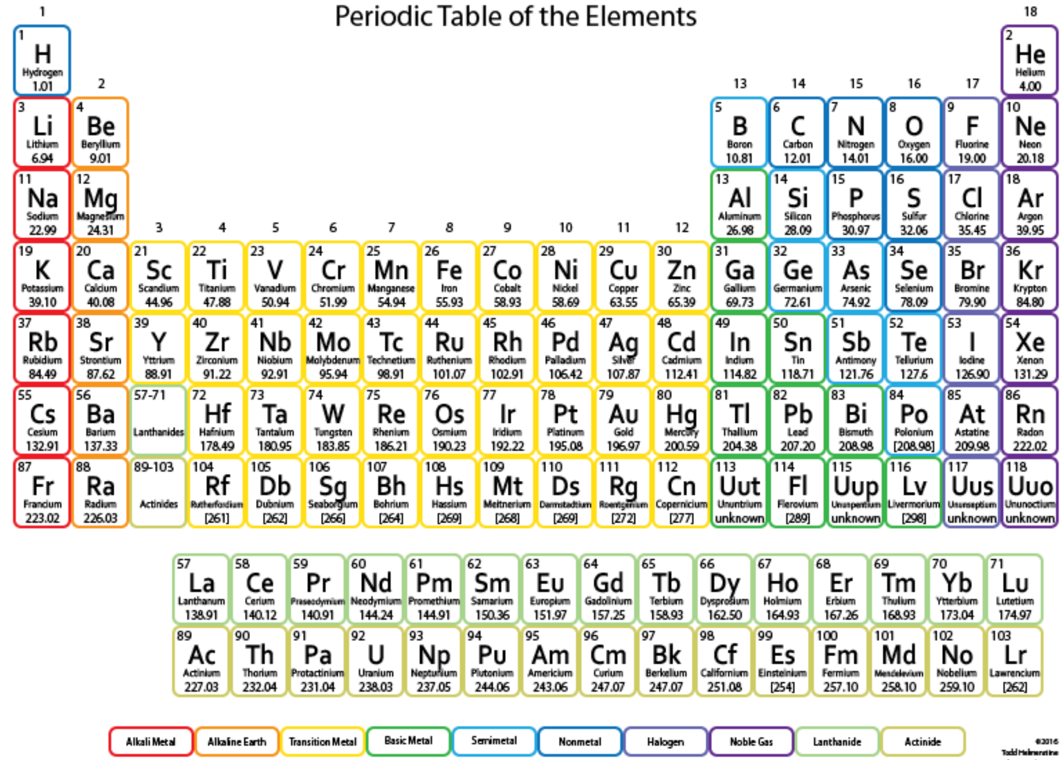


International Centre for Radio Astronomy Research

Spectral line science

O. Ivy Wong

International Centre for Radio Astronomy Research (ICRAR)
@University of Western Australia

28 September 2017 @2017 ATNF Radio School, Narrabri

Curtin University

The University of Western Australia

Lecture inspired by & thanks to:

- **Westpfahl, D. 1999 Spectral line observing**
- **Heiles & Troland 2003 The Millenium Arecibo 21cm Abs Line Survey**
- **Walsh, A. 2009 Single dish spectral line observing**
- **Ellingsen, S. 2011 Spectral line observations – a new dimension**
- **Breen, S. 2012 Observing Strategies**
- **Lacy, M. 2014 Spectral line data analysis**
- **White, S. 2017 Advanced Radio Astronomy Lecture, Curtin**

> Start with a science goal and an object, or set of objects, which can be observed to meet that goal. Develop concise statements of why the goal is important and why the object is an excellent choice for observation. These statements will be invaluable for the written part of the proposal, without them it will be difficult to make a good case for observing.

– Westpfahl 1999

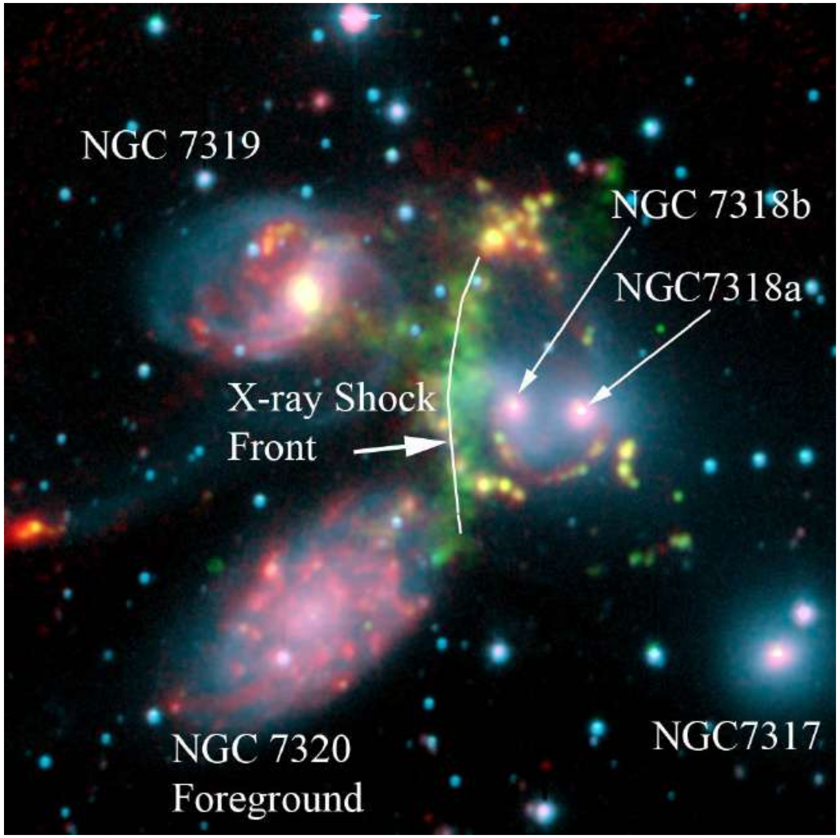
Spectral lines: great tool for studying ISM physics

The WHY

✔ **Kinematics + morphology (3D)**

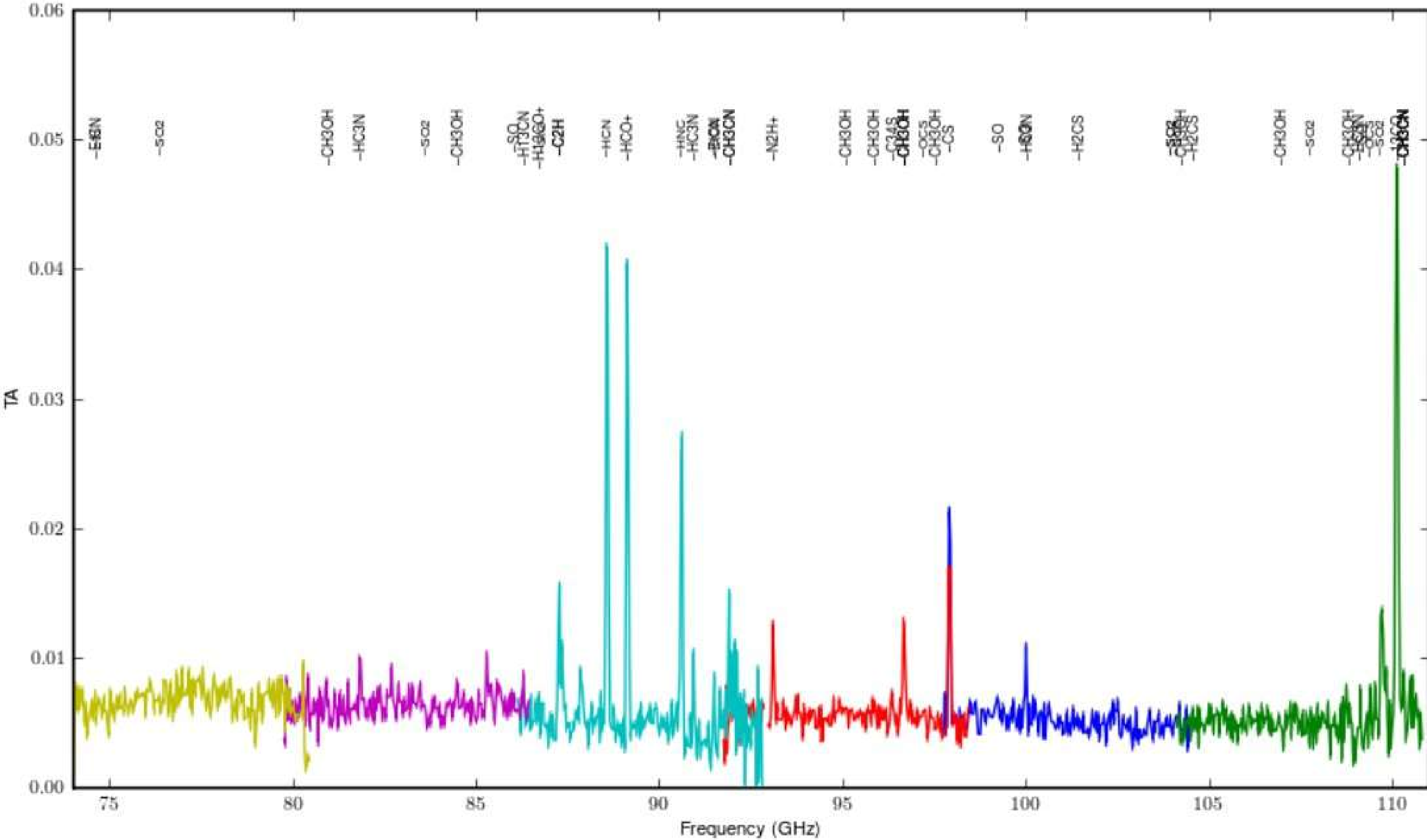
✔ **Physical state (density, temperature, SF history etc) of the interstellar medium (ISM)**

➔ **the physical processes that shape galaxy evolution**



Spectral line ?

The WHAT



Snell + (2010)

Spectral line ?

✔ **Atomic Physics: accurate rest frequencies & intrinsic widths**

✔ **Frequency shift → Doppler shift**

✔ **Radiative Transfer: convert observed intensity**

➔ **Optical depth**

➔ **Excitation / spin temperature**

✔ Provide what continuum cannot**: the 3rd dimension**

Spectral lines are very useful*

✔ Spontaneous emission

➔ Atomic hyperfine/spin/ recombination emission

➔ Rotational molecular emission

✔ HI in absorption

✔ Stimulated emission

➔ Masers

*with the exception of RFI

Velocity definitions (in the Local Universe)

The relativistic expression relating frequency to radial velocity is

$$v = c\frac{\nu_0^2 - \nu^2}{\nu_0^2 + \nu^2} \tag{16}$$

where v is the radial velocity, ν the observed frequency, ν_0 the rest frequency, and c is the speed of light. For various reasons, astronomers usually approximate this formula. There are two common approximations - the "radio definition",

$$v_{\mathrm{radio}} = c(1 - \frac{\nu}{\nu_0}) \tag{17}$$

and the "optical definition",

$$\boxed{v_{\mathrm{optical}} = c(\frac{\nu_0}{\nu} - 1)} \tag{18}$$

The radio definition has the advantage that points sampled at equal increments in frequency translate to equal increments in velocity. However the radio definition is now deprecated by the IAU, but this does not stop it being commonly used.

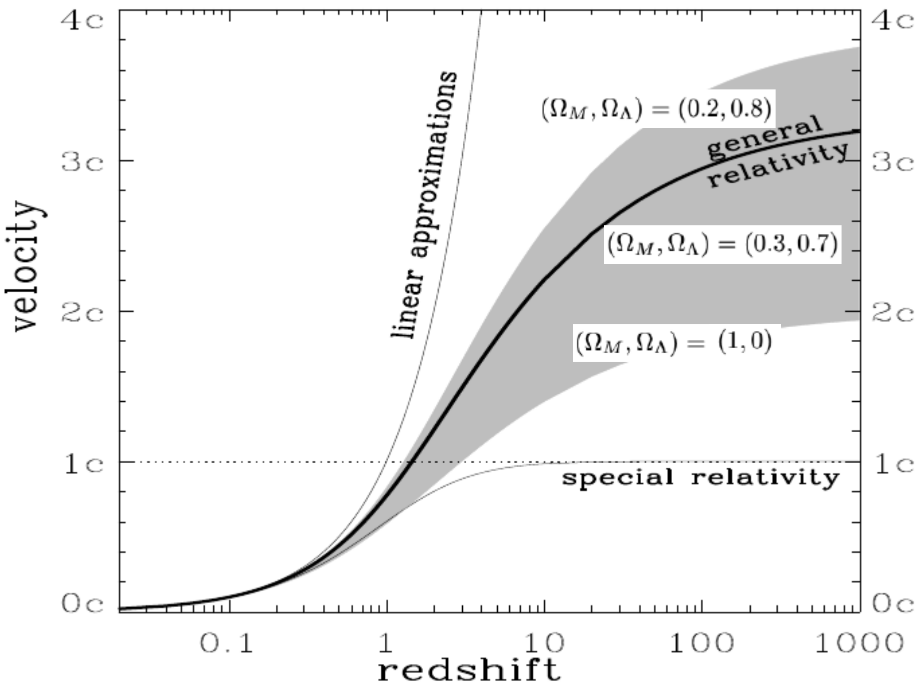
http://www.atnf.csiro.au/people/Tobias.Westmeier/tools_hihelpers.php

@ z > 0.1 (when cosmic expansion matters)

Full GR differentiation btw v_{pec} & v_{cos}

$$V_{\rm pec}(z_{\rm pec}) = V_{\rm SR}(z_{\rm pec})\,, \\ = c\,\frac{\nu_{\rm rest}^2 - \nu_{\rm obs}^2}{\nu_{\rm rest}^2 + \nu_{\rm obs}^2}\,, \\ = c\,\frac{(1+z_{\rm pec})^2 - 1}{(1+z_{\rm pec})^2 + 1}$$

$$V_{\rm cos}(z_{\rm cos}, z_{\rm ref}) = V_{\rm GR}(z_{\rm cos}, z_{\rm ref})\,, \\ = c\,\frac{H(z_{\rm ref})}{1+z_{\rm ref}} \int_0^{z_{\rm cos}} \frac{dz'_{\rm cos}}{H(z'_{\rm cos})}$$



