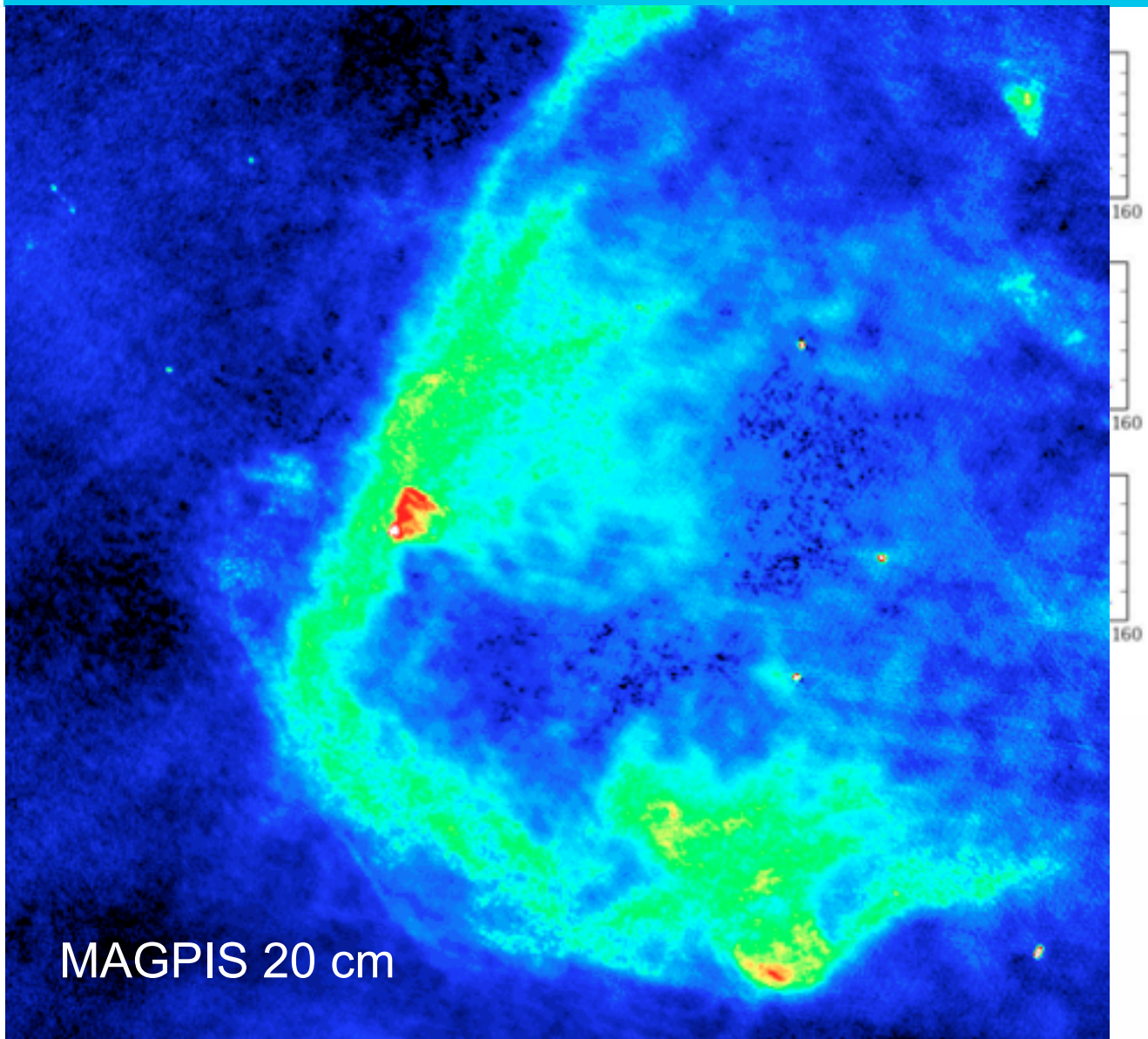

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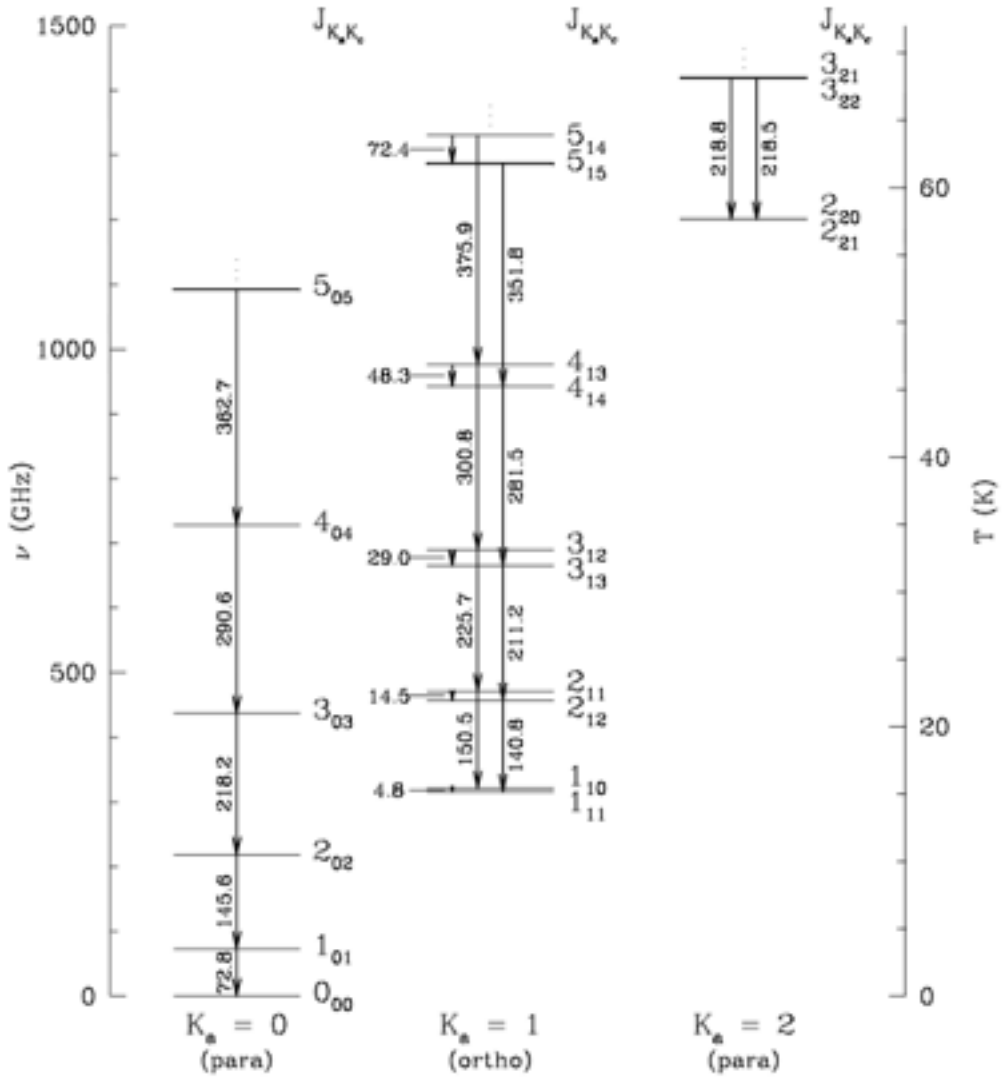
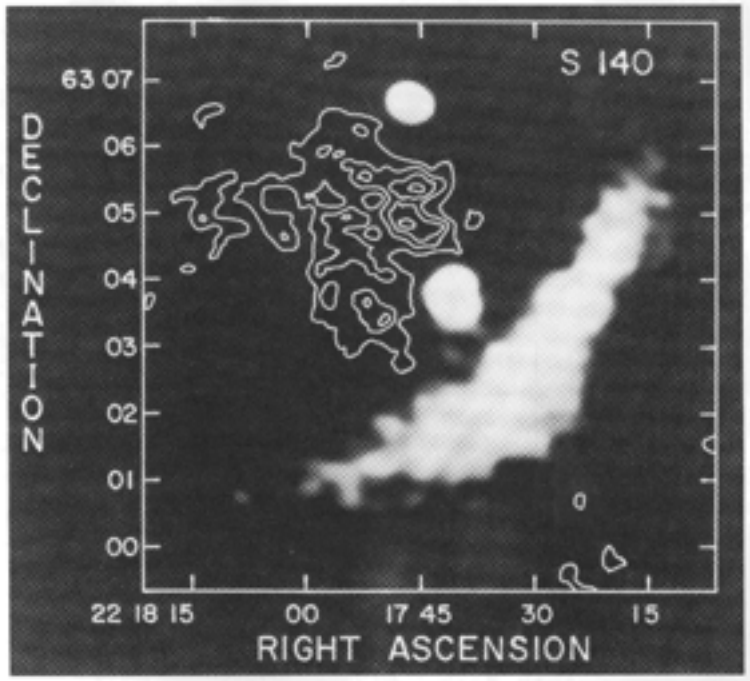
Molecular gas with H_2CO absorption





Evans et al 1987
First VLA detection

Collisional pumping drives population to lower energy states (anti-inversion)

