



International
Centre for
Radio
Astronomy
Research

Periodic Table of the Elements

1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.93	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.73	32 Ge Germanium 72.61	33 As Arsenic 74.92	34 Se Selenium 78.09	35 Br Bromine 79.90	36 Kr Krypton 84.80
37 Rb Rubidium 84.49	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.20	83 Bi Bismuth 208.98	84 Po Polonium [209]	85 At Astatine [209.98]	86 Rn Radon 222.02
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	62 Sm Samarium 150.36	63 Eu Europium 151.97	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97			
89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium [254]	100 Fm Fermium 257.10	101 Md Mendelevium 258.10	102 No Nobelium 259.10	103 Lr Lawrencium [262]			

Alkali Metal Alkaline Earth Transition Metal Basic Metal Semimetal Nonmetal Halogen Noble Gas Lanthanide Actinide

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Spectral line science

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28 September 2017 @2017 ATNF Radio School, Narrabri



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.

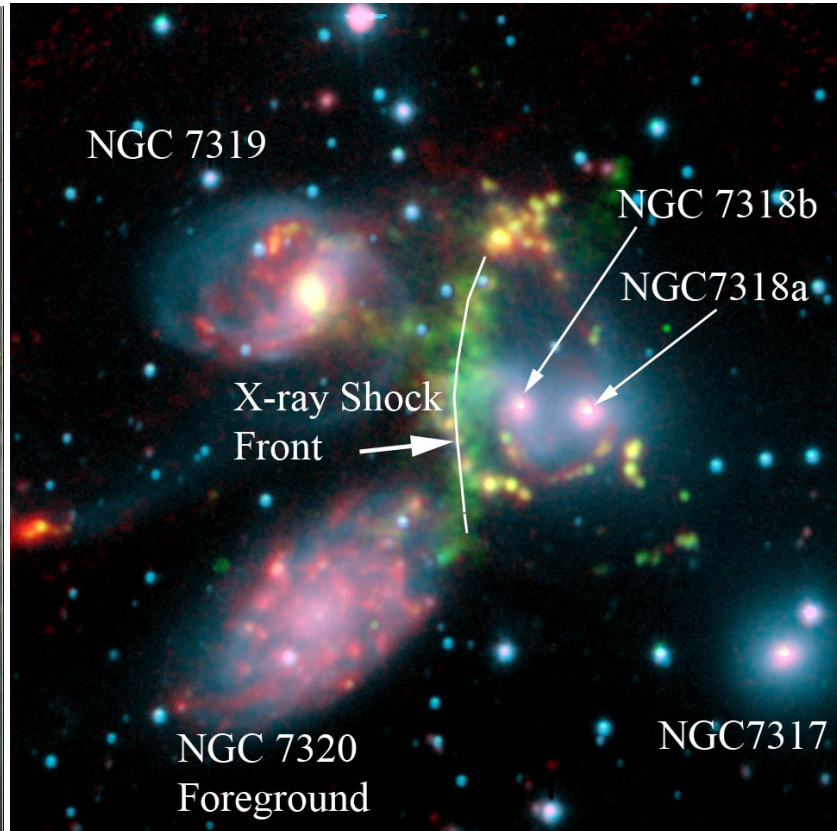
– Westpfahl 1999

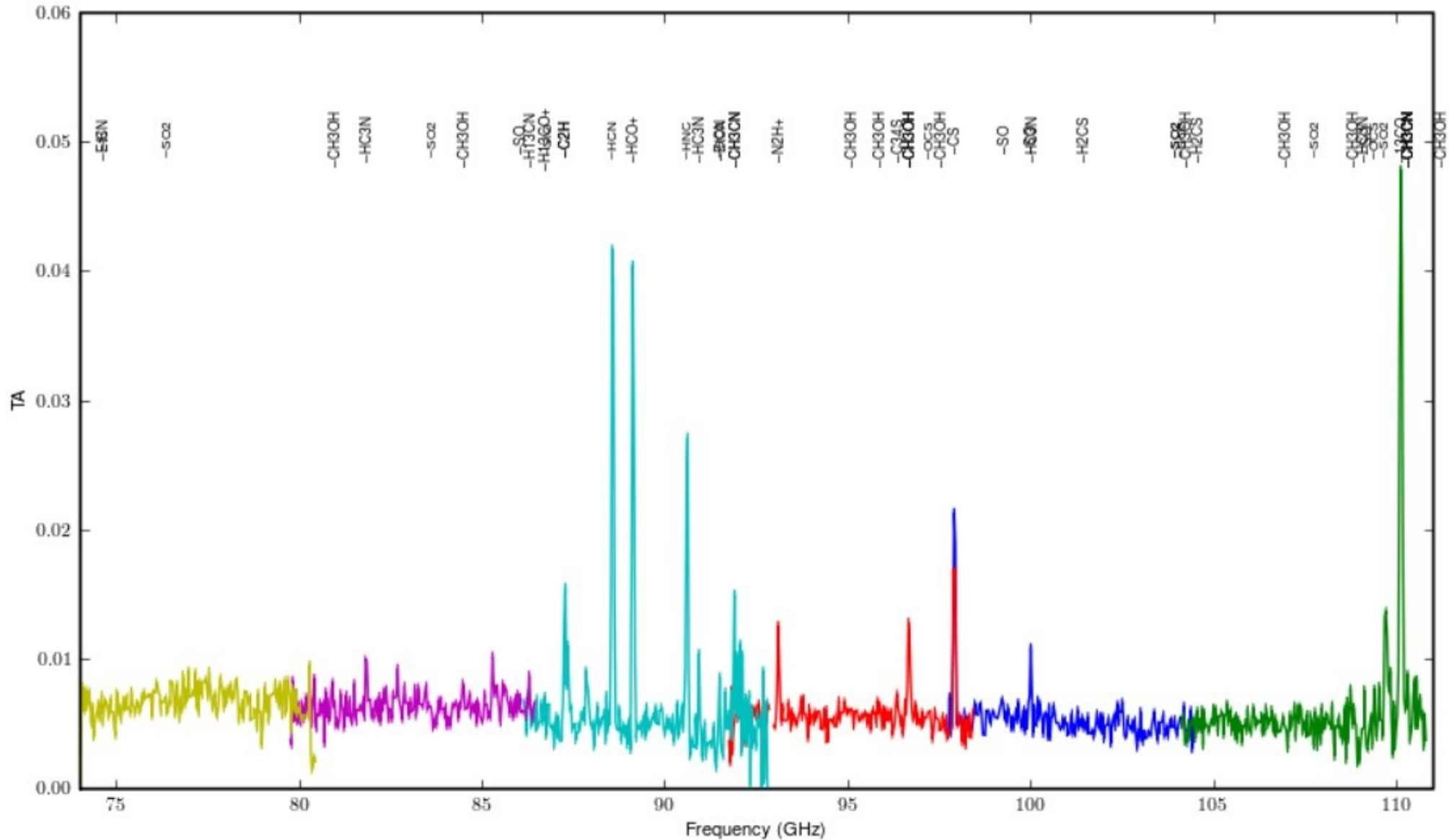


Spectral lines: great tool for studying ISM physics

- ✓ Kinematics + morphology (3D)
 - ✓ Physical state (density, temperature, SF history etc) of the interstellar medium (ISM)
- the physical processes that shape galaxy evolution

The
WHY







Spectral line ?

The HOW

- ✓ **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

$$v = c \frac{\nu_0^2 - \nu^2}{\nu_0^2 + \nu^2} \quad (16)$$

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”,

$$v_{\text{radio}} = c \left(1 - \frac{\nu}{\nu_0}\right) \quad (17)$$

and the “optical definition”,

$$v_{\text{optical}} = c \left(\frac{\nu_0}{\nu} - 1\right) \quad (18)$$

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.