Davis & Lineweaver 2001

Source at z_{cos} observed at z_{ref}=0 →

$$V_{\rm cos}(z_{\rm cos}) = c \int_0^{z_{\rm cos}} E^{-1}(z')dz'\,.$$

where $H(z) = H_0 E(z)\,,\quad E(z) = \sqrt{\Omega_{\rm R}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_{\rm K}(1+z)^2 + \Omega_\Lambda}\,.$

✔ **To avoid confusion:** *best use velocities for describing rest frame motions RATHER THAN observed frame*

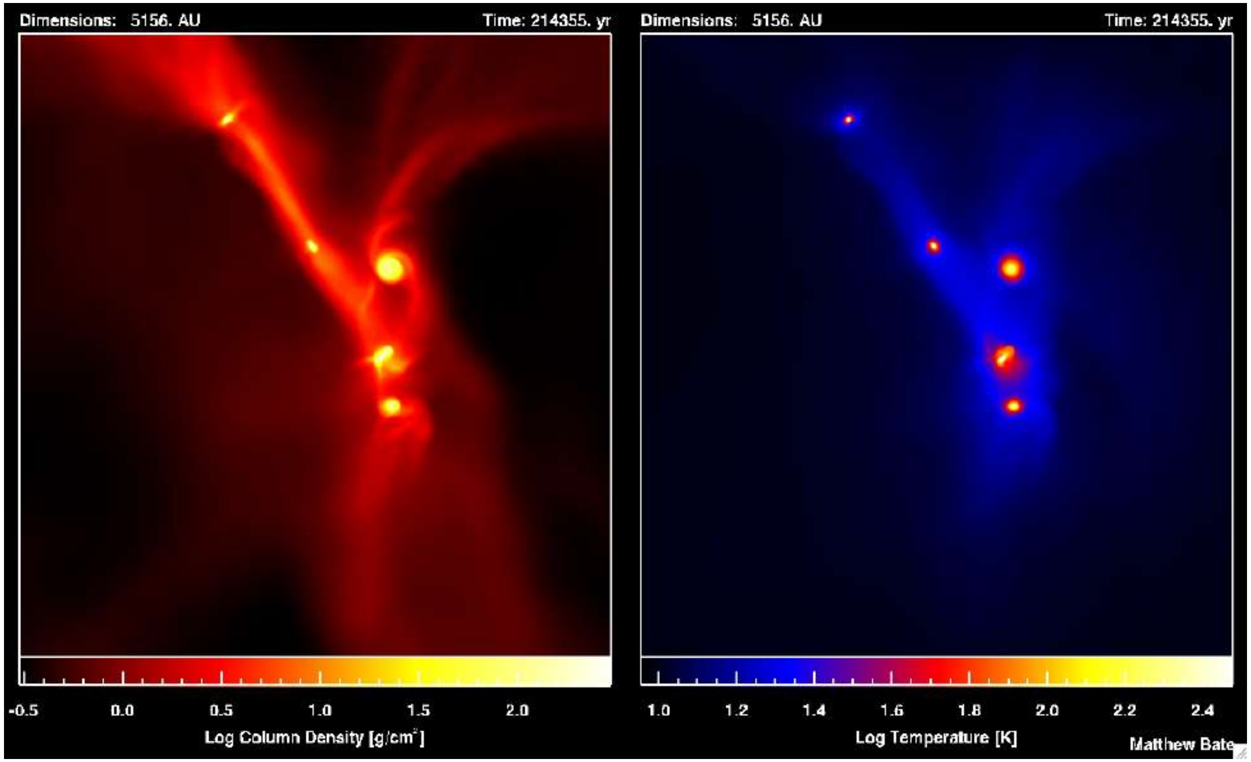
Meyer, M et al 2017, Weinberg 2008, Davis & Lineweaver 2001, Hogg 1999; http://hifi.icrar.org

Star formation

Neutral gas

Molecular gas

Stars

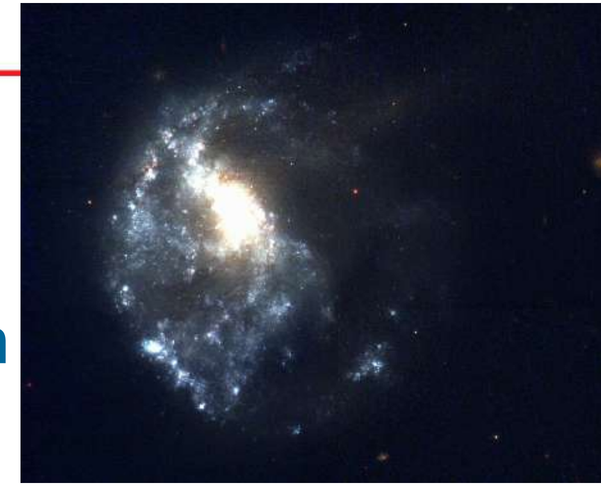


Wide range of temperature/density regimes:

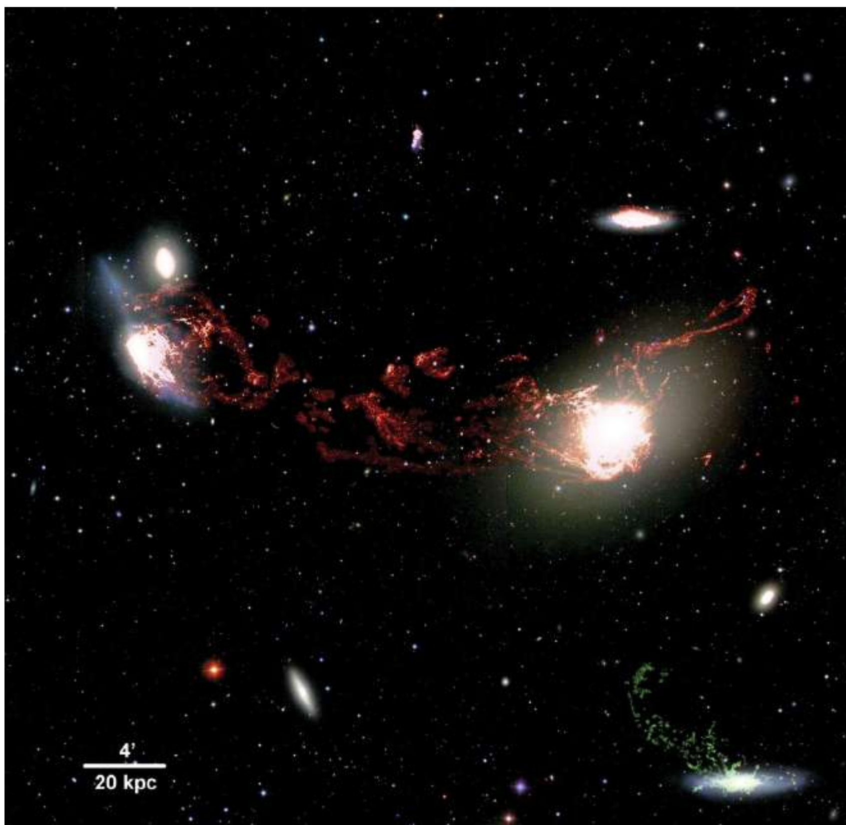
- ✦ cold (~10s of K) dense molecular clouds
- ✦ cool (~10^2 K) neutral gas
- ✦ warm (~>10^4 K) ionised gas
- ✦ hot (~>10^6 K) low-density ionised gas (eg SNR bubbles)

Galaxy evolution

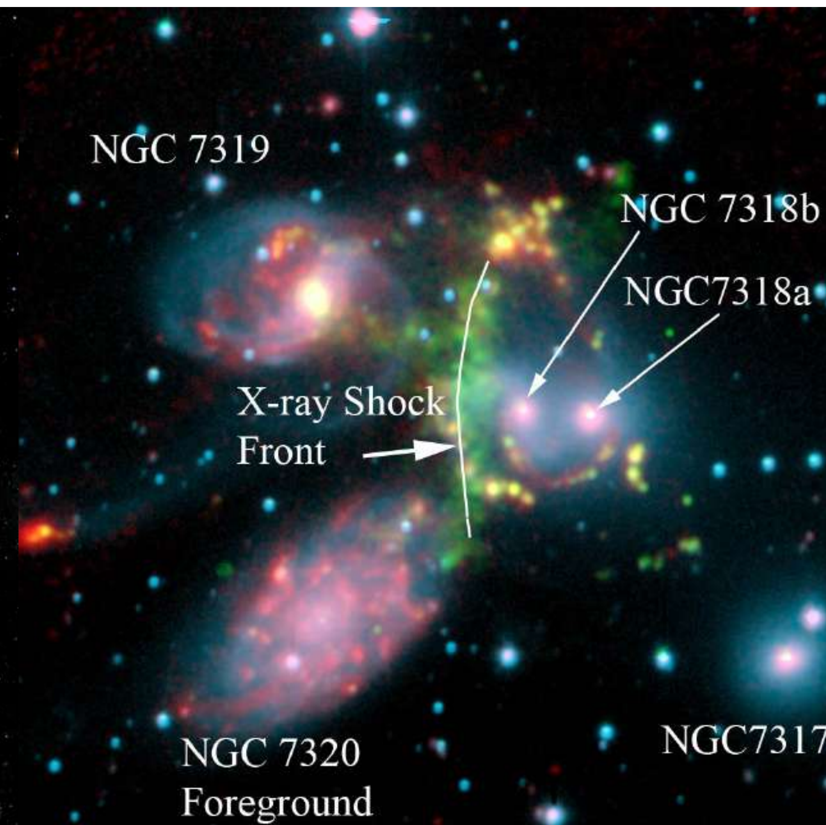
- ✔ **Physical processes that affect “regular” ISM of galaxies**
  - ✔ **Impact on ISM gas phases → impact star formation history & galaxy evolution**



Pellerin+2010; Elagali+17 *in prep*



Kenney+2008



Appleton+2006

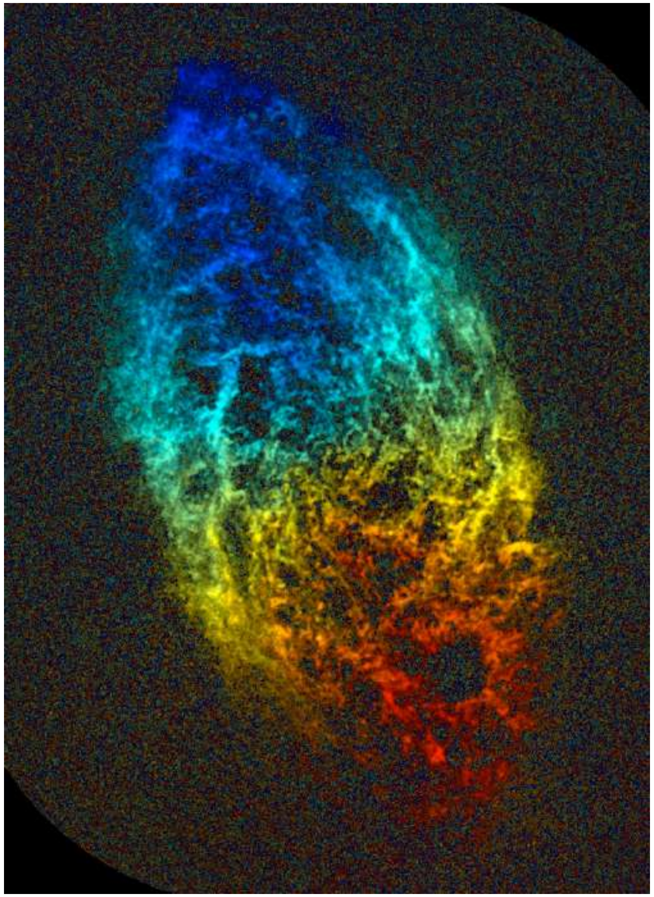
3D astronomy: the "new" tool in optical astronomy

IFS = Integral field spectroscopy

The HI radial velocity field of the nearby spiral galaxy M33 is shown here by colours corresponding to Doppler redshifts and blueshifts, relative to the center of mass.