Shows up in absorption against CMB when $T_{ex} < T_{CMB}$

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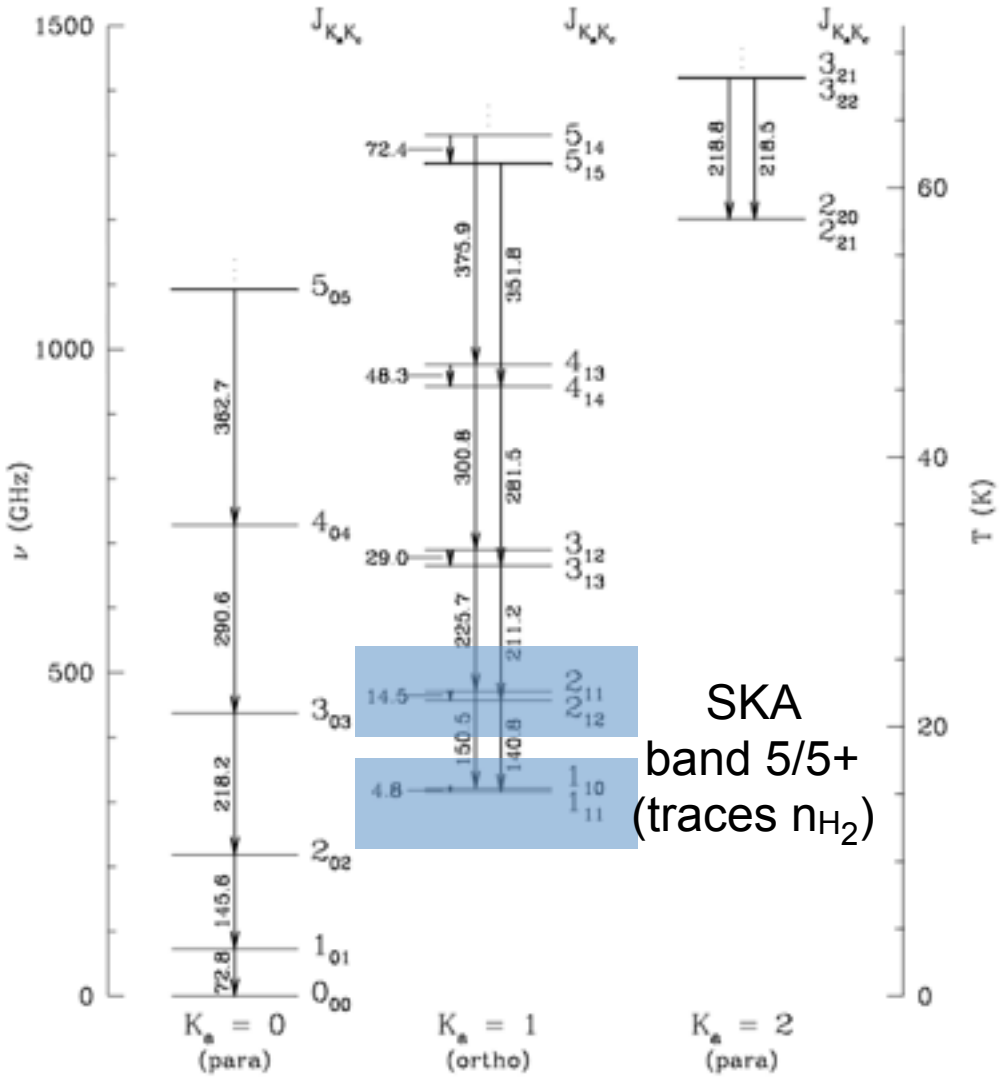
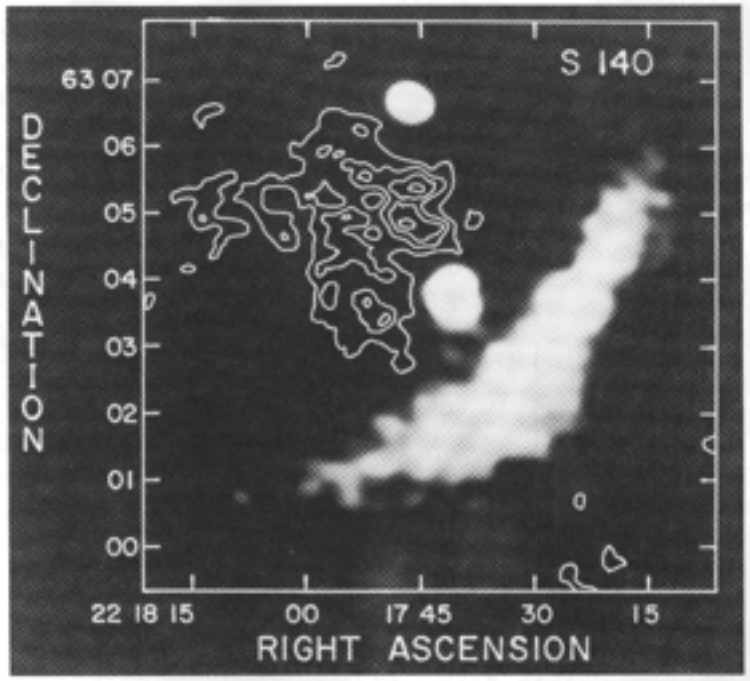


SKA band 5/5+ (traces n_{H_2})



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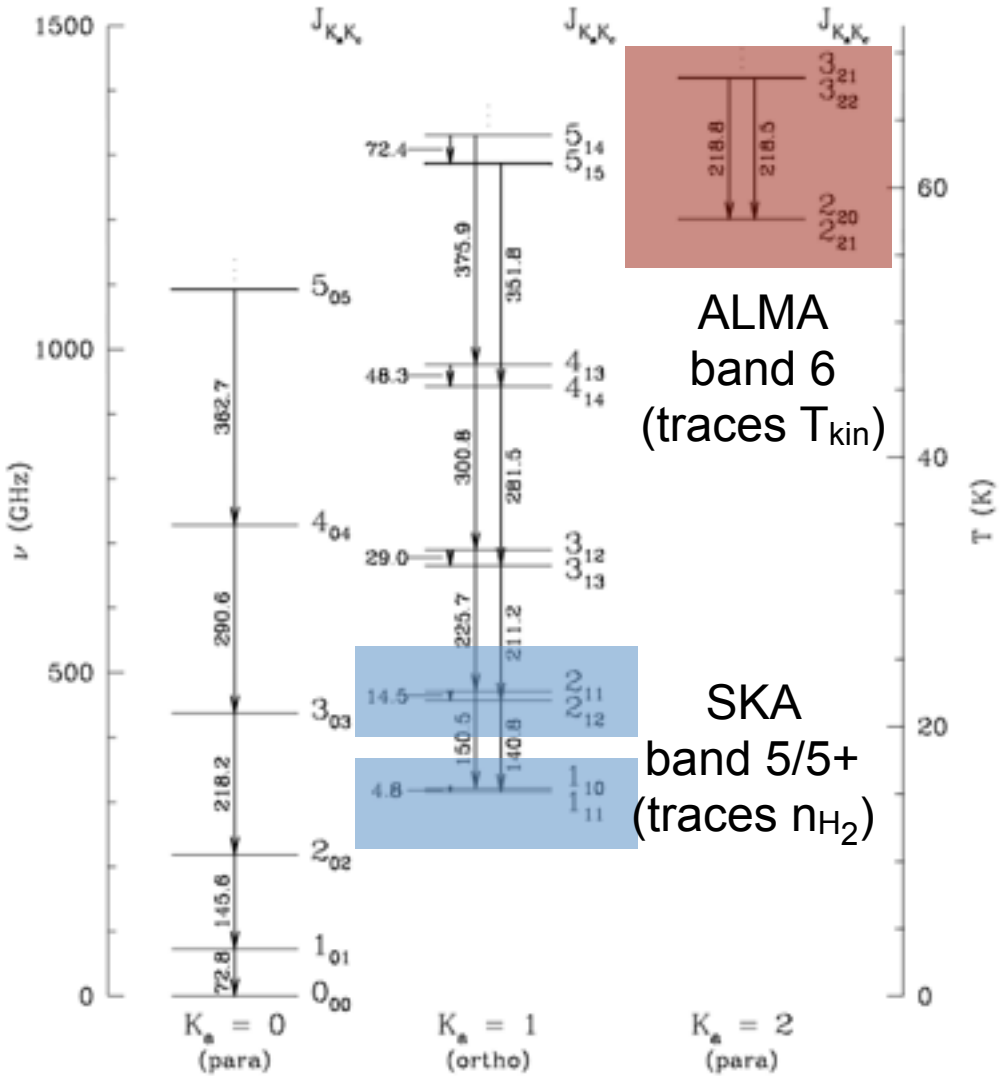