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

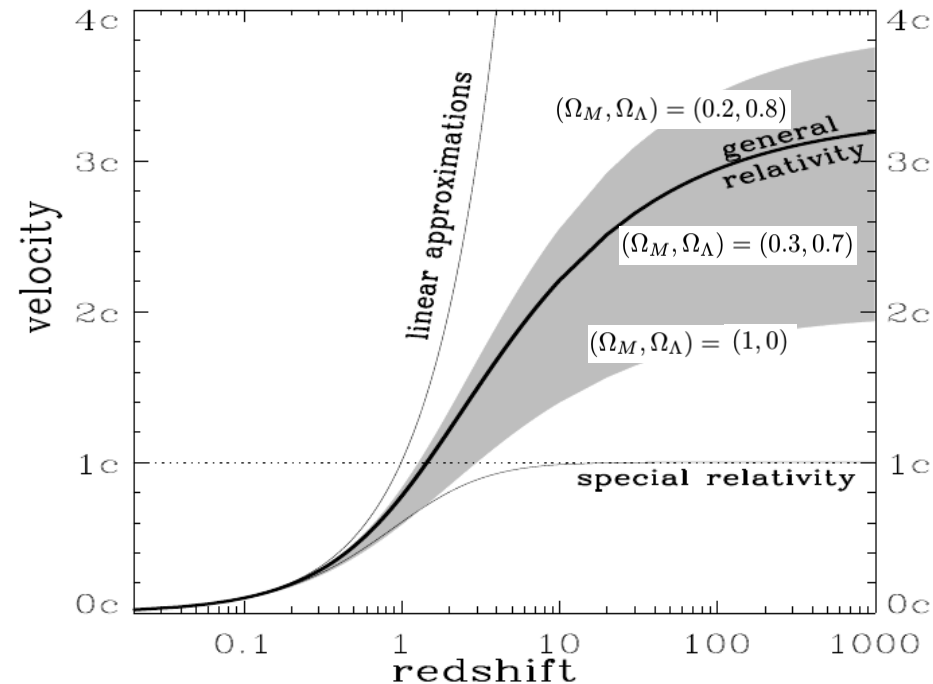
$$\begin{aligned} V_{\text{pec}}(z_{\text{pec}}) &= V_{\text{SR}}(z_{\text{pec}}), \\ &= c \frac{v_{\text{rest}}^2 - v_{\text{obs}}^2}{v_{\text{rest}}^2 + v_{\text{obs}}^2}, \\ &= c \frac{(1 + z_{\text{pec}})^2 - 1}{(1 + z_{\text{pec}})^2 + 1} \end{aligned}$$

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

Source at z_{cos} observed at $z_{\text{ref}} = 0 \rightarrow$

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

where $H(z) = H_0 E(z)$, $E(z) = \sqrt{\Omega_R(1+z)^4 + \Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda}$.