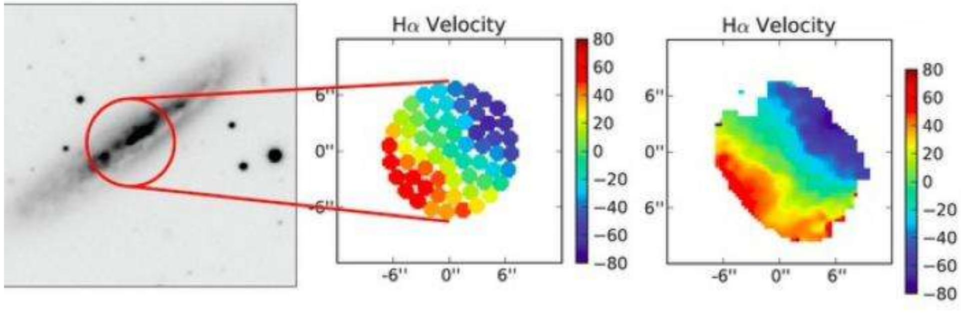
Radio

Optical



Credit: Thilker, Braun & Walterbos

sami galaxy survey

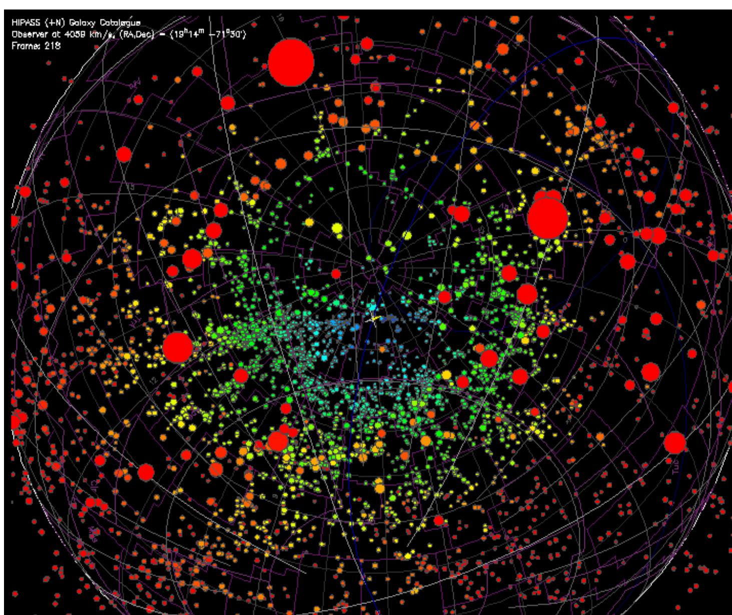


Credit: Lisa Kewley

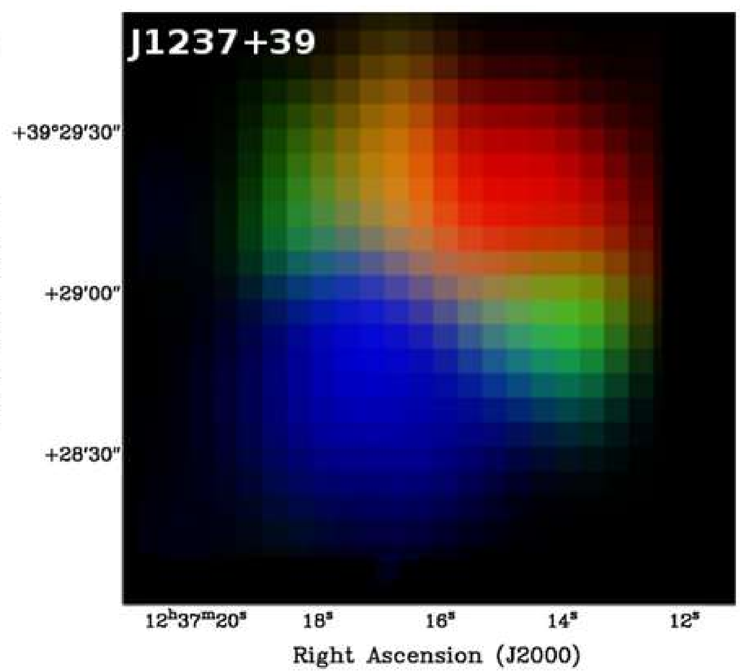
The 3rd dimension

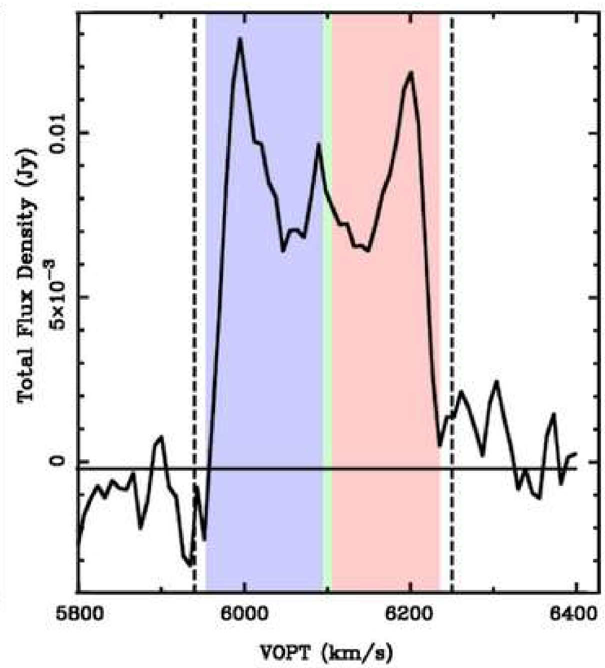
✔ **Single dish / low angular resolution → $\Delta\upsilon$: ~distance of galaxy**

✔ **Synthesis observations → higher angular & freq resolution → kinematics**



Credit: HIPASS data (Mark Calabretta)





Wong+(2015)

Moment maps

Moment definitions

0 = total flux

$$M_0 = \Delta v \sum A(v)$$

1 = intensity weighted (IW) velocity

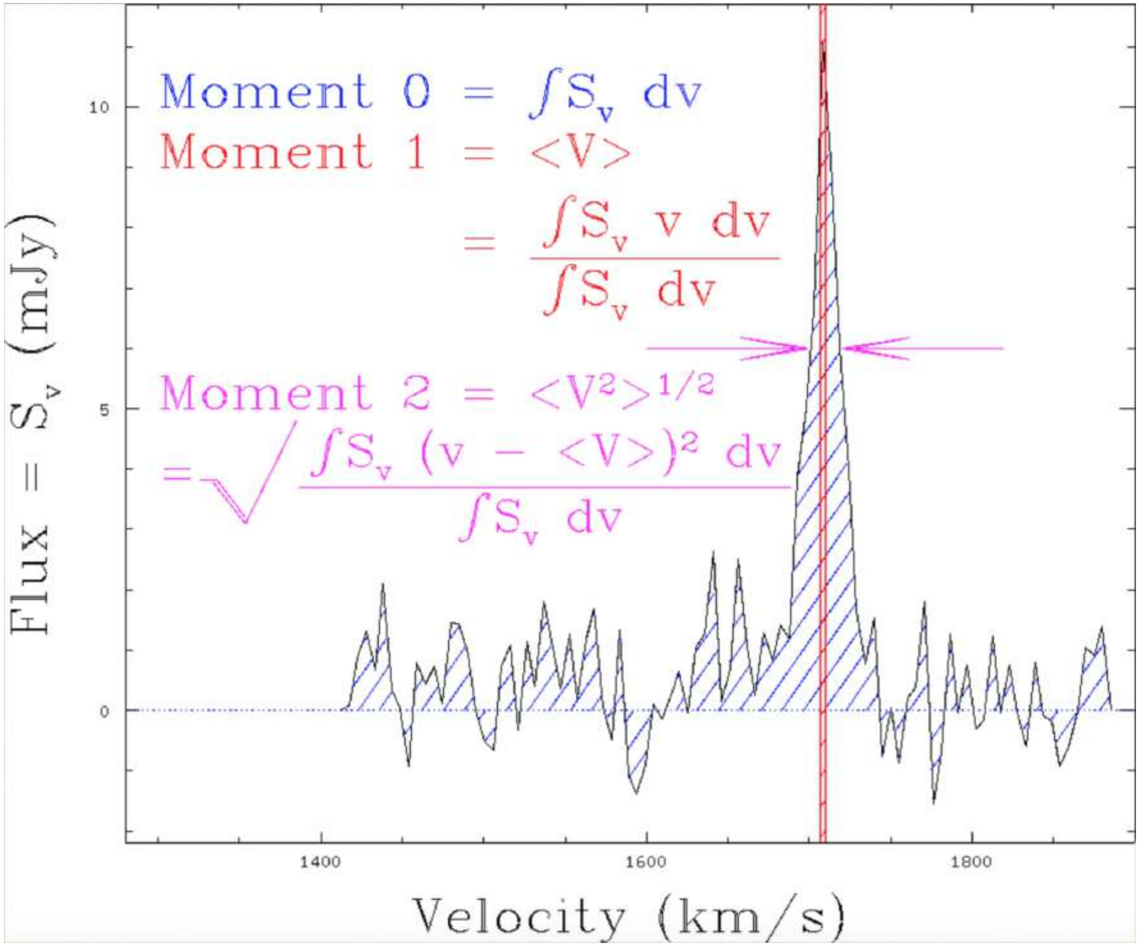
$$M_1 = \frac{\sum vA(v)}{\sum A(v)}$$

2 = IW velocity dispersion

$$M_2 = \sqrt{\frac{\sum (v - M_1)^2 A(v)}{\sum A(v)}}$$

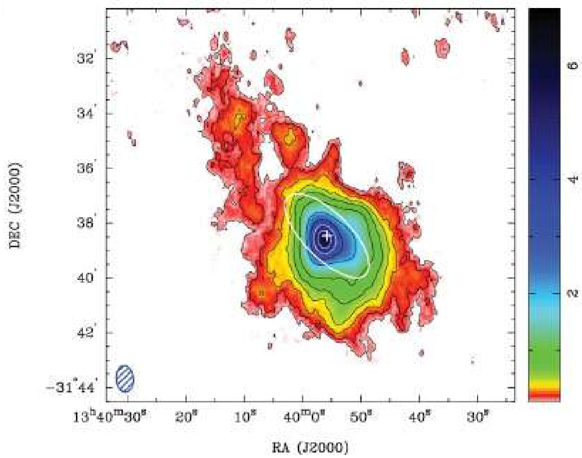
3 = skewness/line asymmetry

4 = kurtosis

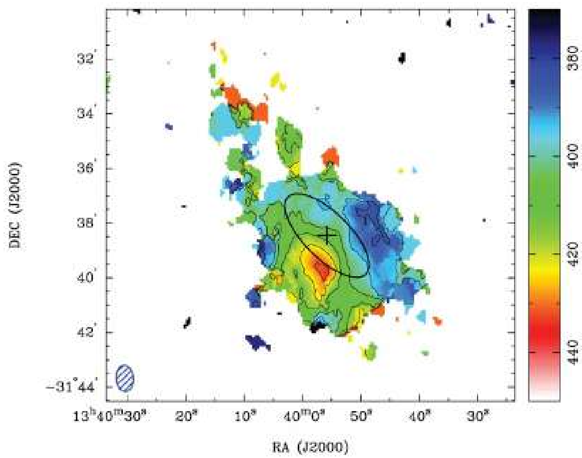


Example moment maps of NGC 5253

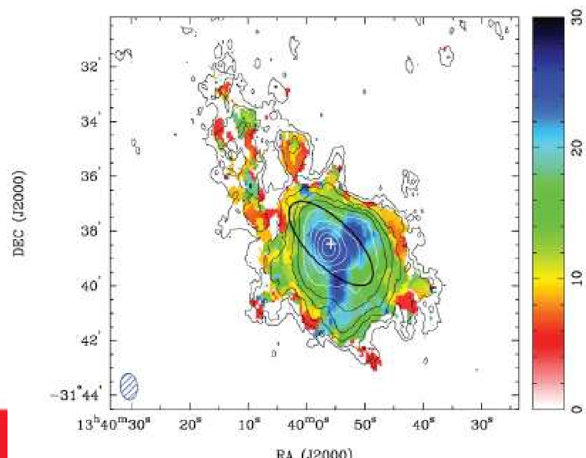
Moment 0

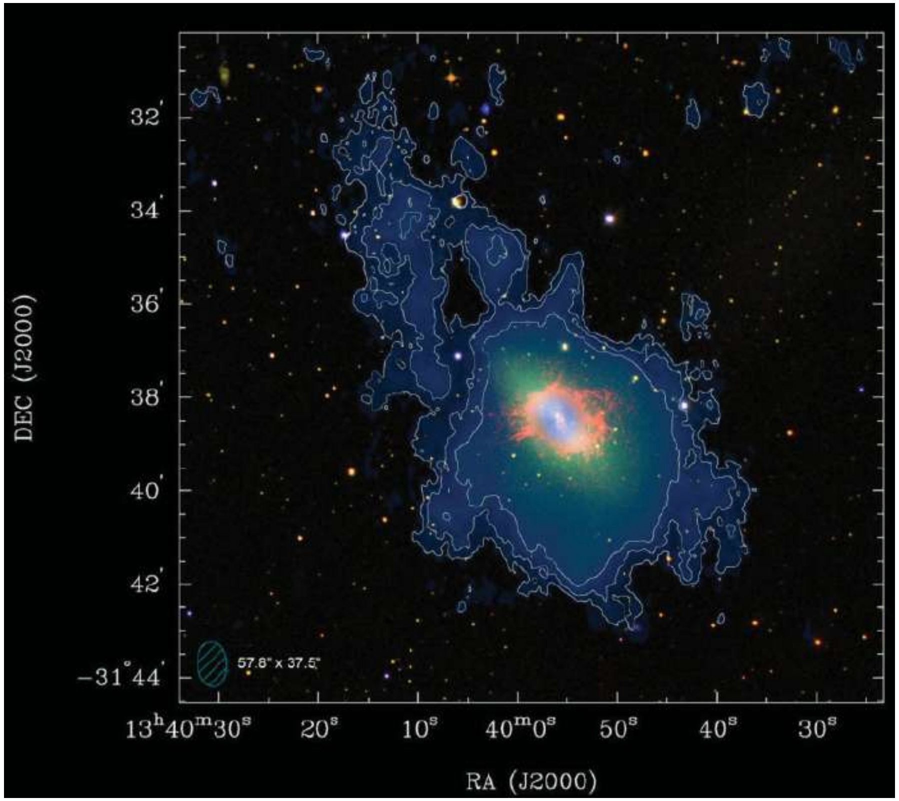


Moment 1



Moment 2





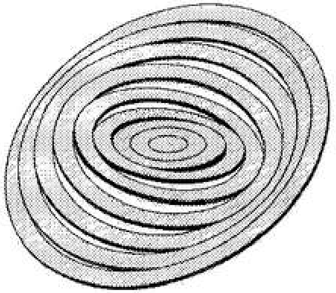
Lopez-Sanchez et al 2012

Modelling disk kinematics

Tilted Ring Fitting Code

- HOME
- Input and Syntax
- Modelling Strategy
- Model Geometry
- Model Fitting
- Output
- Parameter Index
- Examples
- GUI
- Bugs and Development
- Download and Installation
- Contact and Feedback
- Credits