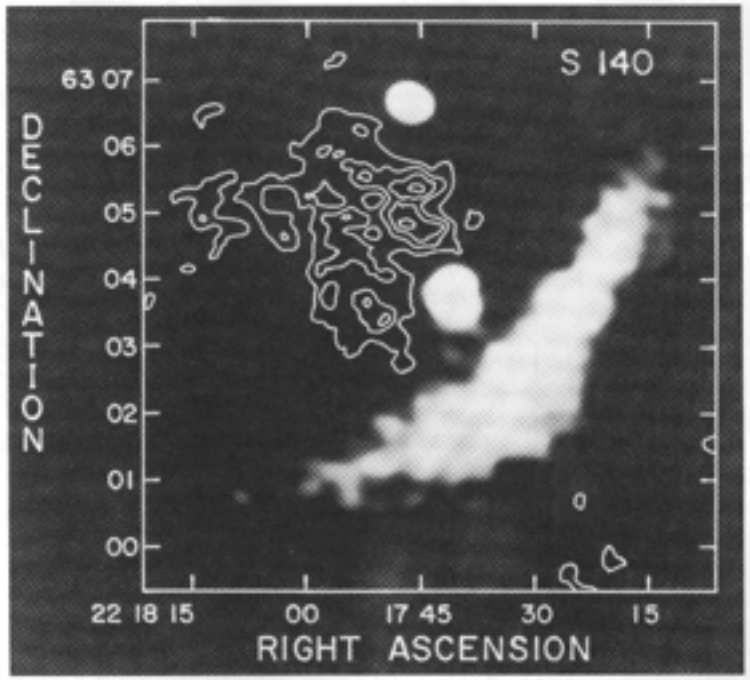

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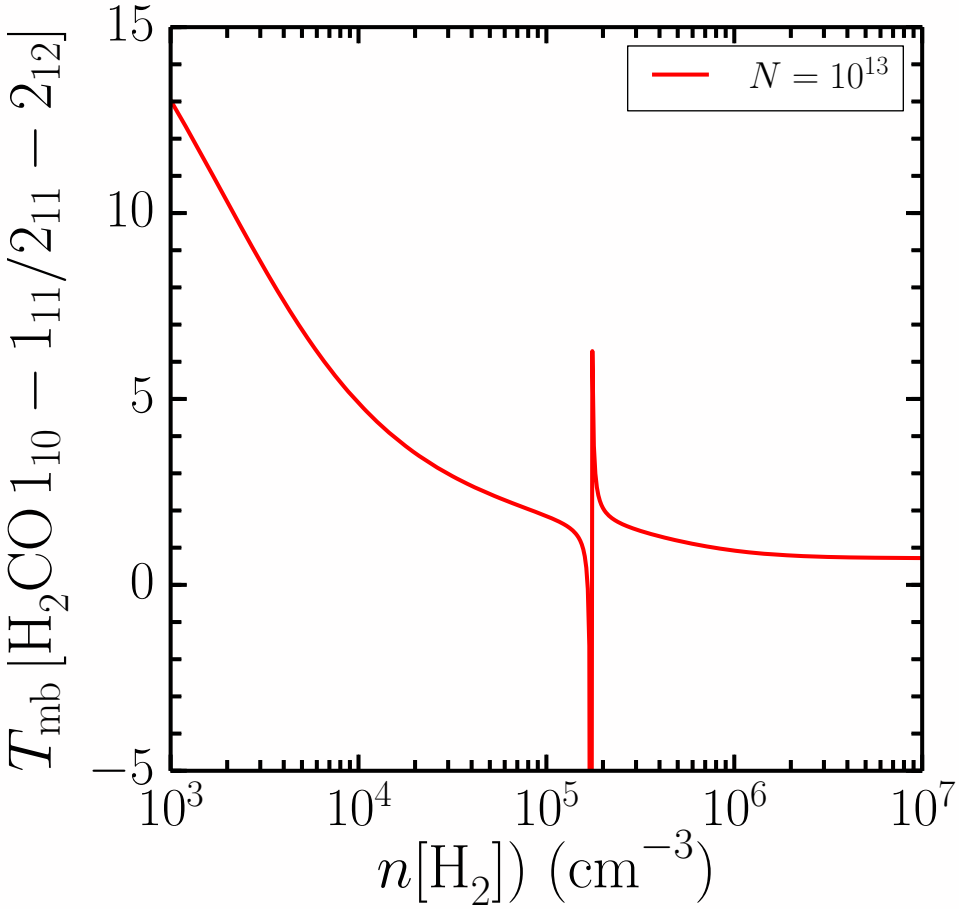
Advantages of anomalous absorption

1. Distance independent tracer
   The Milky Way, nearby galaxies, starbursts... (Mangum et al 2013)

2. Excellent and unique tracer of gas *density*
   Line ratio between 4.8 GHz & 14.4 GHz fixes gas density to ~0.2 dex with good dynamic range: 10^3 - 10^6 cm^{-3}
   (Ginsburg et al 2011)

3. Unaffected by line trapping, sub-thermal excitation or high optical depths
   - unlike CO, where $n(H_2)$ may not be constrained within 2 orders of magnitude

4. Removing the scatter in SF "laws"
   e.g. Krumholz 2014



Discontinuity shows where lines go into emission

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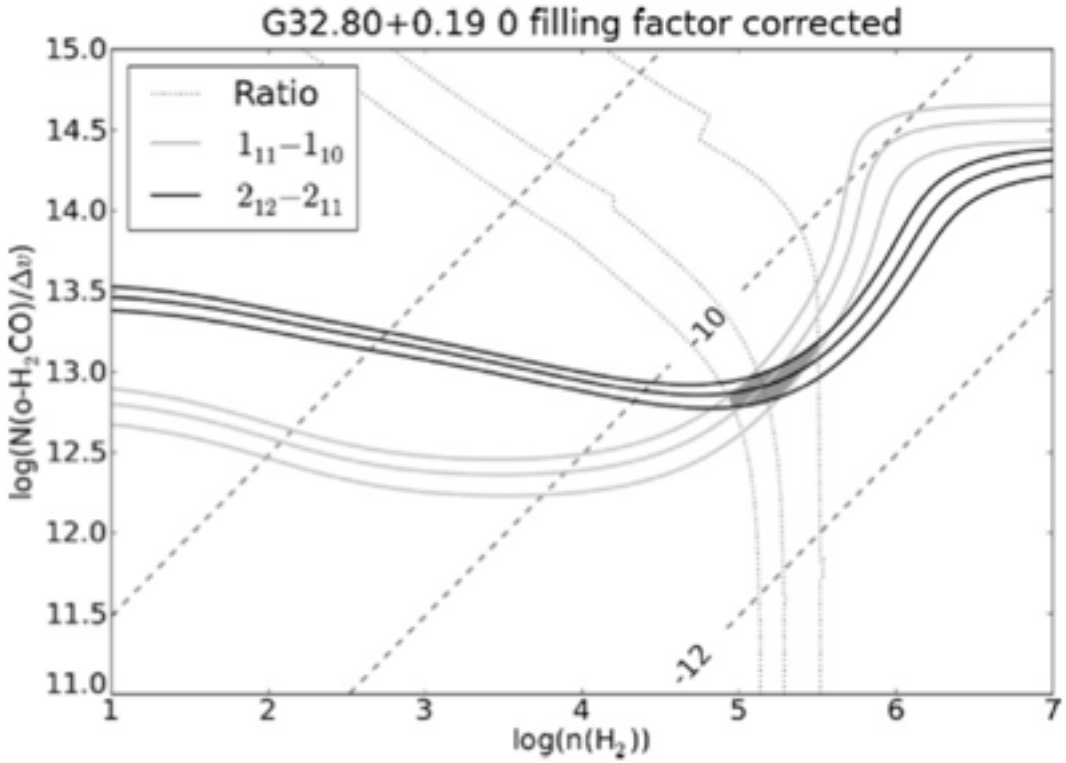

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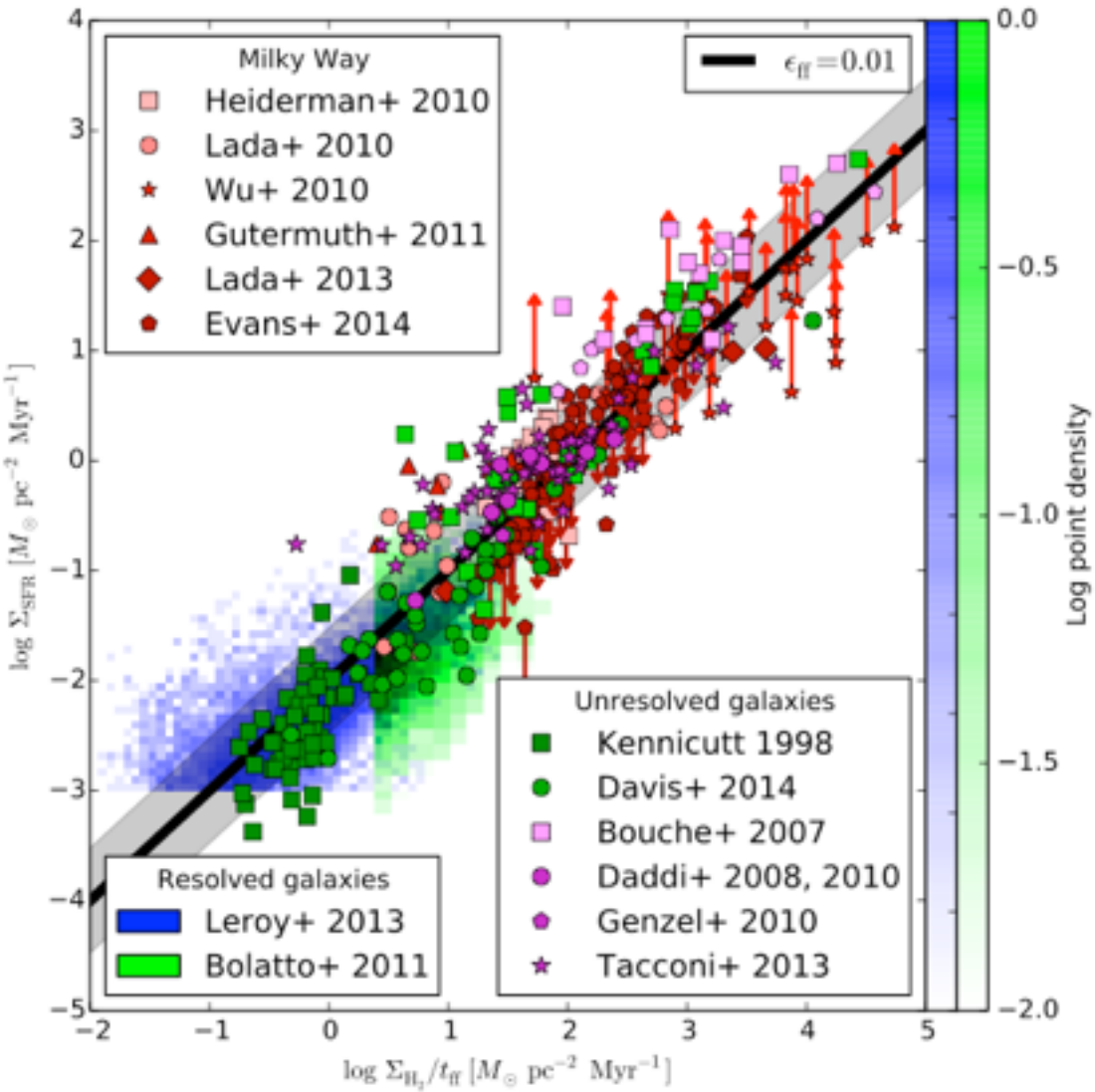