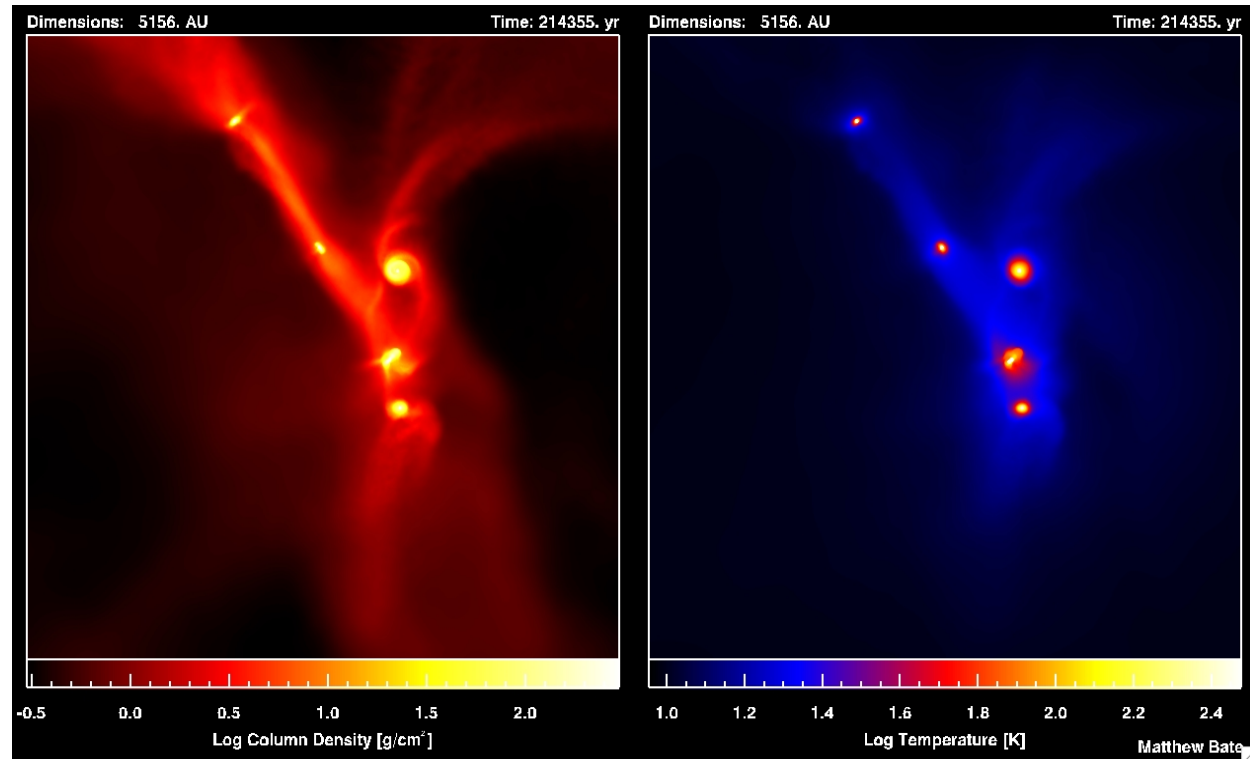
Davis & Lineweaver 2001

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

Neutral gas

Molecular gas