Tilted **R**ing **F**itting **C**ode (TiRiFiC) is a computer program to construct simulated (high-resolution) astronomical spectroscopic 3d-observations (data cubes) of simple kinematical- and morphological models of rotating (galactic) disks. It is possible to automatically optimise the parametrisations of constructed model disks to fit spectroscopic (3d-) observations via a χ^2 minimisation. **TiRiFiC** depends on several free non-standard libraries, but **is a standalone routine** (after compilation). In former development stages, TiRiFiC has been implemented as a task in the Groningen Image Processing System (GIPSY) software package. From version 2.2.0 on, the GIPSY implementation is not longer supported and will not be installed. The source code of TiRiFiC can be downloaded from



Tilted-ring model of M83 by Rogstad et al. (1974)

2D BAYESIAN AUTOMATED TILTED-RING FITTING OF DISK GALAXIES IN LARGE HI GALAXY SURVEYS: 2DBAT

SE-HEON OH[1,2,3], LISTER STAVELEY-SMITH[2,3], KRISTINE SPEKKENS[4], PETER KAMPHUIS[5] & BÄRBEL S. KORIBALSKI[6]

MNRAS, accepted

Sep 2017

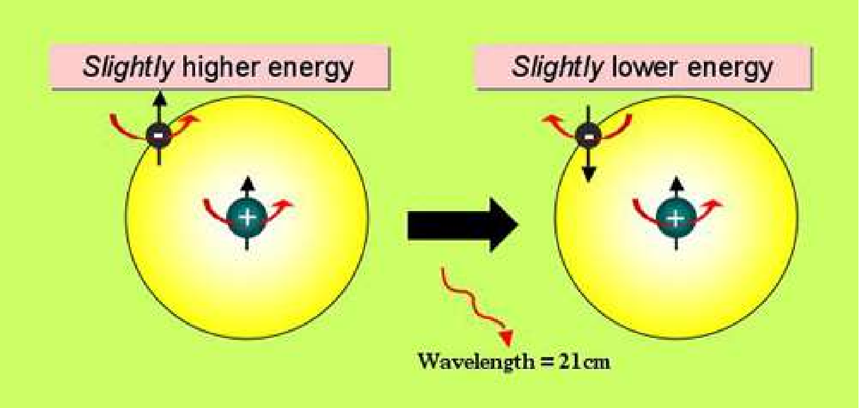
ABSTRACT

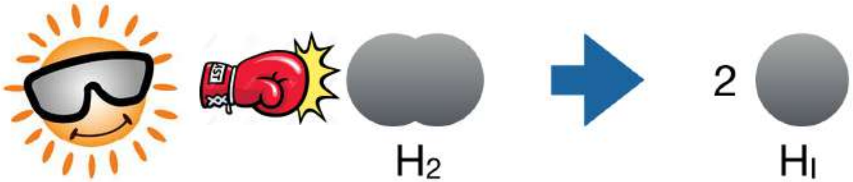
We present a novel algorithm based on a Bayesian method for 2D tilted-ring analysis of disk galaxy velocity fields. Compared to the conventional algorithms based on a chi-squared minimisation procedure, this new Bayesian-based algorithm suffers less from local minima of the model parameters even with highly multi-modal posterior distributions. Moreover, the Bayesian analysis, implemented via Markov Chain Monte Carlo (MCMC) sampling, only requires broad ranges of posterior distributions of the parameters, which makes the fitting procedure fully automated. This feature will be essential when performing kinematic analysis on the large number of resolved galaxies expected to be detected in neutral hydrogen (HI) surveys with the Square Kilometre Array (SKA) and its pathfinders. The so-

Jozsa+2007; Kamphuis+ 2015; Oh+2017

Types of spectral lines (1)

- ✔ **Emission lines**
  - ✔ **Hyperfine / spin-flip transition**
    - ➢ **HI → emission at 1.4204 GHz**

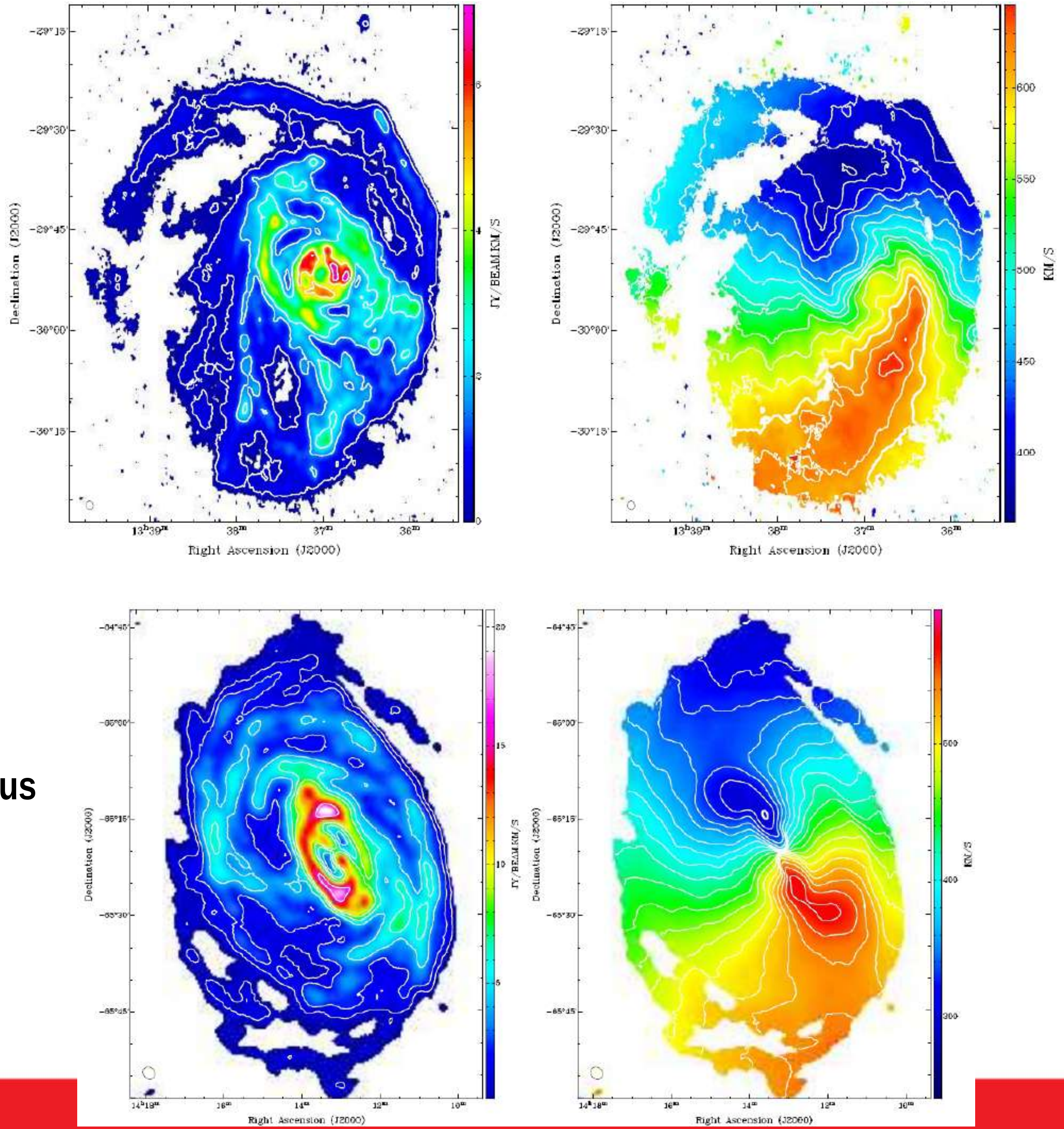




LVHIS finds giant HI halos in nearby galaxies

M83

Circinus



Koribalski+2017

Calculating HI emission column densities

✔ **Detecting HI in emission relies on HI column densities**

Flux densities to brightness temps: $T_B = \frac{\lambda^2 S}{2 k_B \Omega}$ → $T_B = \frac{1.36\,\lambda^2 S}{a \times b}$

Brightness temp (K); wavelength (cm); flux density S (mJy); a and b (arcsec)

Assuming that the gas is optically thin (τ << 1), $N_{\rm HI} = 1.823 \times 10^{18} \int T_B \, dv$

Column density $N_{\rm HI}$ (cm^{-2}); v ($\mathrm{km\,s}^{-1}$)

✔ **At z >> 0.1,**

$$\left(\frac{T_B}{K}\right) = 6.86 \times 10^5 \, (1+z)^3 \left(\frac{S_\nu}{\rm Jy}\right) \left(\frac{\Omega_{\rm bm}}{\rm arcsec^2}\right) = 6.06 \times 10^5 \, (1+z)^3 \left(\frac{S_\nu}{\rm Jy}\right) \left(\frac{ab}{\rm arcsec^2}\right)^{-1}$$

specify widths at rest frame as $\Delta V_{\rm obs}$ & observed frame as $\Delta \nu_{\rm obs}$

$$\Delta V_{\rm rest} \simeq \frac{c(1+z)}{\nu_{\rm HI}} \Delta\nu_{\rm obs} = \frac{c}{\nu_{\rm obs}} \Delta\nu_{\rm obs}$$

http://www.atnf.csiro.au/people/Tobias.Westmeier/tools_hihelpers.php & Meyer + (2017)

Calculating HI masses

✔ **In nearby galaxies,**

$$\frac{M_{\mathrm{H\,I}}}{M_{\odot}} = 0.236 \times \frac{S_{\mathrm{int}}}{\mathrm{Jy\,km\,s^{-1}}} \times \left(\frac{d}{\mathrm{kpc}}\right)^{2}$$

✔ **At z >> 0.1,**

$$S = \frac{L}{4\pi D_L^2}$$

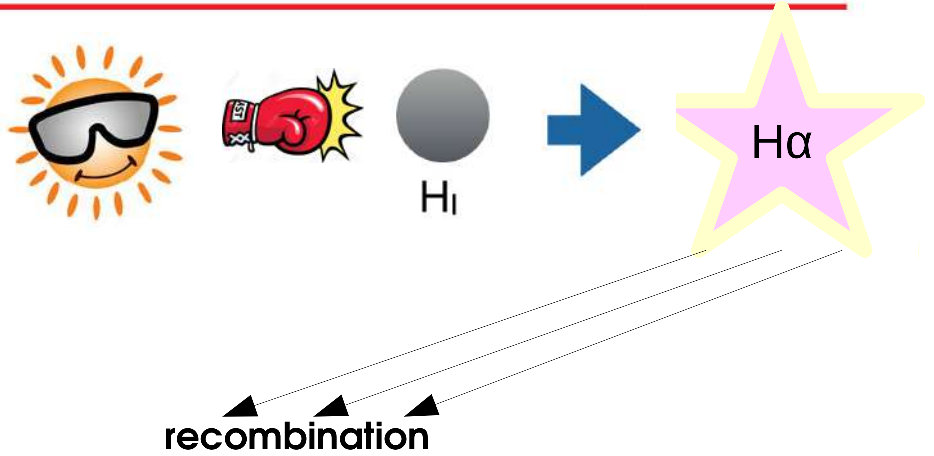
$$S^V = \int S_\nu dV$$

$$\left(\frac{S^{V_{\mathrm{obs}}}}{\mathrm{Jy\,km\,s^{-1}}}\right) = \frac{c(1+z)^2}{\nu_{\mathrm{HI}}}\left(\frac{S}{\mathrm{Jy\,Hz}}\right),$$
$$\simeq 2.11 \times 10^{-4}\,(1+z)^2\left(\frac{S}{\mathrm{Jy\,Hz}}\right)$$

$$\left(\frac{M_{\mathrm{HI}}}{h_{\mathrm{C}}^{-2} M_{\odot}}\right) \simeq 49.7\left(\frac{D_L}{h_{\mathrm{C}}^{-1}\mathrm{Mpc}}\right)^2\left(\frac{S}{\mathrm{Jy\,Hz}}\right)$$

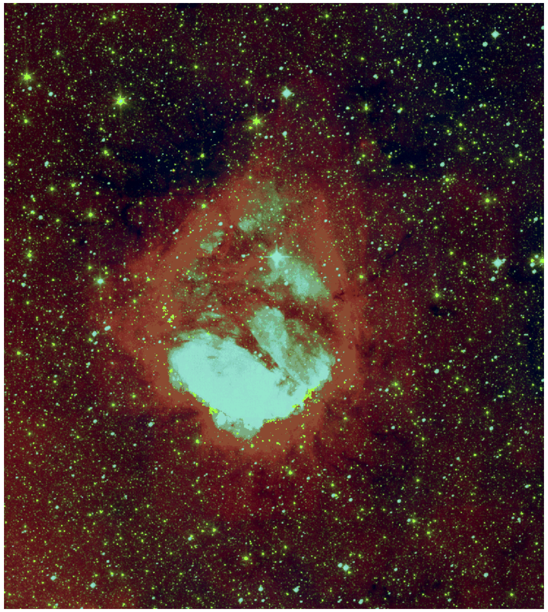
http://www.atnf.csiro.au/people/Tobias.Westmeier/tools_hihelpers.php & Meyer + (2017) & Hogg (1999)