Galactic tomography of the ISM

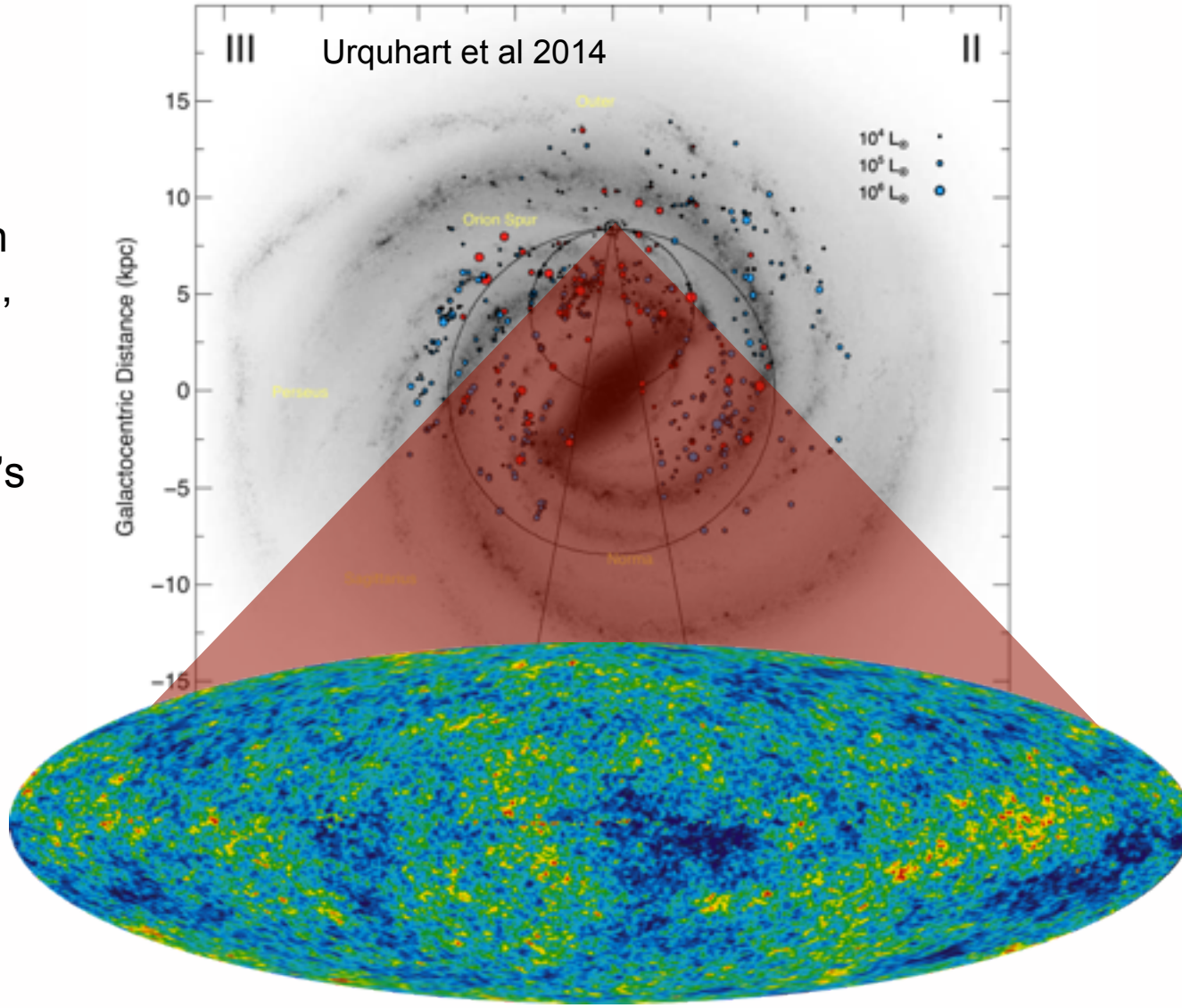
Anomalous absorption against CMB is not the only absorption that will be measured.

Will also be able to measure absorption against continuum sources (HII regions, PNe etc)

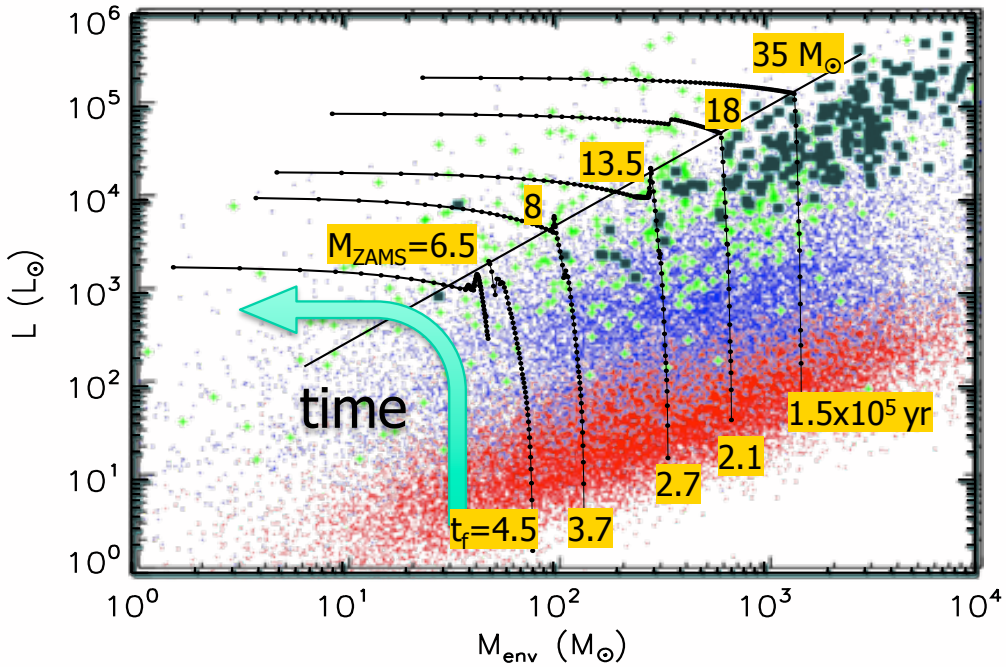
All of these HII regions will have velocities (simultaneous RRLs) & ~100's with accurate distances from SKA VLBI parallax (Green AASKA2015)

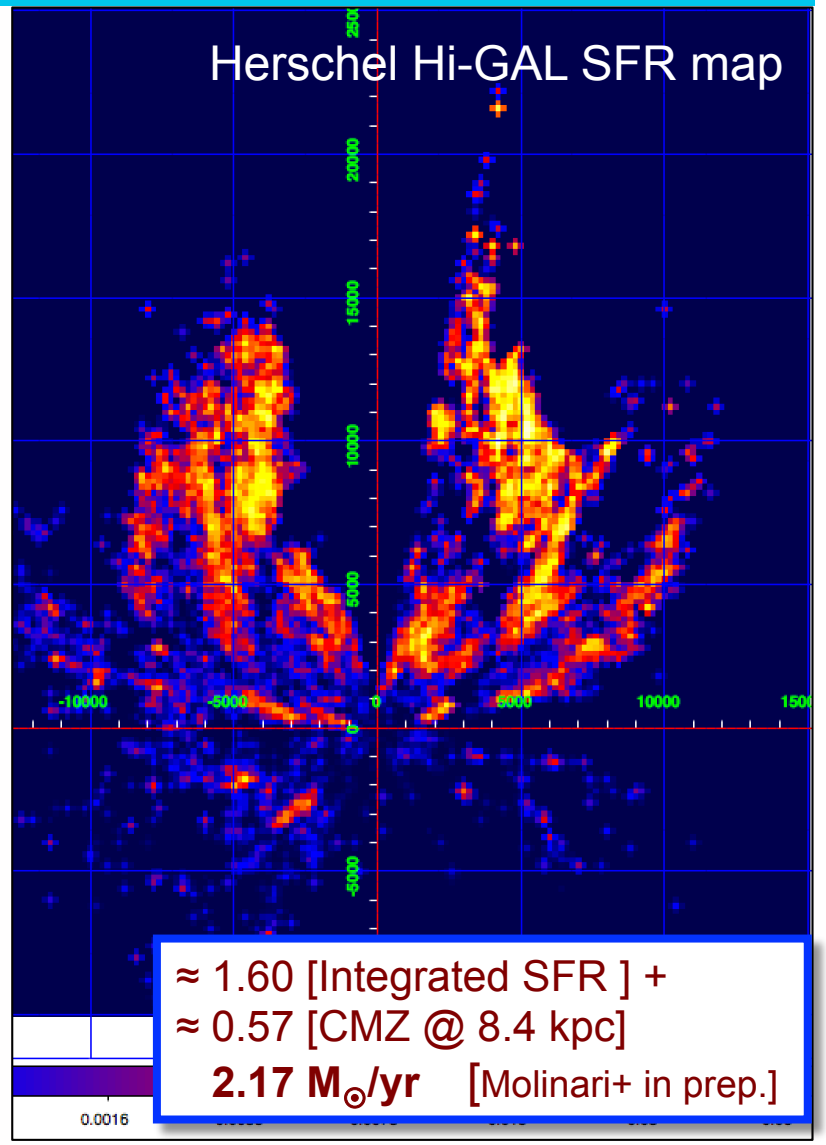
Network of illuminating sources - constrain absorption to particular distances

Tomography of the molecular ISM



Calibrating the radio SFR relation





Band 5 continuum valuable tracer of ionising photon budget, Star Formation Rate (SFR) & evolutionary state of star-forming clumps

Multiwavelength combination to constrain SFR & disentangle thermal/non-thermal mechanisms