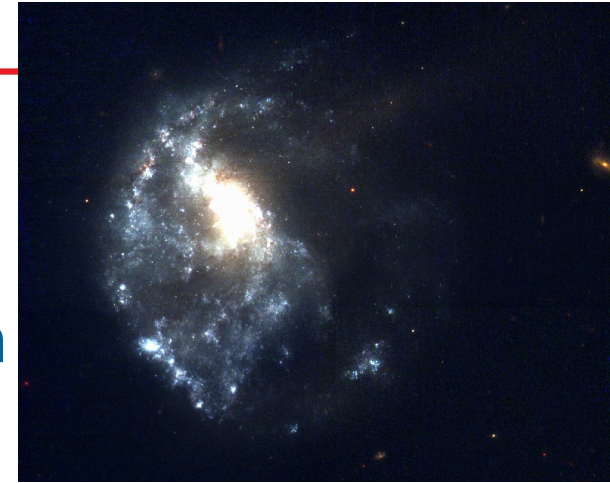
Stars



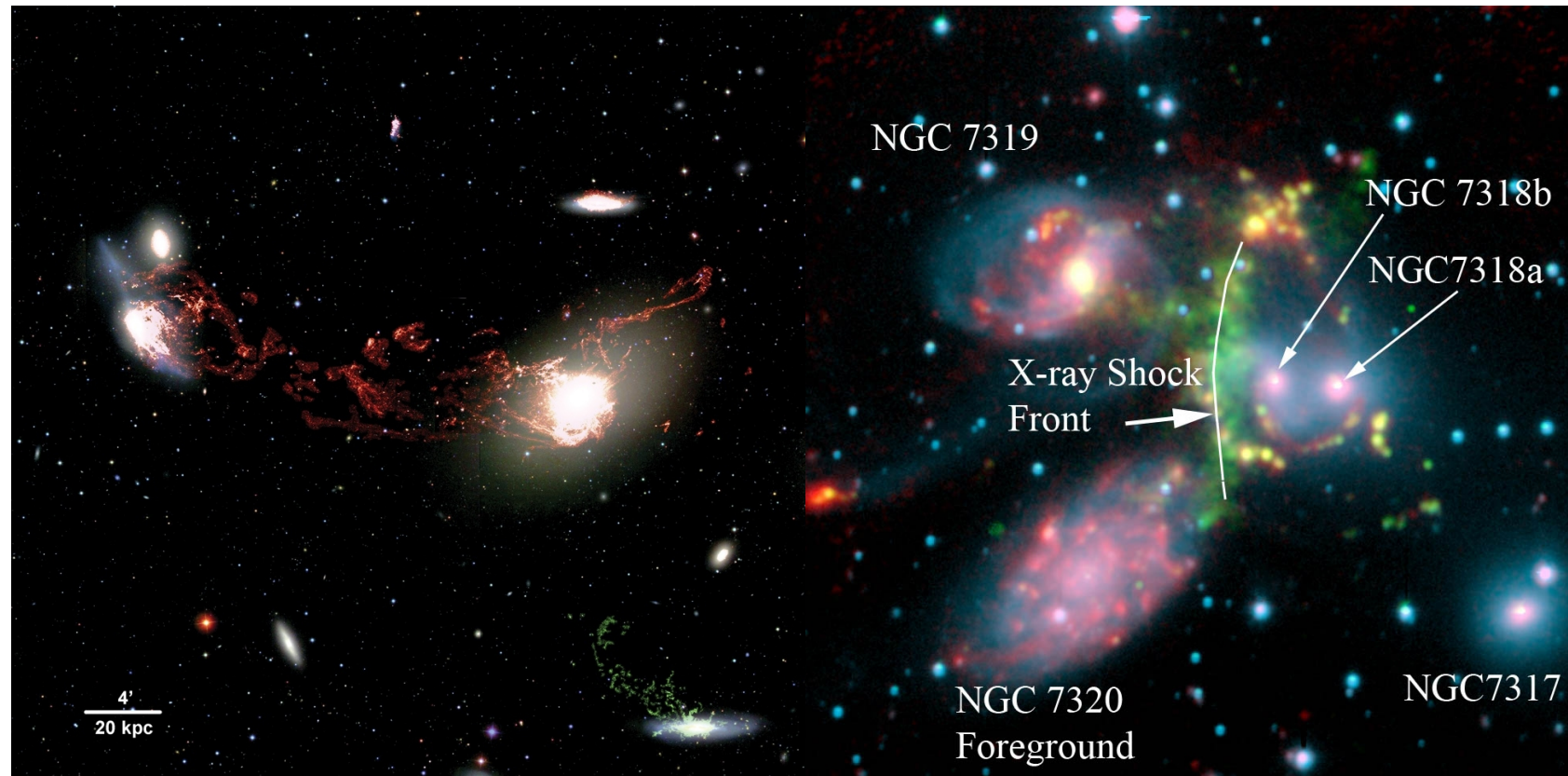
Wide range of temperature/density regimes:

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

- ✓ 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

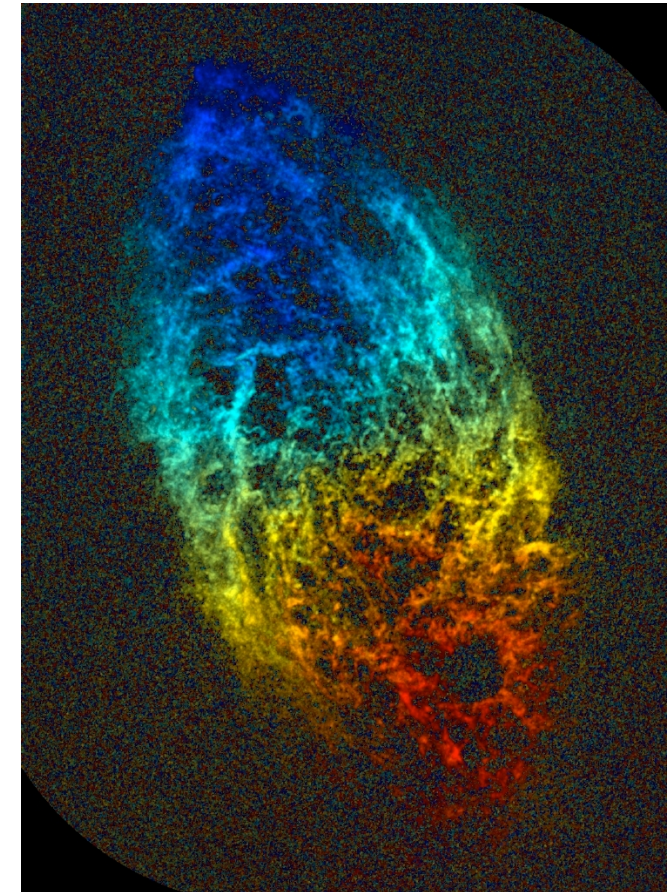
Appleton+2006



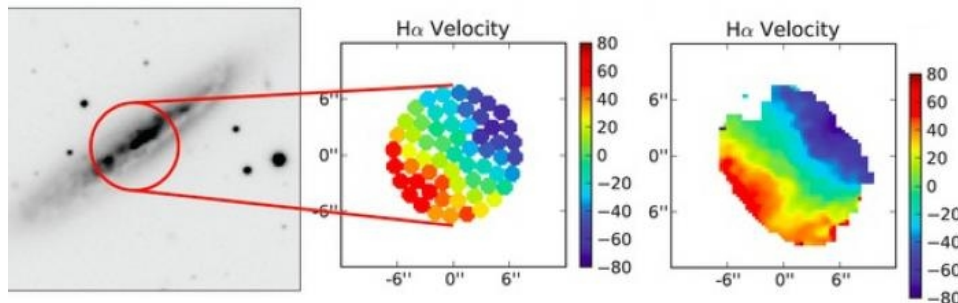
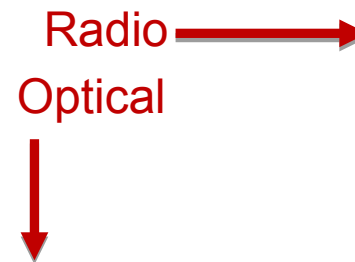
3D astronomy: the “new” tool in optical astronomy

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.