Types of spectral lines

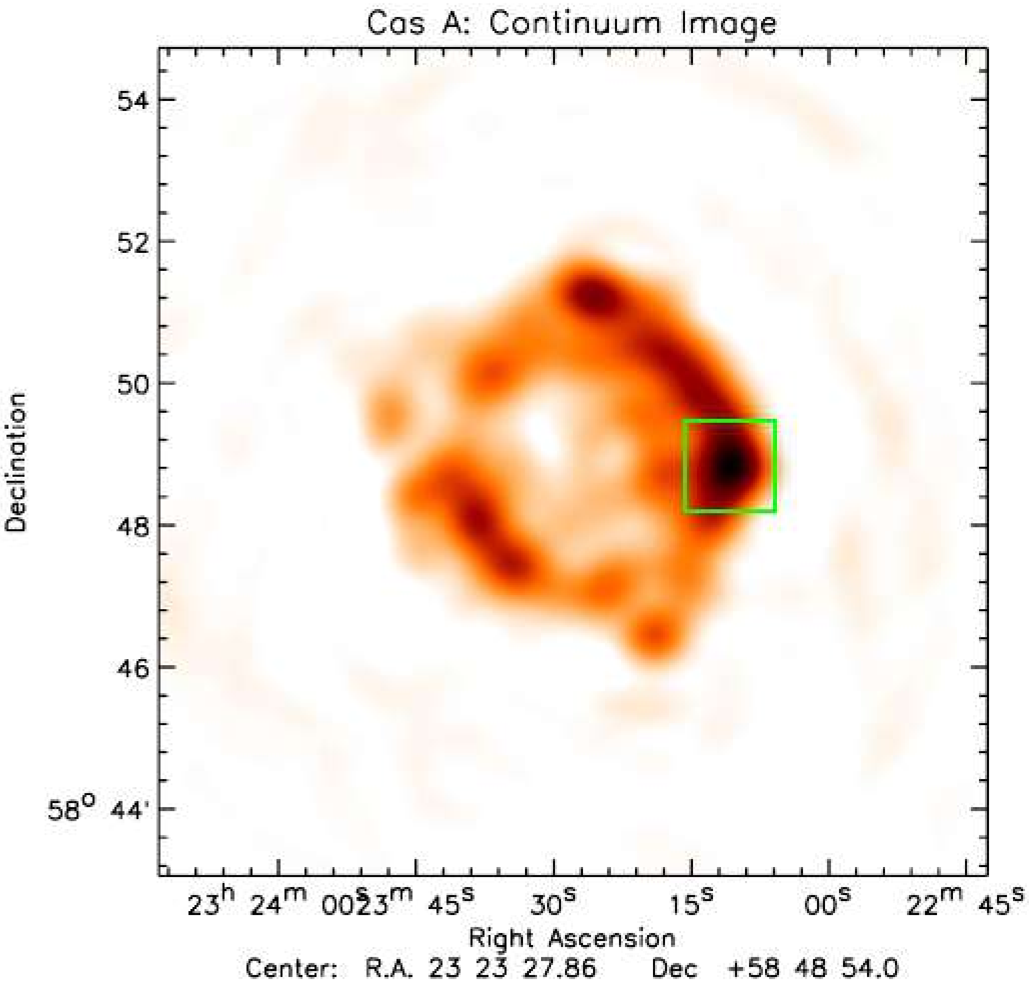


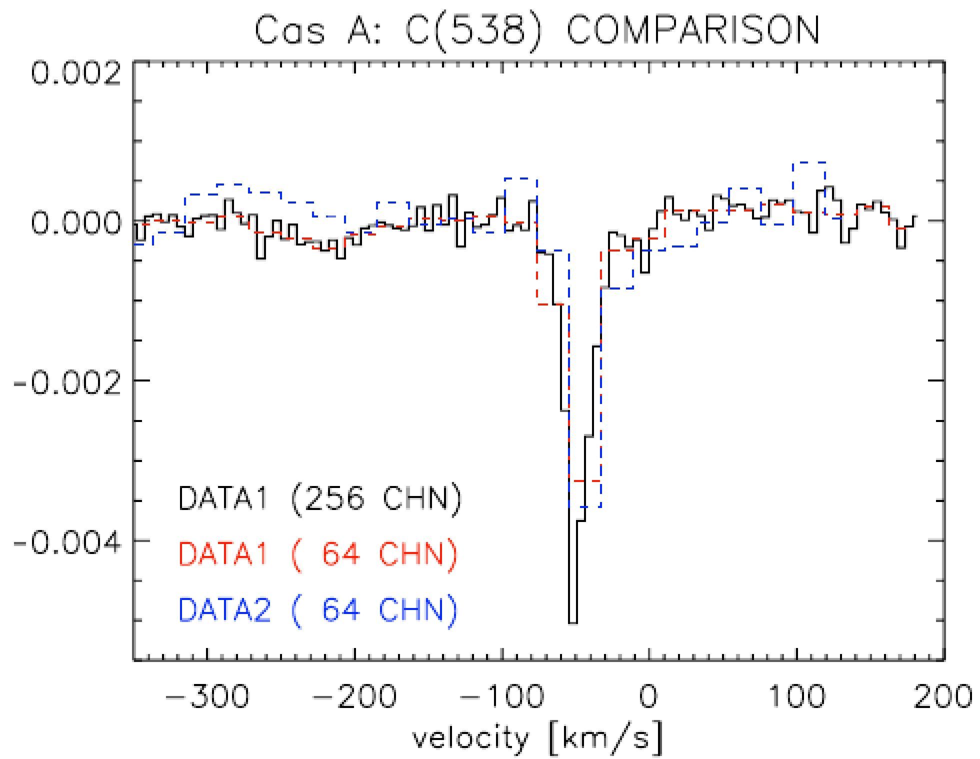
✔ **Radio recombination lines**

- **H40a → ~100 GHz**
- **H109a → 5 GHz**
- **H600a → 30 MHz**
- **C538a → 42 MHz (Asgekar+2013)**



C538 RRL in absorption from Cas A using LOFAR





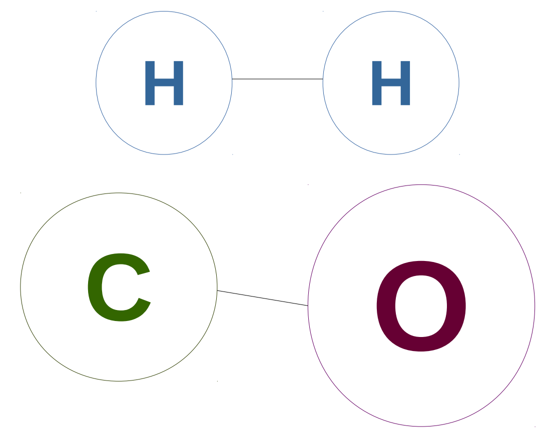
Asgekar+2013

Types of spectral lines (2)

✔ **Emission lines**

✔ **Rotational molecular transitions**

- H_2 vs CO (weak vs strong transitions)
- Eg. ^{12}CO (J=1 – 0) → 115 GHz
  ^{12}CO (J=2 – 1) → 230 GHz
  ^{12}CO (J=3 – 2) → 346 GHz



permanent electric dipole

Spontaneous emission coefficient , $A \propto \nu^3$ → lines more prominent at higher ν

In molecular clouds, spontaneous emission time >> collisional time
- when collisional rate equals A→ critical density, $n^* \approx A/\sigma v$ cross section σ (cm^2); v ($cm\ s^{-1}$)

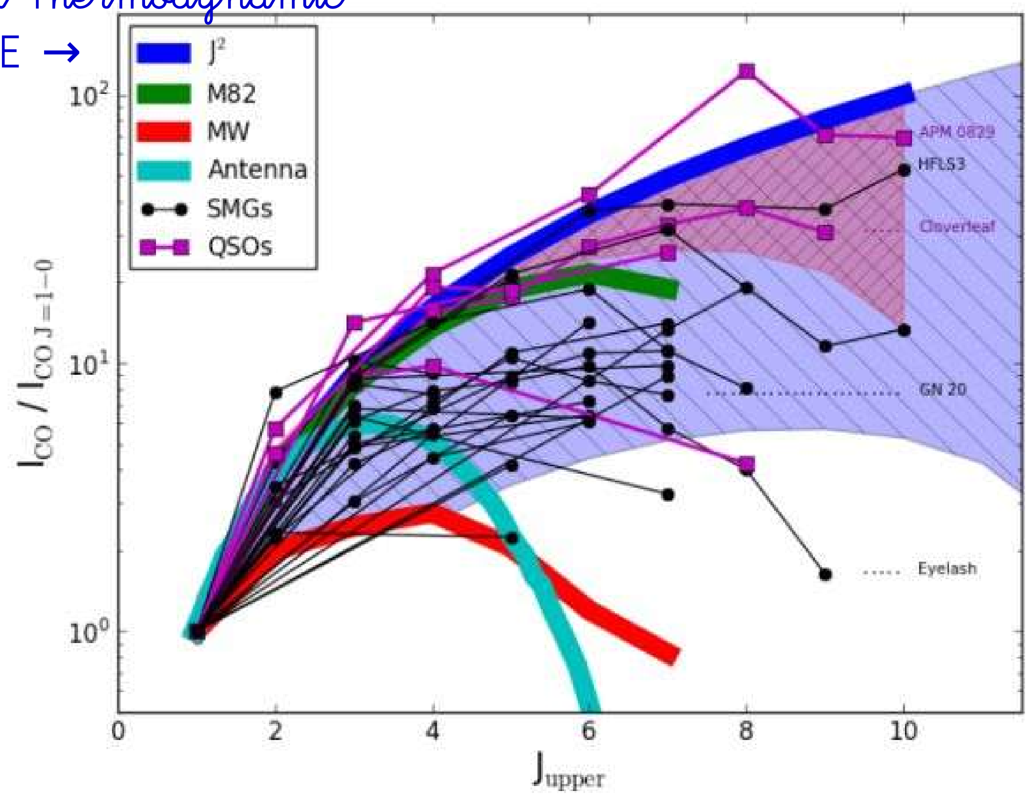
→ Since typically $\sigma \sim 10^{-15}$ cm^2 & $v = 10^5$ $cm\ s^{-1}$, molecules with higher A are only excited at higher densities (eg. $n^*(CO) \sim 700\ cm^{-3}$, $n^*(HCN) \sim 10^5\ cm^{-3}$)

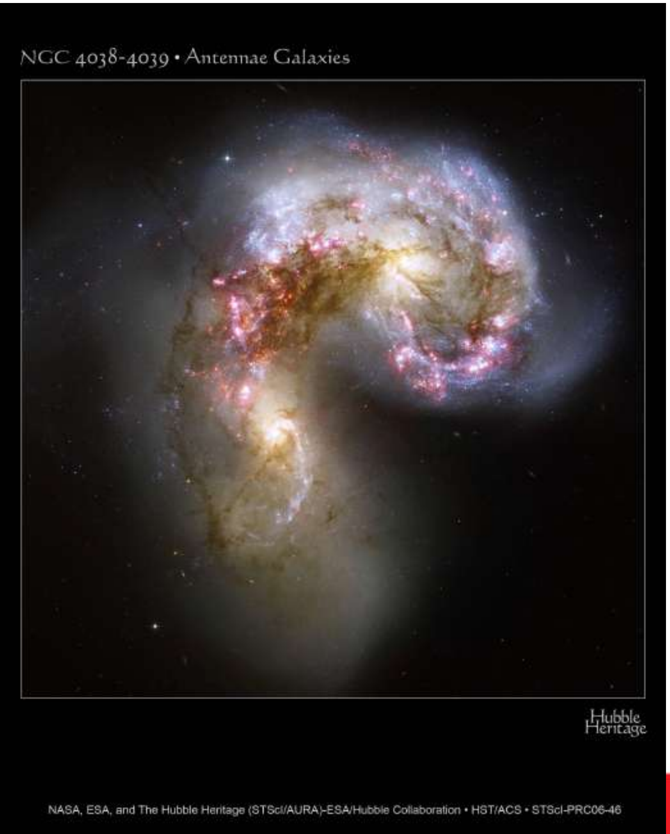
ref. Herzberg, Molecular spectra & molecular structure (1950)

Nearly 200 molecules detected in ISM as of Oct 2015 (www.astro.uni-koeln.de/cdms)

CO spectral line energy distribution

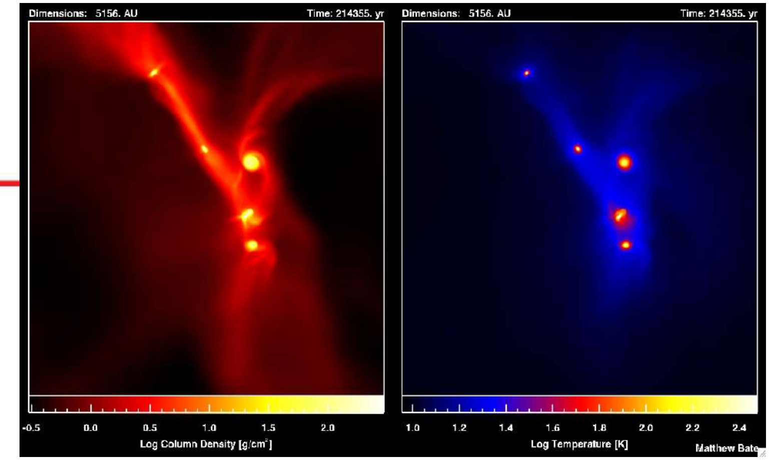
Assuming Local Thermodynamic Equilibrium, LTE →