Synergy with Continuum SWG

Tomography of stellar clusters

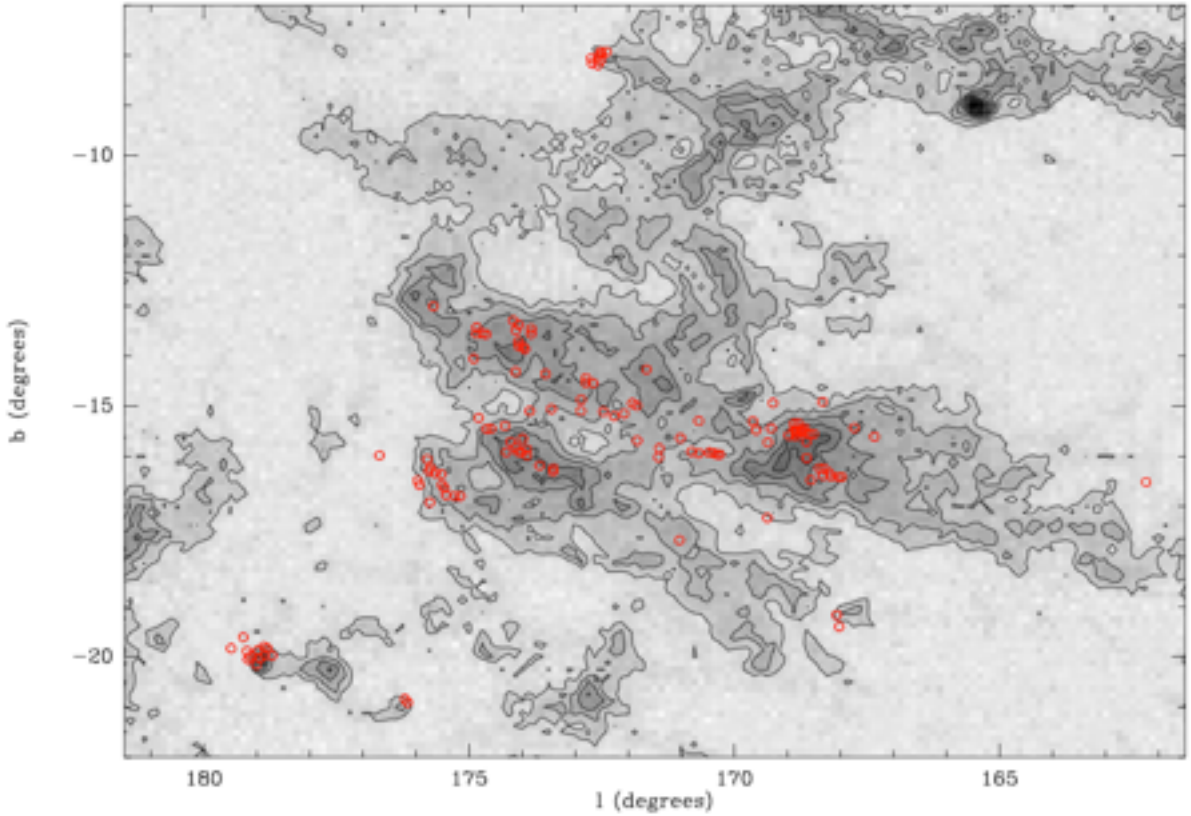
μJy sensitivity allows large numbers of YSOs to be detected via their thermal continuum (e.g. Dzib et al 2015)

SKA could realistically detect all nearby young stars in Band 5

SKA VLBI can measure parallaxes to 1% precision

Determine 3D structure of nearby stellar clusters (SKA1) & spiral arms (with full SKA)

Adding proper motions & kinematic information gives 6D picture of stellar structure and places strong constraints on cluster formation models



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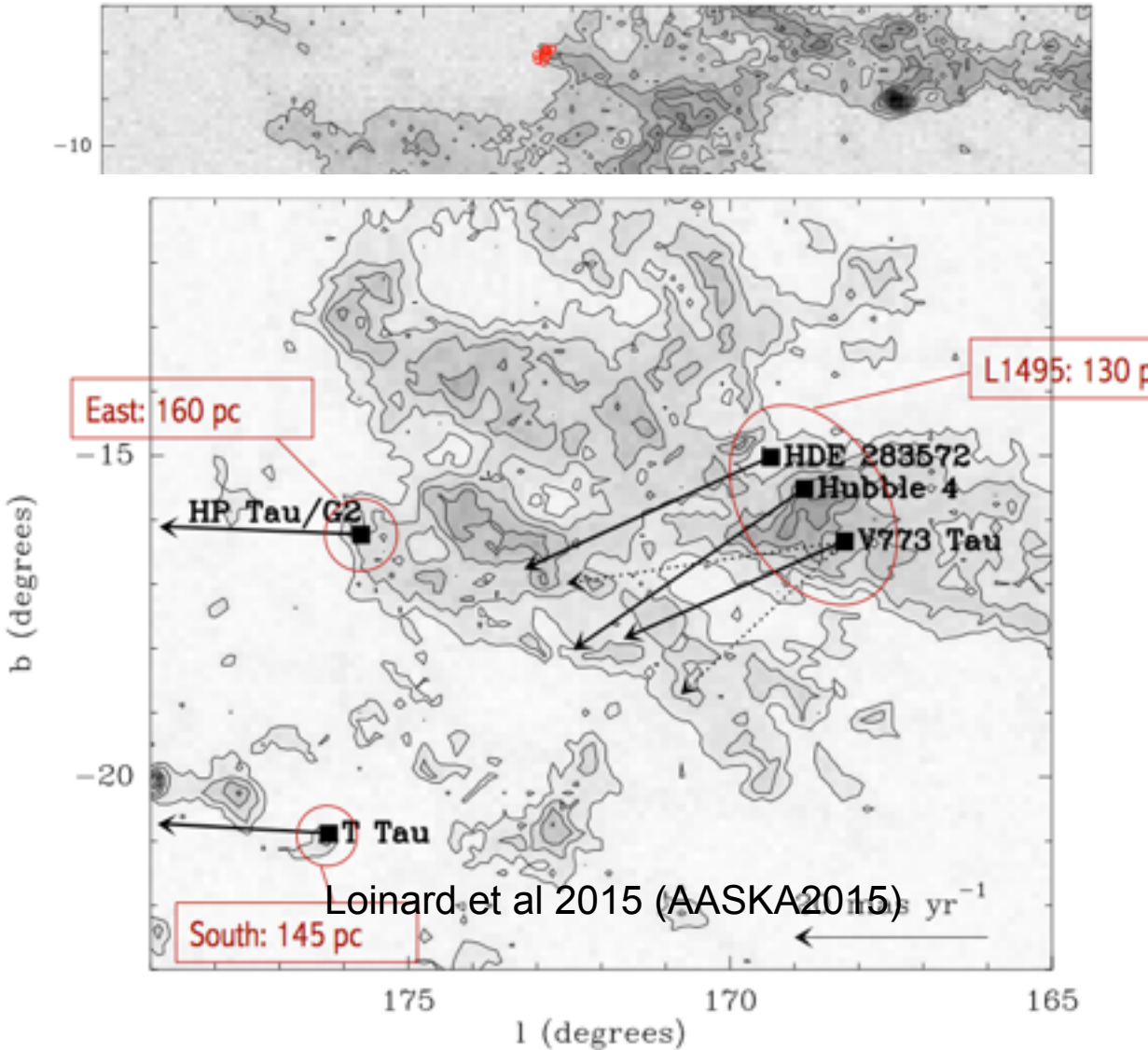
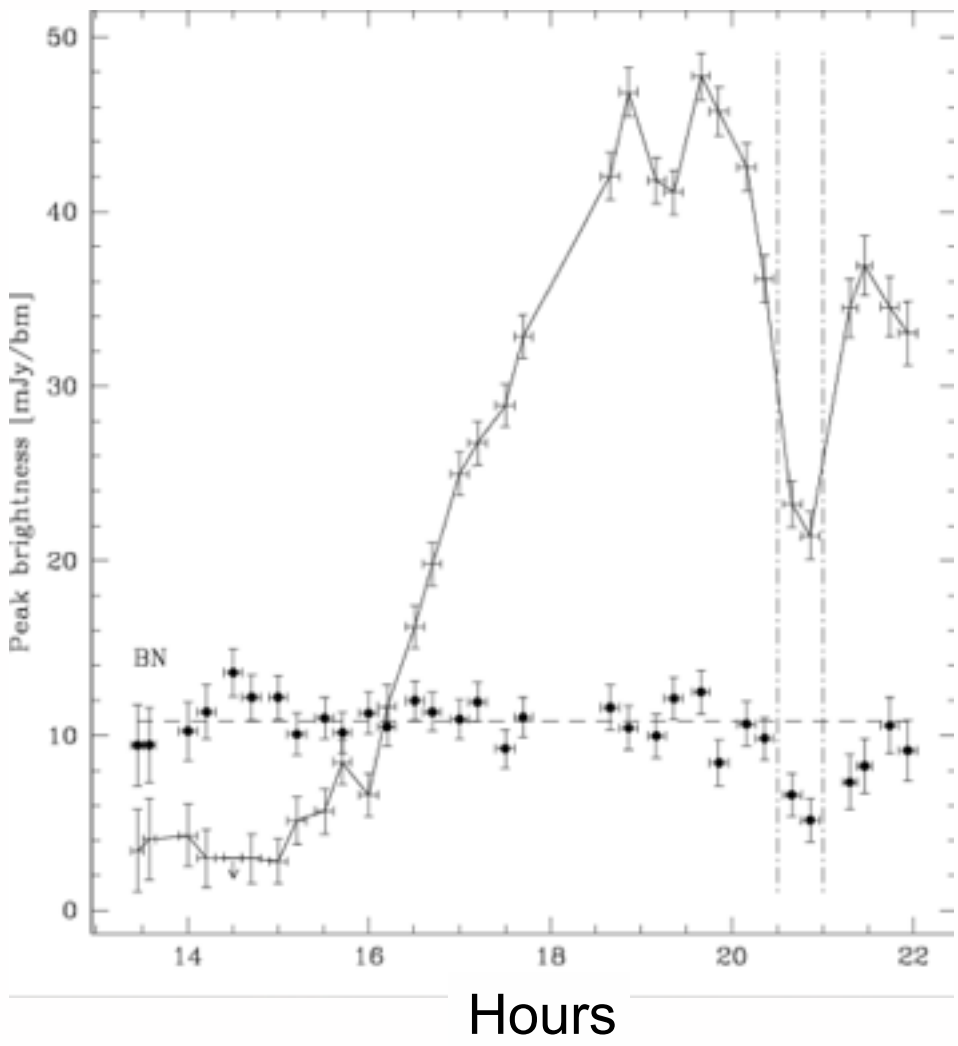


Loinard et al 2015 (AASKA2015)

Star Formation in the Time Domain



Radio YSOs are variable, e.g. Forbrich, Menten & Reid 2008 - Orion YSO, Av ~ 160, no IR counterpart.

Thermal vs non-thermal mechanism?

Periodicity, spots, rotation rates?

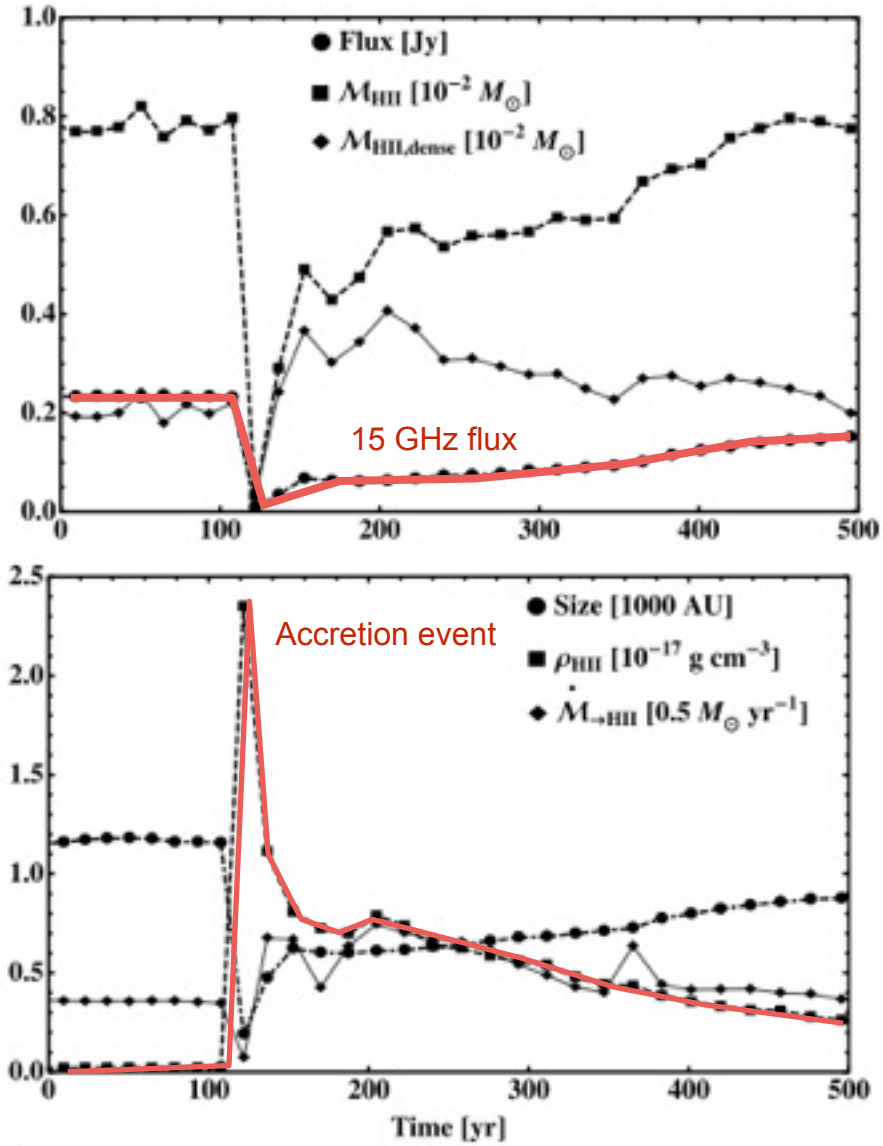
Class 0 sources can have 40% flux variations within one month

HII region variability: Evolution of exciting star / inflow

SKA sensitivity is key and can extend the very few current time-consuming studies to survey all clusters within 4 kpc (Fuller et al. AASKA2015).

Star Formation in the Time Domain

Galvan-Madrid et al 2011



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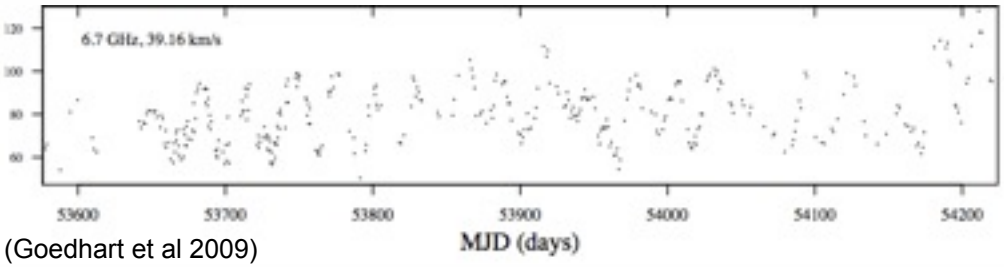
Periodic Variability in 6.7 GHz methanol maser



(Goedhart et al 2009)

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Non thermal & thermal radio jets

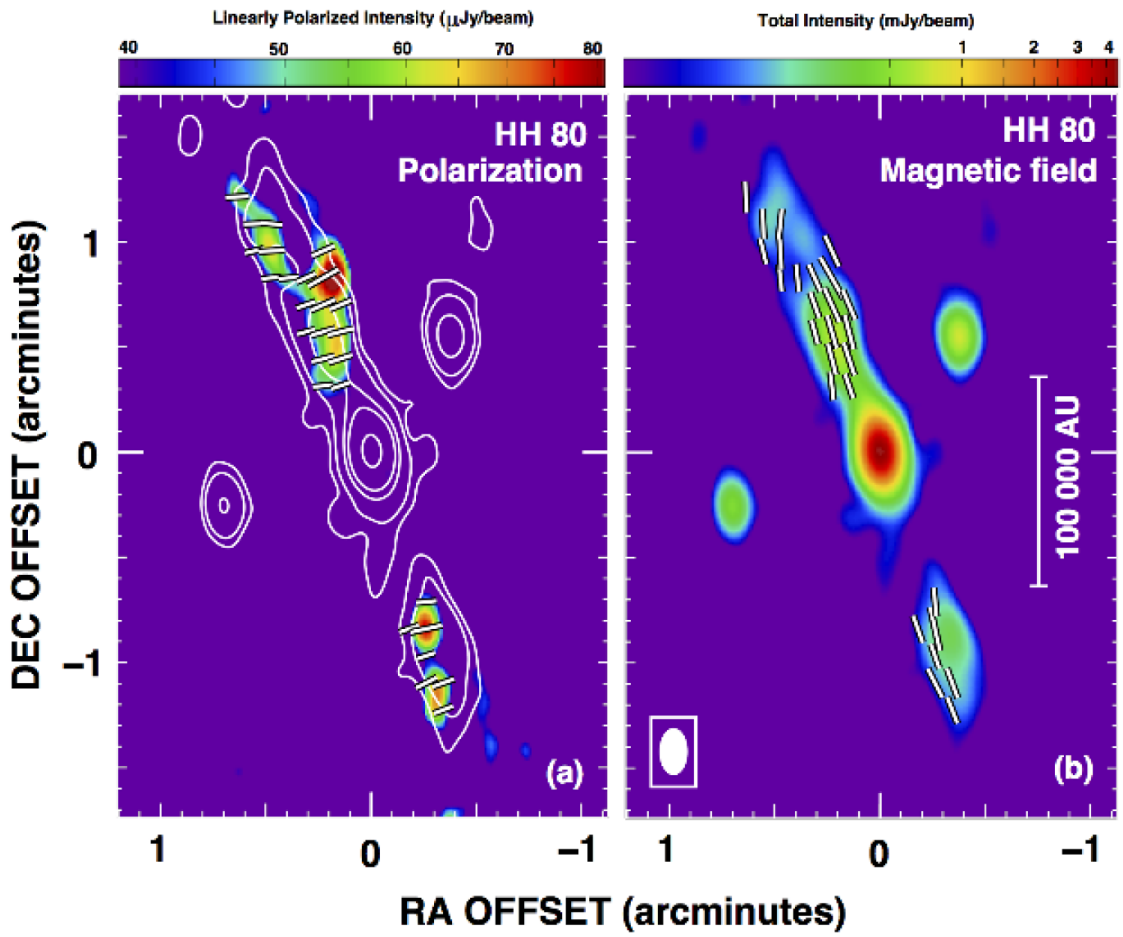
YSO jets recently observed to have faint levels of linear polarisation from synchrotron emission

Could measure for the first time the magnetic field strength & morphology of the jets