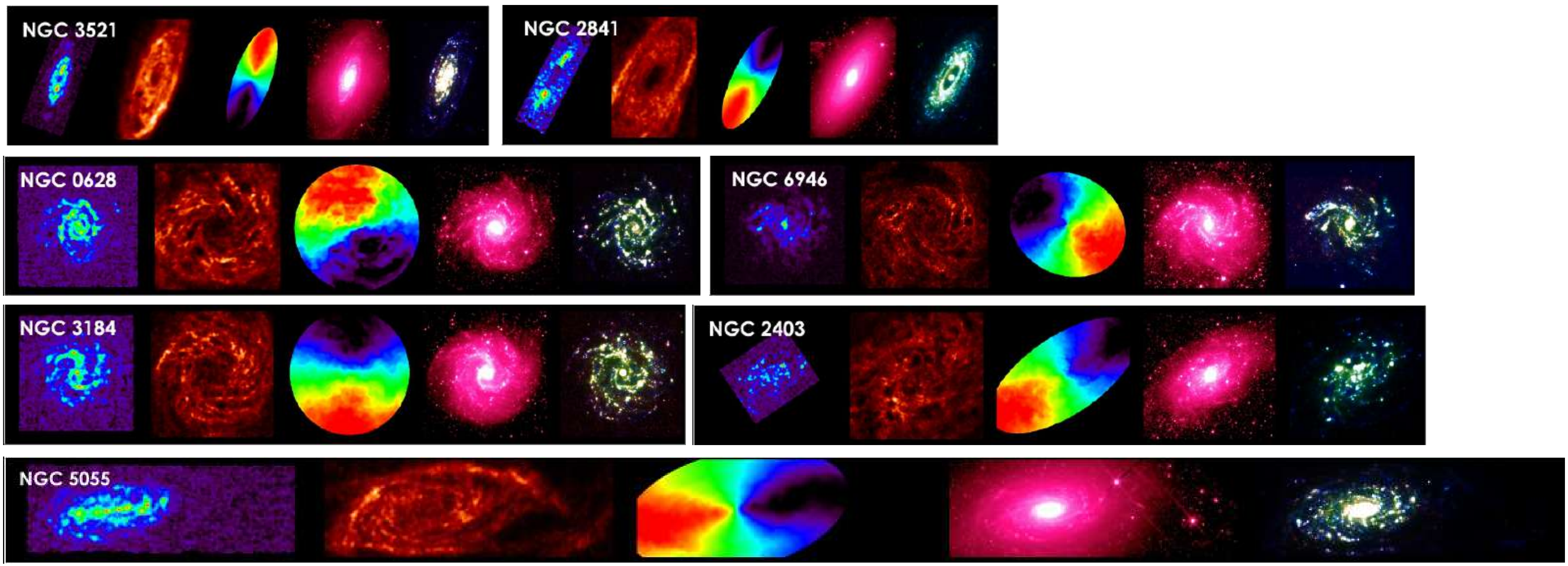


Casey, Narayanan & Cooray 2014

Typical location of CO



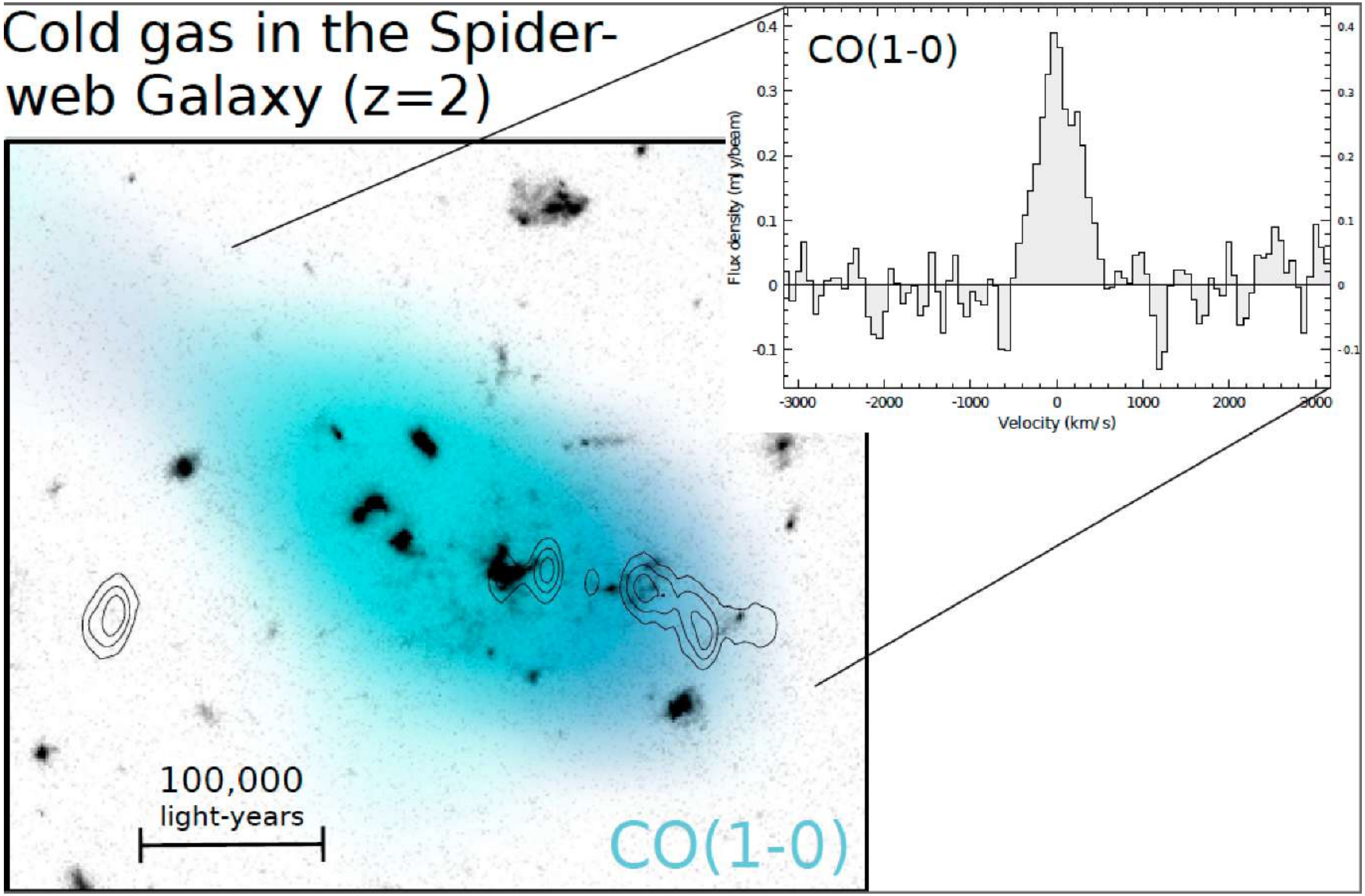
✔ Heracles survey of 18 THINGS galaxies



✔ CO usually found in strongly star-forming regions within optical disk

Leroy et al 2009

Stop Press – CO found between galaxies!



Emonts et al 2016

Caveat emptor/lector

$^{12}CO(1\text{-}0) \rightarrow H_2$?

$$N_{\mathrm{H_2}} = X_{\mathrm{CO}} I_{\mathrm{CO}}$$

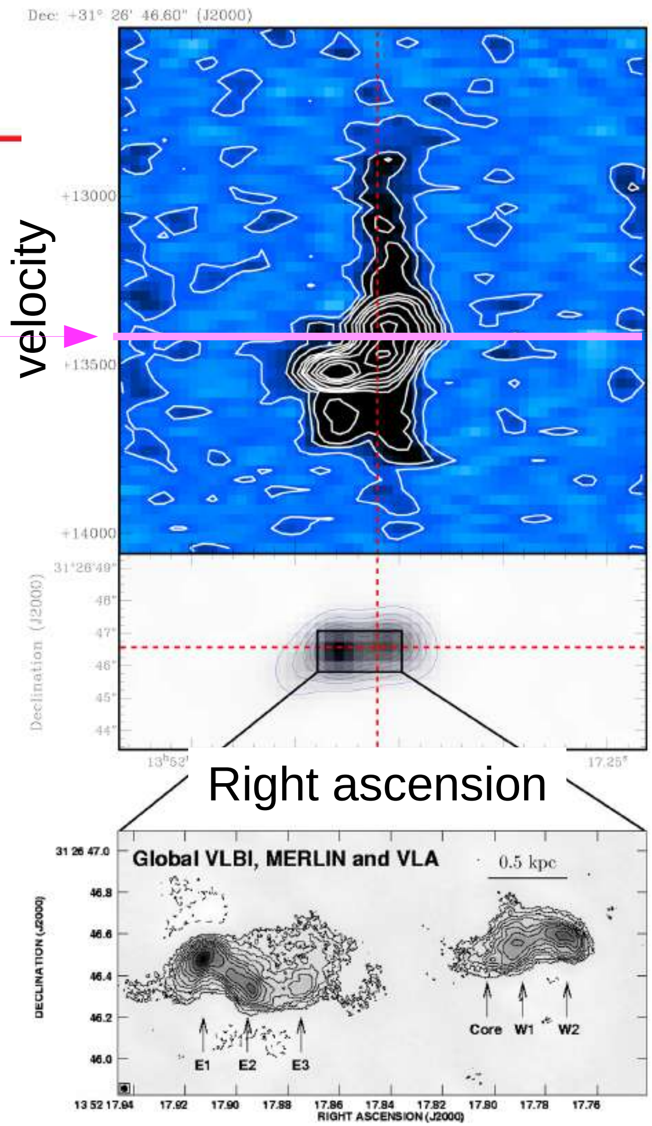
$$\Sigma_{\mathrm{H_2}} = \alpha_{\mathrm{CO}} I_{\mathrm{CO}}$$

$$\mathrm{M_{mol}} = 1.05 \times 10^4 \left(\frac{X_{\mathrm{CO}}}{2 \times 10^{20} \ \frac{\mathrm{cm^{-2}}}{\mathrm{K\ km\ s^{-1}}}} \right) \frac{S_{\mathrm{CO}} \Delta v \, D_{\mathrm{L}}^2}{(1+z)}$$

*** **Homework: what are the dependencies of X?**

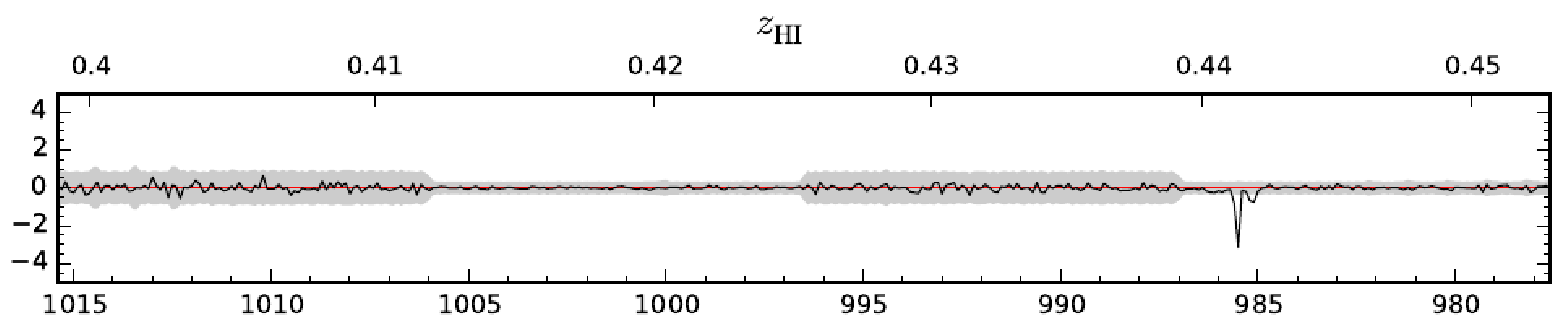
Types of spectral lines (3)

systemic velocity



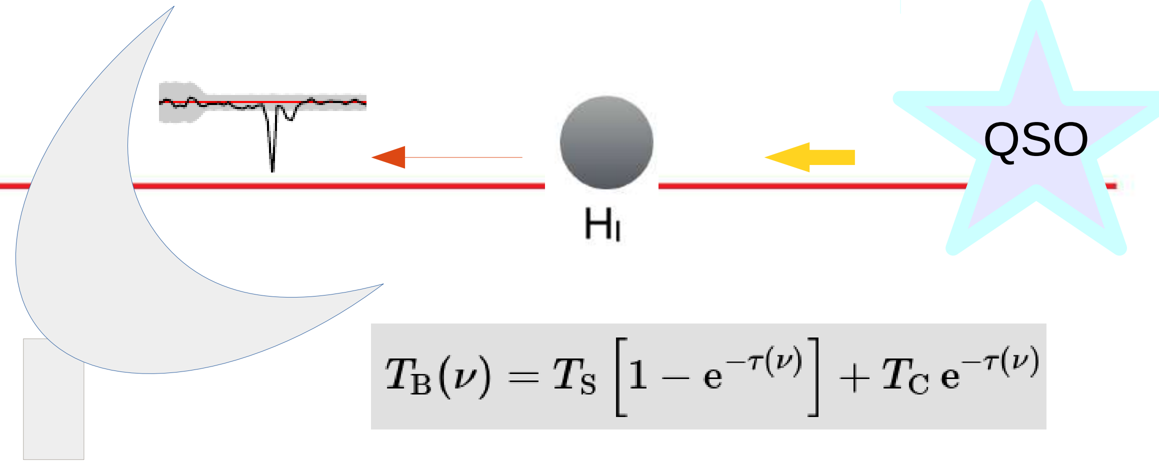
- ✔ **Absorption lines**
  - ✔ **against bright AGN → HI abs can be from host galaxy or intervening absorber**
  - ✔ **If associated with host, this is the colder gas component**
    - **→ eg. Interaction btw radio AGN & circumnuclear ISM**

Mahony+ (2013)



Allison+ (2015)

HI absorption lines



$$T_\mathrm{B}(\nu) = T_\mathrm{S}\left[1 - \mathrm{e}^{-\tau(\nu)}\right] + T_\mathrm{C}\,\mathrm{e}^{-\tau(\nu)}$$

Assuming that the gas is optically thin ($\tau \ll 1$), $\rightarrow e^{-\tau(\upsilon)} = 1 - \tau(\upsilon)$

$$T_\mathrm{B}(\nu) = T_\mathrm{S}\,\tau(\nu) + T_\mathrm{C}\,[1 - \tau(\nu)]$$

Brightness temp of Spectral Line, $T_L = T_C - T_B$ $\rightarrow$

$$\tau(\nu) = \frac{T_\mathrm{L}(\nu)}{T_\mathrm{C} - T_\mathrm{S}}$$

Extracting column densities from optical depth:

$$N_\mathrm{H\,I} = C\,T_\mathrm{S}\int \tau(\nu)\,\mathrm{d}\nu \xrightarrow{\text{for } T_S \ll T_C} N_\mathrm{H\,I} = C\,T_\mathrm{S}\int \frac{T_\mathrm{L}(\nu)}{T_\mathrm{C}}\,\mathrm{d}\nu$$

rel strength of absorption line

***** Homework: estimate N_{HI} for z ~0.3**

http://www.atnf.csiro.au/people/Tobias.Westmeier/tools_hihelpers.php & Meyer + (2017)

Homework reading: probing the CNM with HI abs

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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Using 21 cm absorption surveys to measure the average H I spin temperature in distant galaxies

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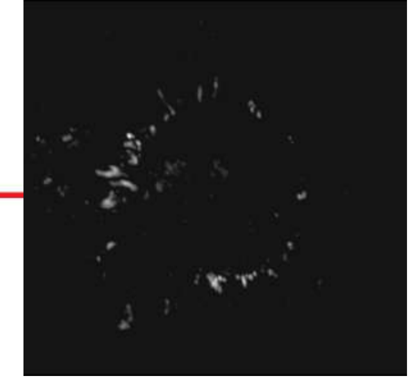
Types of spectral lines (4)



SiO maser (TX cam)

✔ **Stimulated emission**

✔ **Maser = Microwave Amplification by Stimulated Emission Radiation**

- like lasers, involve population inversion from higher → lower levels <u>but</u> unlike lasers occur naturally in star-forming regions, around late-type stars, AGN etc.