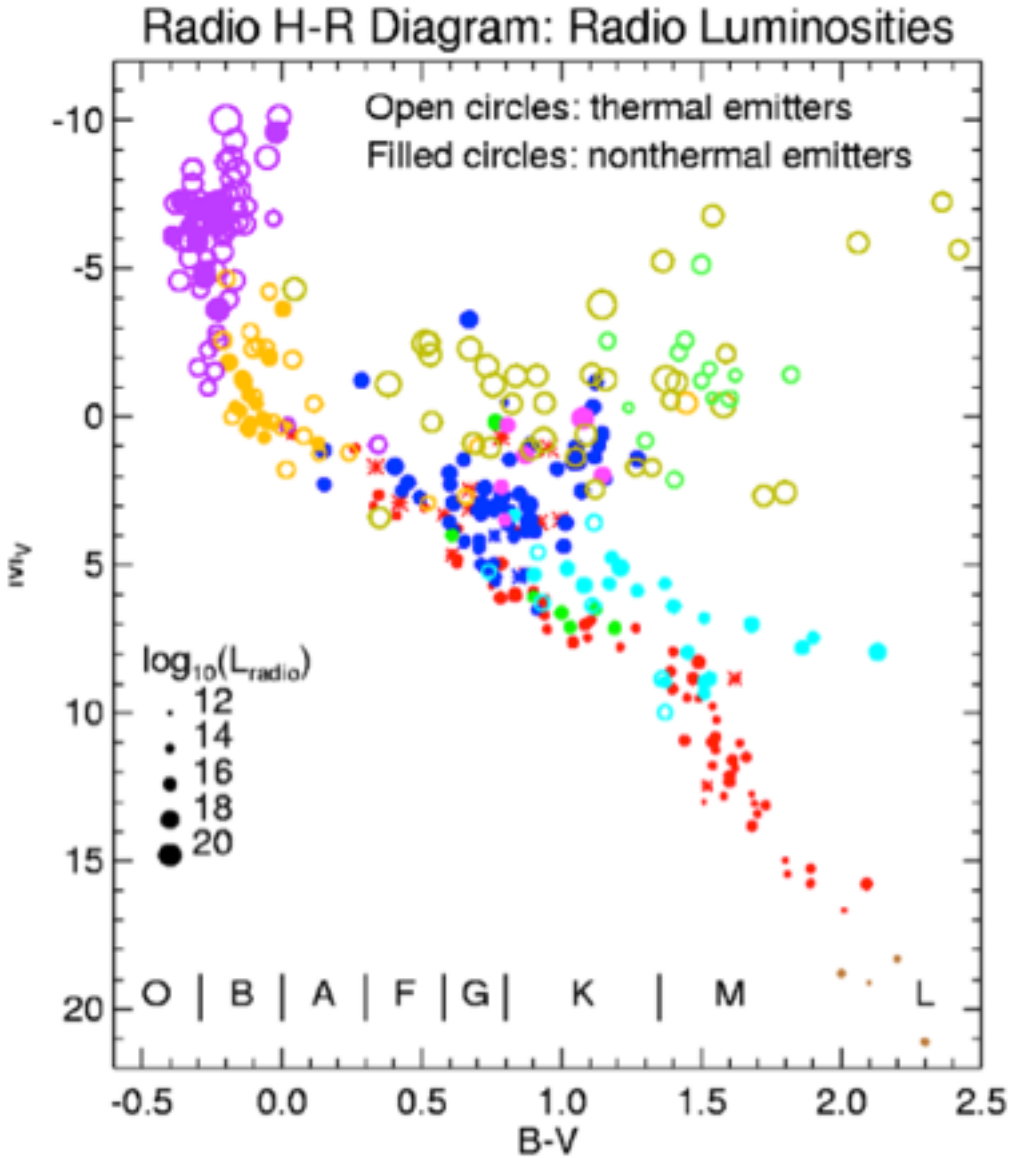
But synchrotron emission is only a small fraction of total emission

SKA can detect & image magnetic field in a large sample of YSO jets.

Also highly important to disentangle the jet contribution to thermal emission from the circumstellar disk for Cradle of Life disk studies



Radio stars



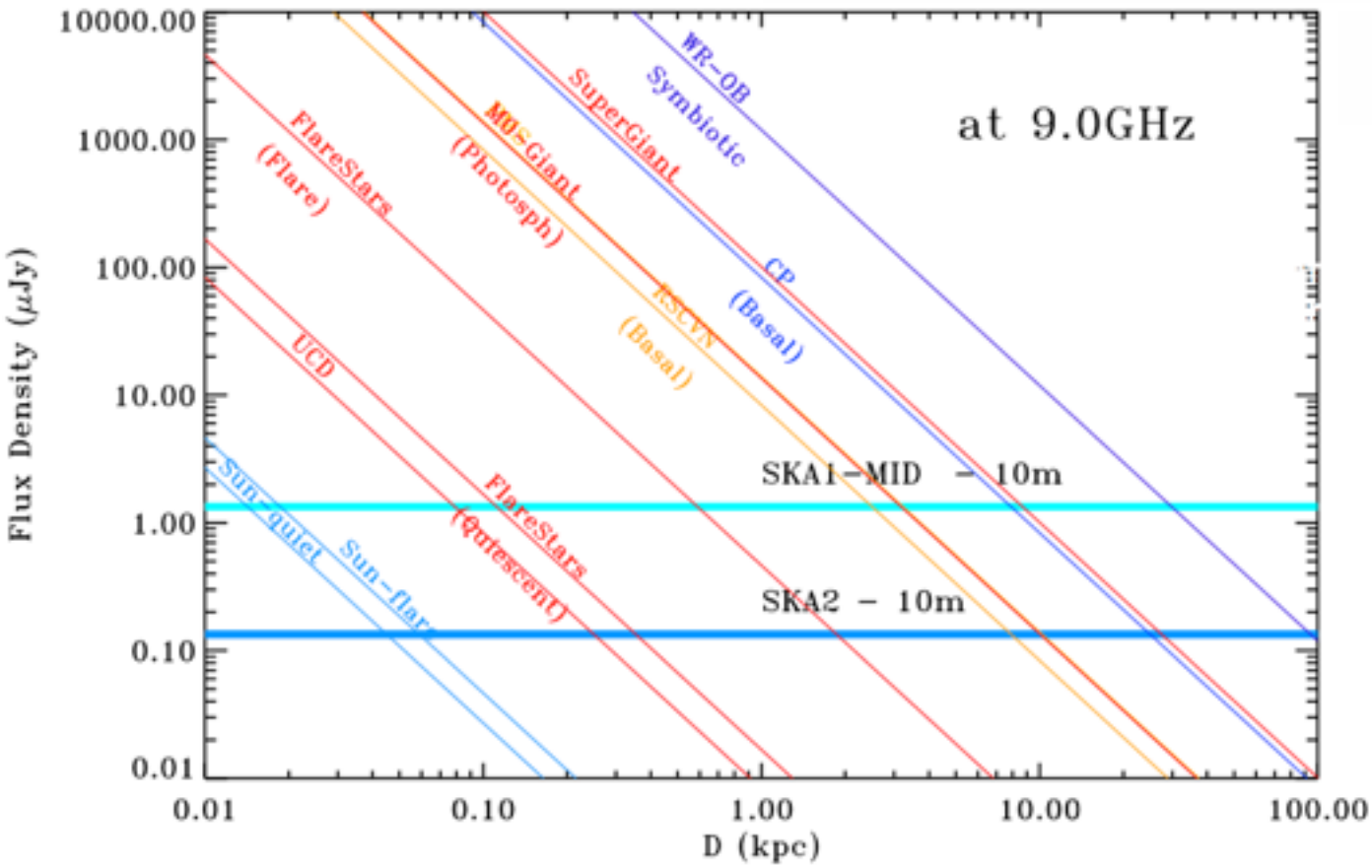
Currently ~420 radio detected stars (Guedel 2002)

Radio probes astrophysical phenomena not detectable by other means:

B field & topology in flare stars, RS CVn
HII region in dust enshrouded sources
Wind-wind interactions
Stellar magnetospheres
Planetary nebulae shaping by jets?

SKA will address current problems of limited sensitivity & selection bias

Radio stars



10 minute observations with SKA1 & full SKA

SKA1 - all WR & OB plus CP, PMS, RSCNS & SG to the Galactic Centre

Full SKA - solar analogues to 50 pc & all above classes in the MW & in nearby galaxies

A real revolution in stellar astrophysics

Evolved stars

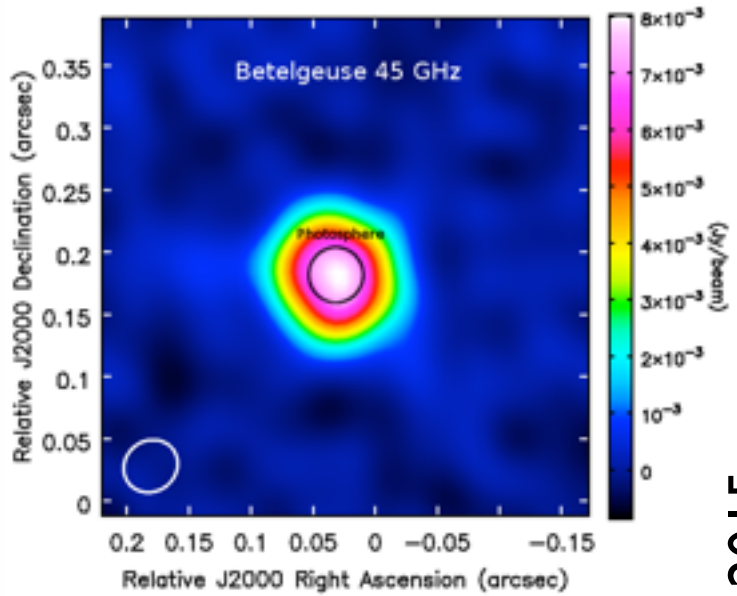
Multi-frequency continuum emission probes various layers of the partially ionized atmosphere (i.e., chromospheres and winds).

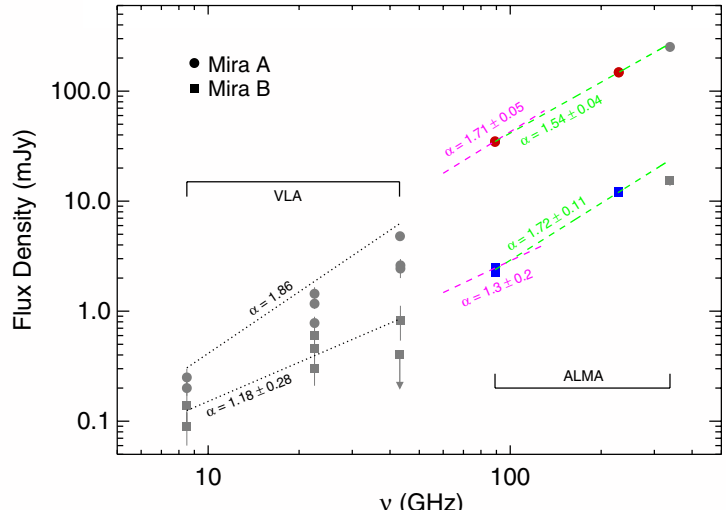
High frequencies (e.g. 10-45 GHz) sample the first few stellar radii, while low frequencies (< 10GHz) sample beyond ~5 stellar radii.

Spatially resolved observations provide direct measurements of the gas temperature at these various depths. High S/N observations allow inhomogenities/ spots to be detected.

Key ingredients to study the unknown mass-loss mechanism.

- Currently only possible for a handful of stars (e.g. Betelgeuse).
- Important complement to long baseline ALMA at shorter wavelengths





Vlemmings et al. 2015

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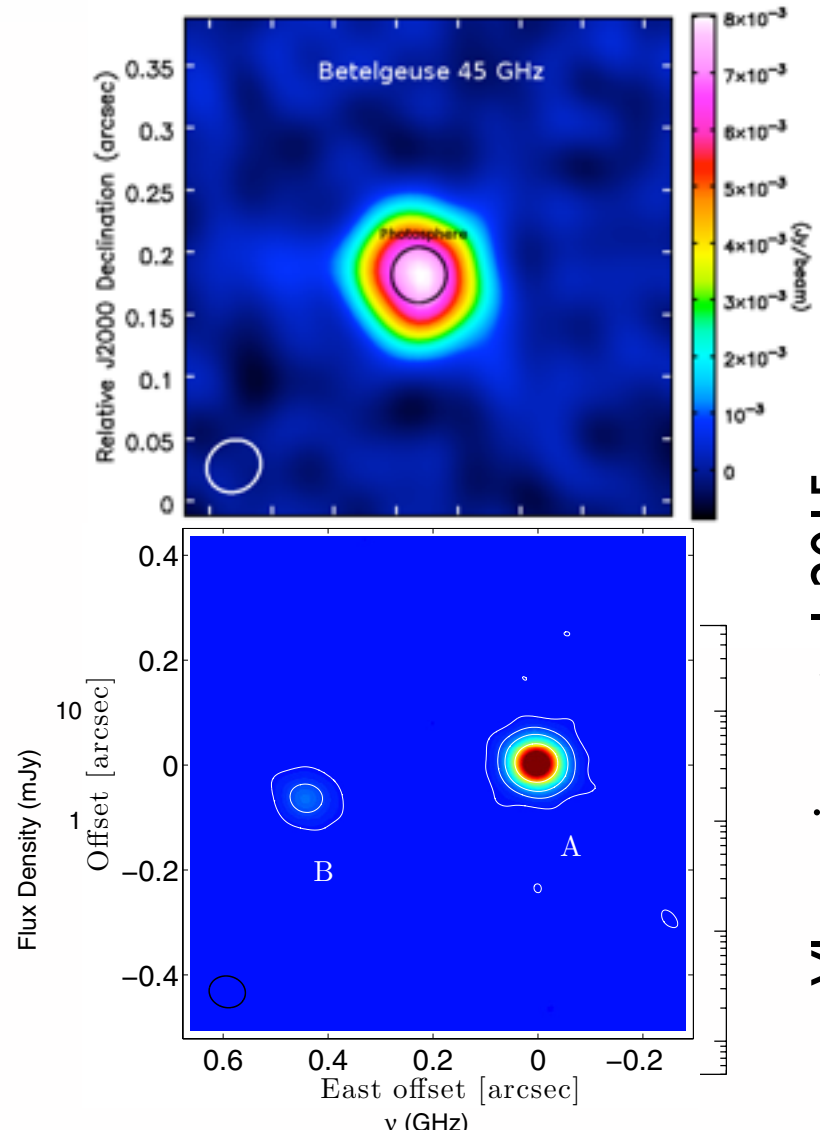
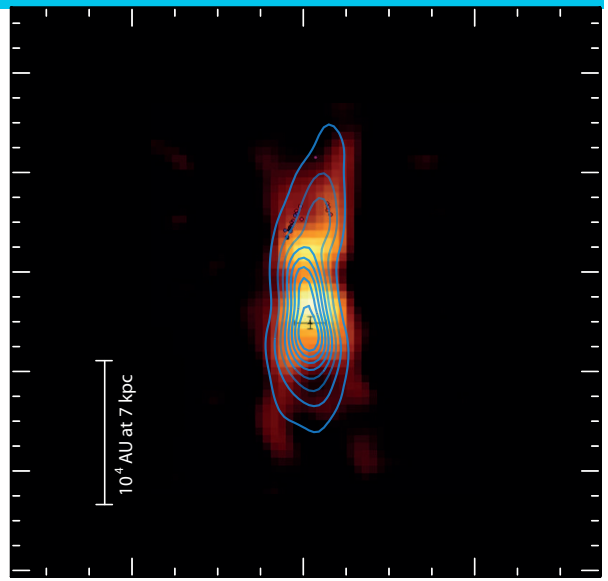
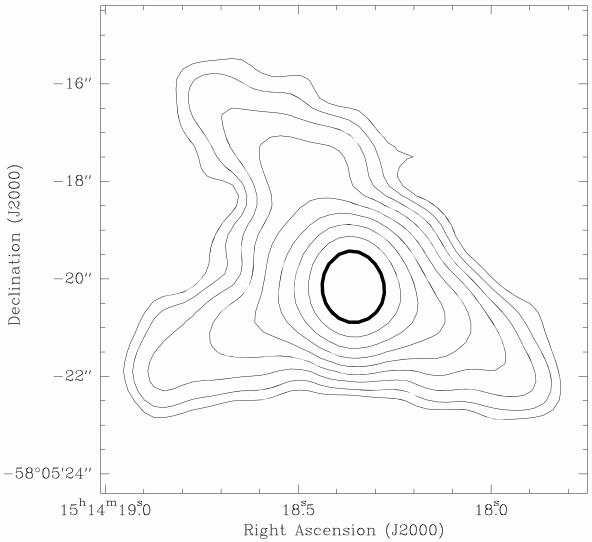


Vlemmings et al. 2015

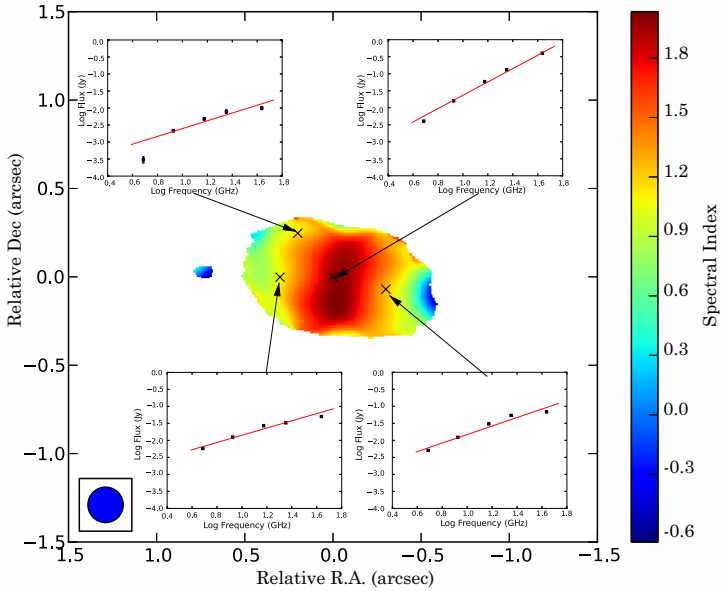
(pre-) PNe outflow shaping

- Determine the jet launching mechanism
  - Synchrotron emission from young post-AGB jets
  - thermal brehmsstrahlung and synchrotron from young PNe
  - Water and OH masers
    - kinematics, Zeeman splitting and astrometry

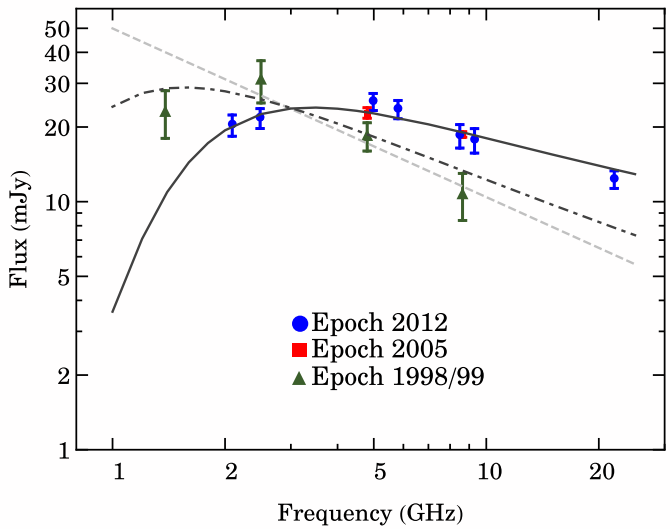




Suarez et al. 2015



Tafoya et al. 2013



Pérez Sánchez et al. 2013

Summary

SKA covers important Milky Way physics in breadth and depth

» The multiphase Milky Way - ionised, neutral, molecular

» Mass flow into and out of the Milky Way

» Formation of molecular clouds

» Tomography, Tomography, Tomography
(neutral, molecular, stars)

» Time domain radioastronomy of stars & YSOs

» The full radio HR diagram & stellar evolution

Commensality will be the key to achieving maximum science output

http://astronomers.skatelescope.org/science-working-groups/milky-way/

- Should add a slide about NH3 and H2O masers plus continuum 15GHz+ because
- Robert Braun is talking about extending Band 5 to 24+ GHz.

- Add maser and continuum emission from evolved stars