- masers are common ∵ common conditions: non-LTE (low T & density → radiatively pumped) + rules of quantum mechanics *Warning: some masers are pumped by collisions*

✔ **Common masers: OH (1612, 1665, 1667, 1720 MHz)** SF/late-stage stellar evolution

CH_3OH (Class II: 6.7 GHz, Class I: 36+44 GHz) Detected in galaxy centres

H_2O (22 GHz)

SF/late-stage stellar evolution /AGN

✔**Useful probes of small scale structures**

→ eg. Determination of SMBH mass in NGC 4258 from $H_2$0 maser kinematics (Miyoshi+1995)

SPLASH

The Southern Parkes Large-Area Survey in Hydroxyl

PI: Dawson & Walsh

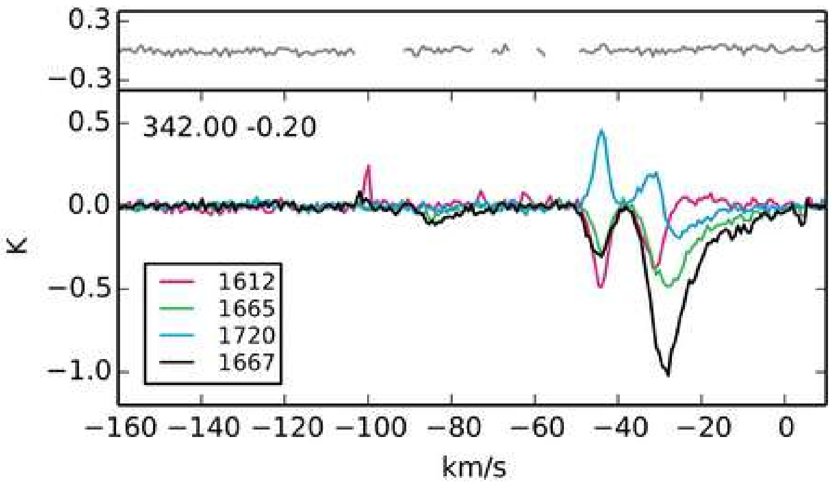


Figure 3. Example spectra showing primarily diffuse OH. The grey spectra above each panel show $[T_b(1612) + T_b(1720)] - [T_b(1667)/9.0 + T_b(1665)/5.0]$, with voxels in the vicinity of maser emission flagged out (blank ranges). The diffuse OH lines show their characteristic pattern – main-line signal with $|T_b(1667)| \gtrsim |T_b(1665)|$ (usually in absorption), with a symmetrical pattern of emission and absorption in the satellite lines. The data in these figures have been binned to a channel width of 0.7 km s^{-1}.

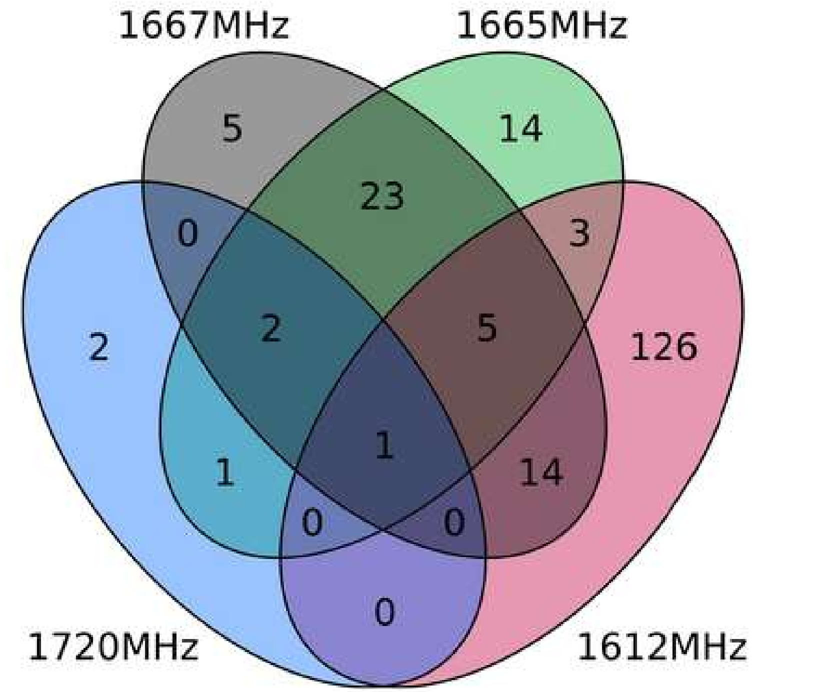
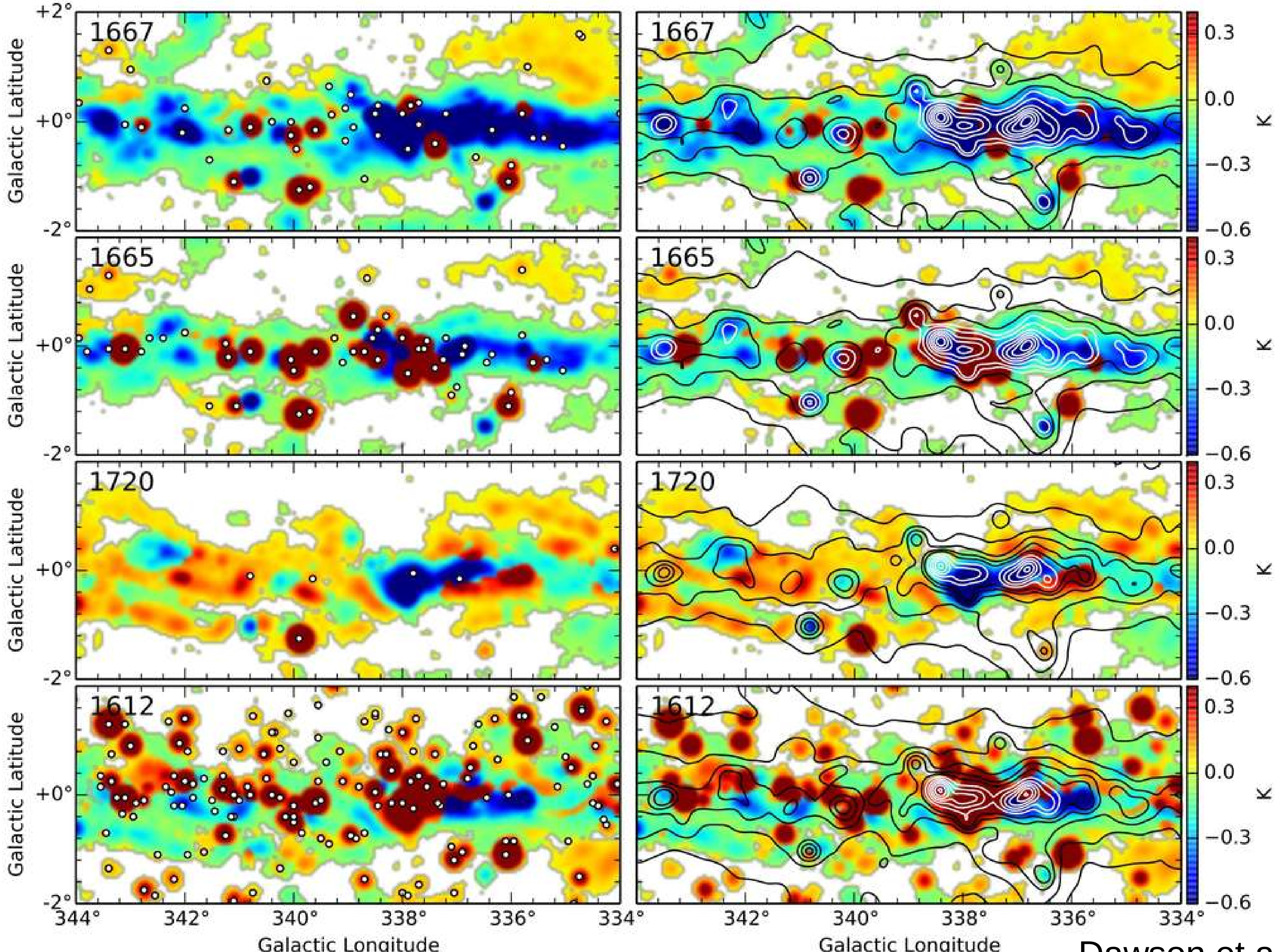


Figure 6. Venn diagram showing the overlap in occurrence of masers and maser candidates in the four OH lines.

Dawson et al 2014

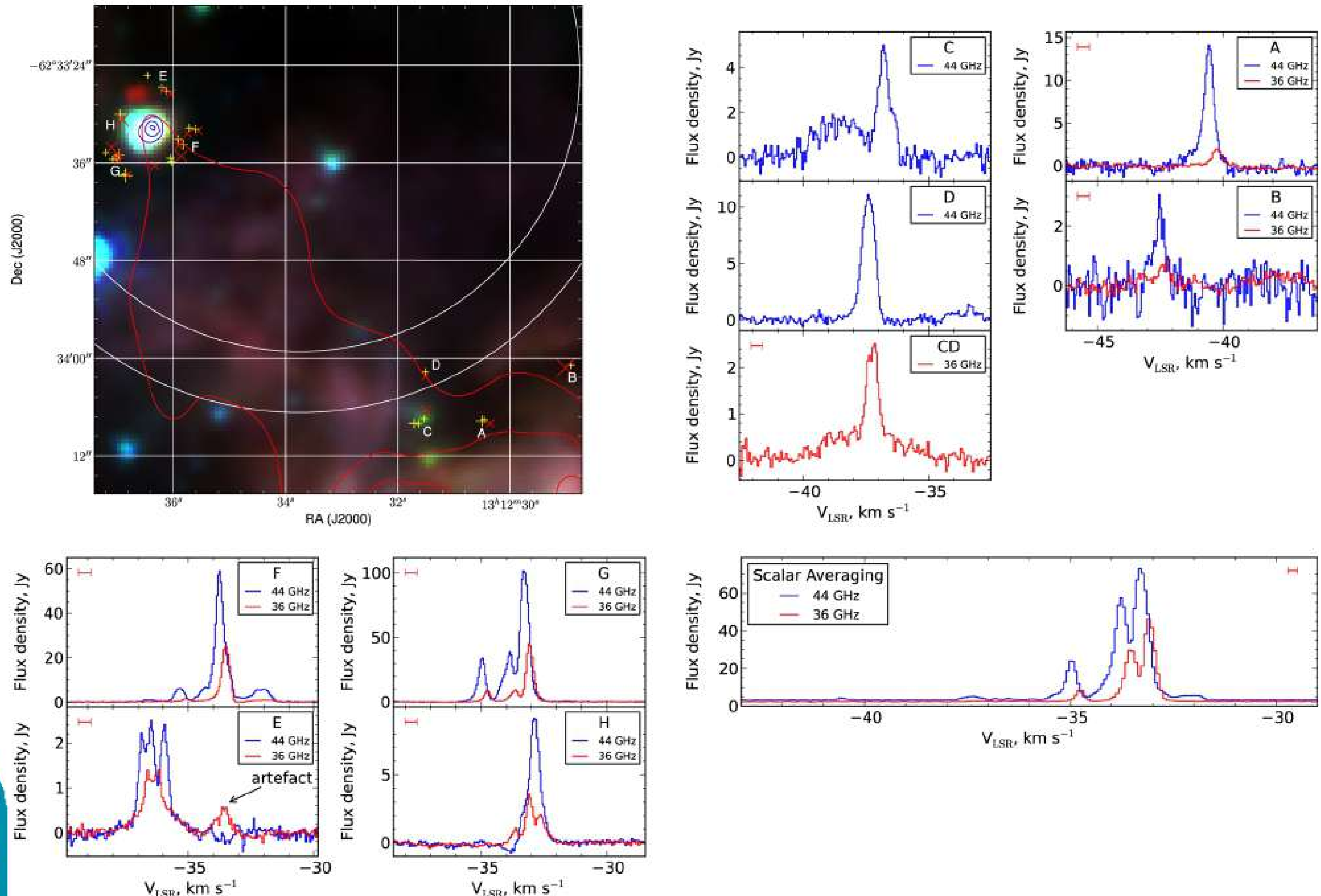
SPLASH

The Southern Parkes Large-Area Survey in Hydroxyl



Dawson et al 2014

2592 *M. A. Voronkov et al.*



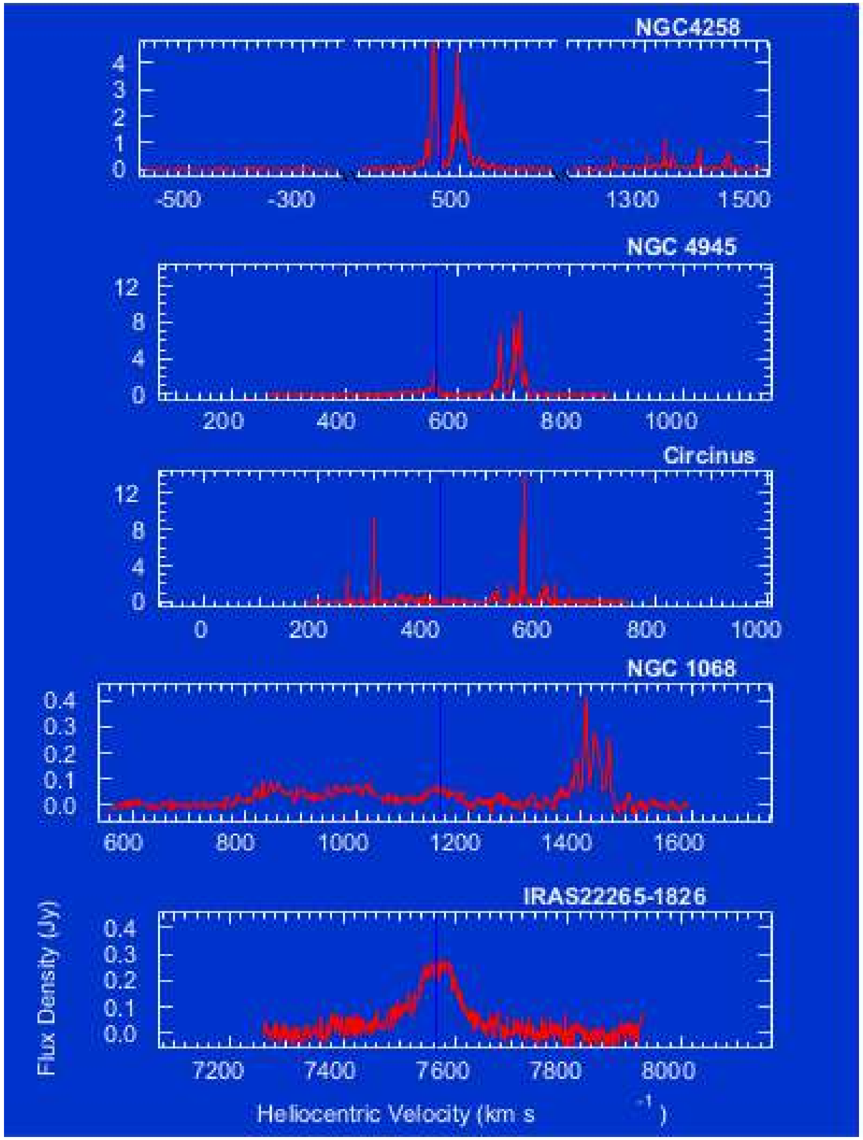
ATCA follow-up of MMB: 0.4 arcsec localisation of 71 Galactic Plane Cls 1 Methanol masers @36 & 44 GHz (Voronkov +2014)

Water masers

Taxonomy

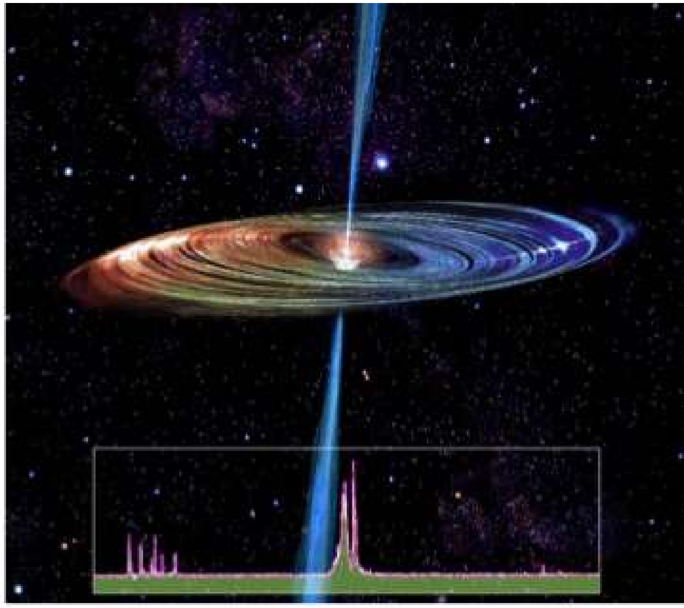
Velocity symmetry,
narrow-lines dominate

Single-emission feature,
broad-hump dominates



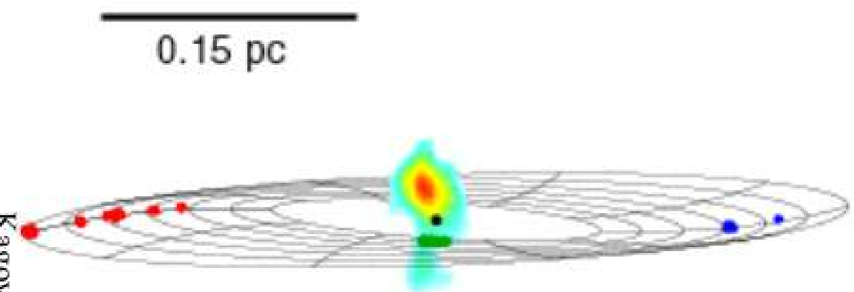
White 2017

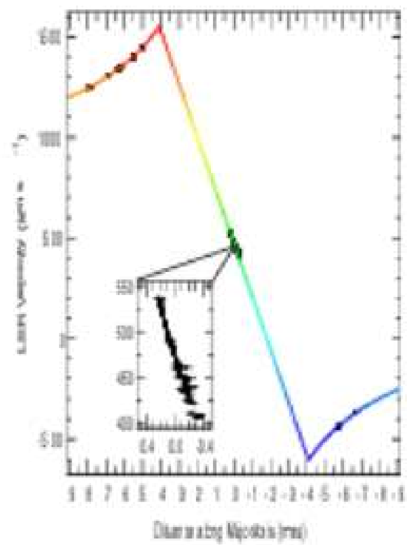
Water masers → most accurate mass estimator of SMBH



Kagoya/Inoue

NGC4258: The archetypal accretion disk maser





NGC 4258

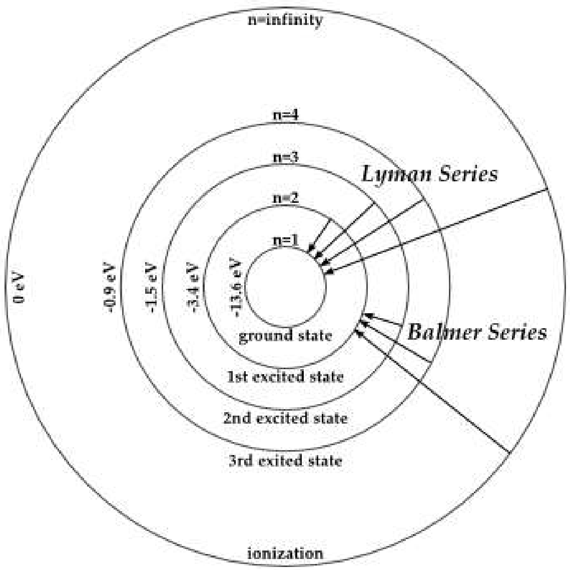
Review

Accretion Disk: *Miyoshi et al. 95*
Jet @ 4000R_s: *Herrnstein et al. 97*
Accelerations: *Nakai et al. 95*
Greenhill et al. 95
Bragg et al. 00
Distance±7%: *Herrnstein et al. 99*
BH Mass = $3.9 \times 10^6\ M_{sun}$

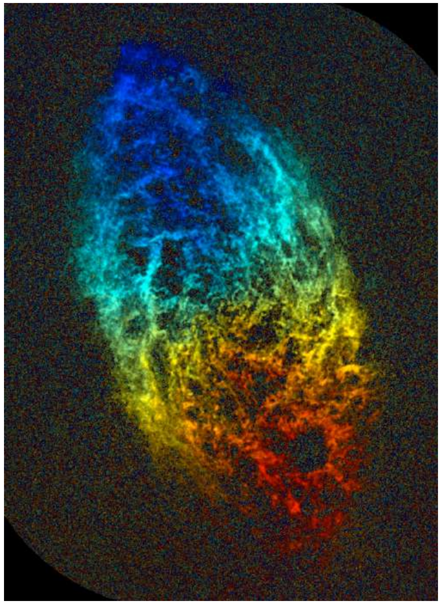
Stay tuned for Maria's lecture on VLBI + marvel at the usefulness of masers

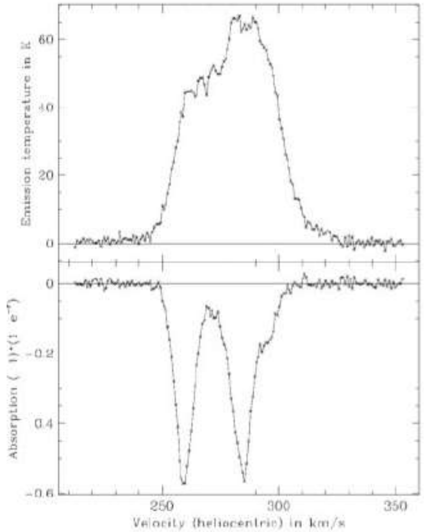
Spectral line **SCIENCE**

Radio recombination lines

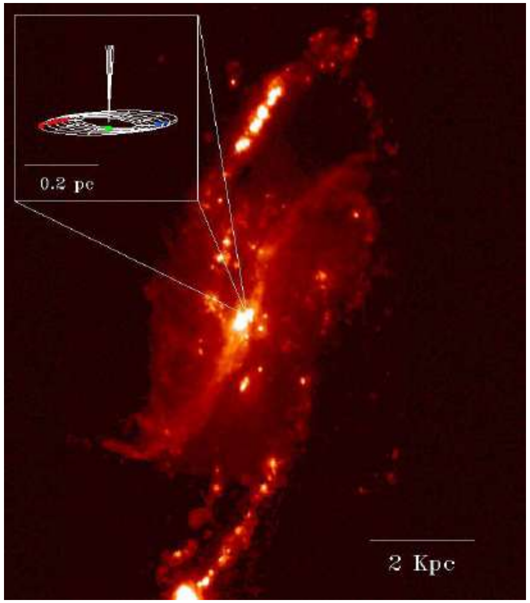


HI emission
and absorption

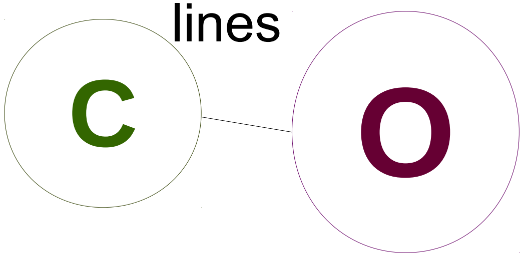


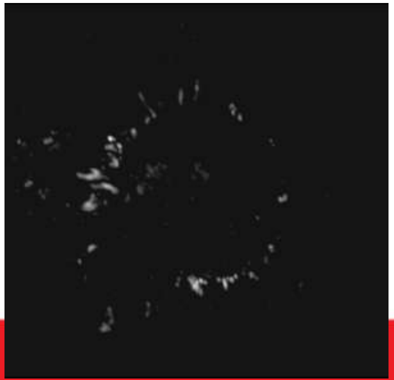


Optical
depth



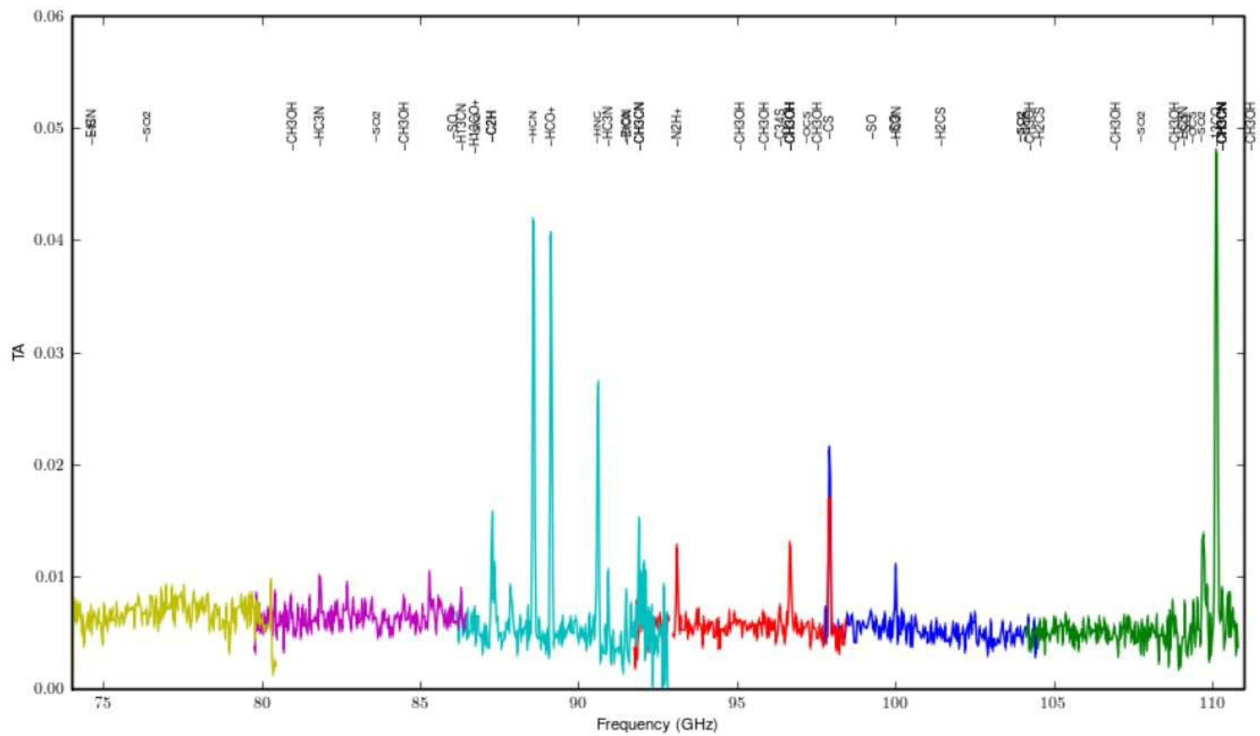
Molecular
lines





Masers

LMT RSR: 73 – 111 GHz in a single pointing



Any questions?

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