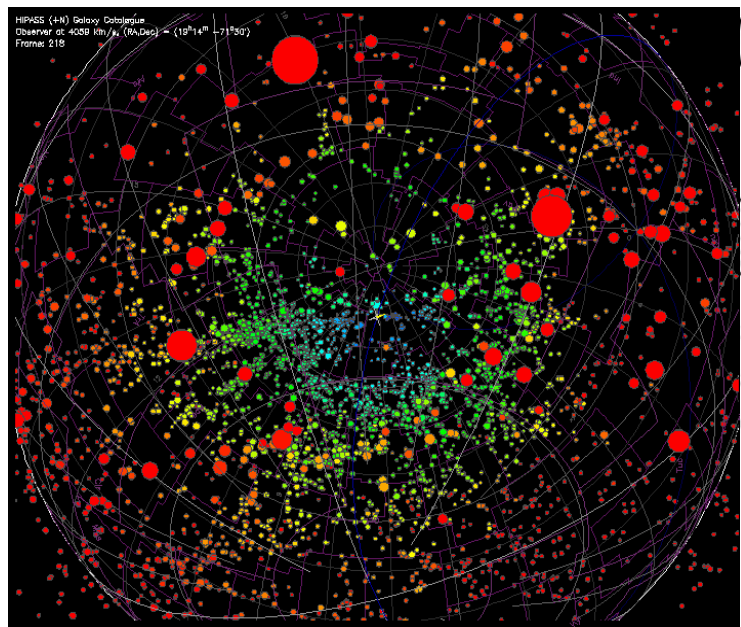


Credit: Thilker, Braun & Walterbos

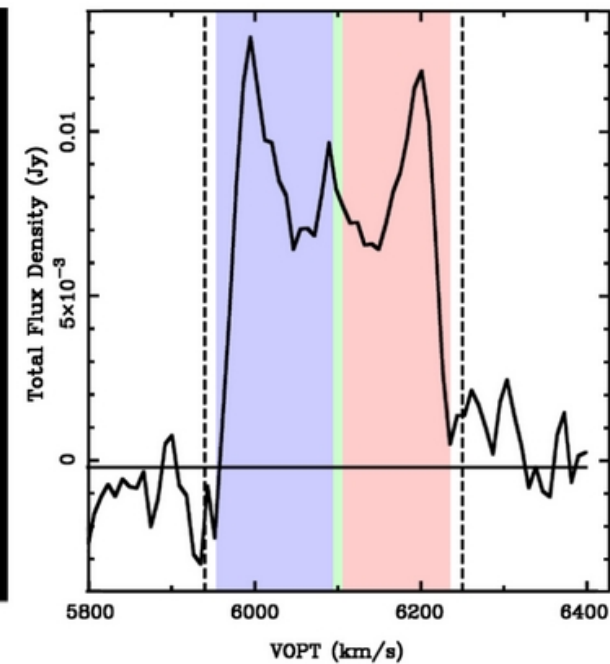
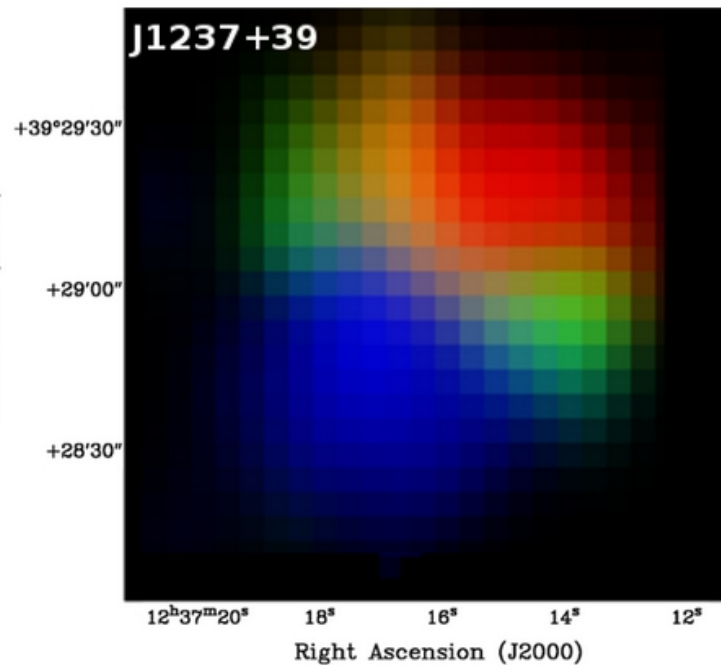


Credit: Lisa Kewley

- ✓ Single dish / low angular resolution → Δv : ~distance of galaxy
- ✓ Synthesis observations → higher angular & freq resolution → kinematics



Credit: HIPASS data (Mark Calabretta)



Wong+(2015)

Moment definitions

0 = total flux

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

1 = intensity weighted (IW) velocity

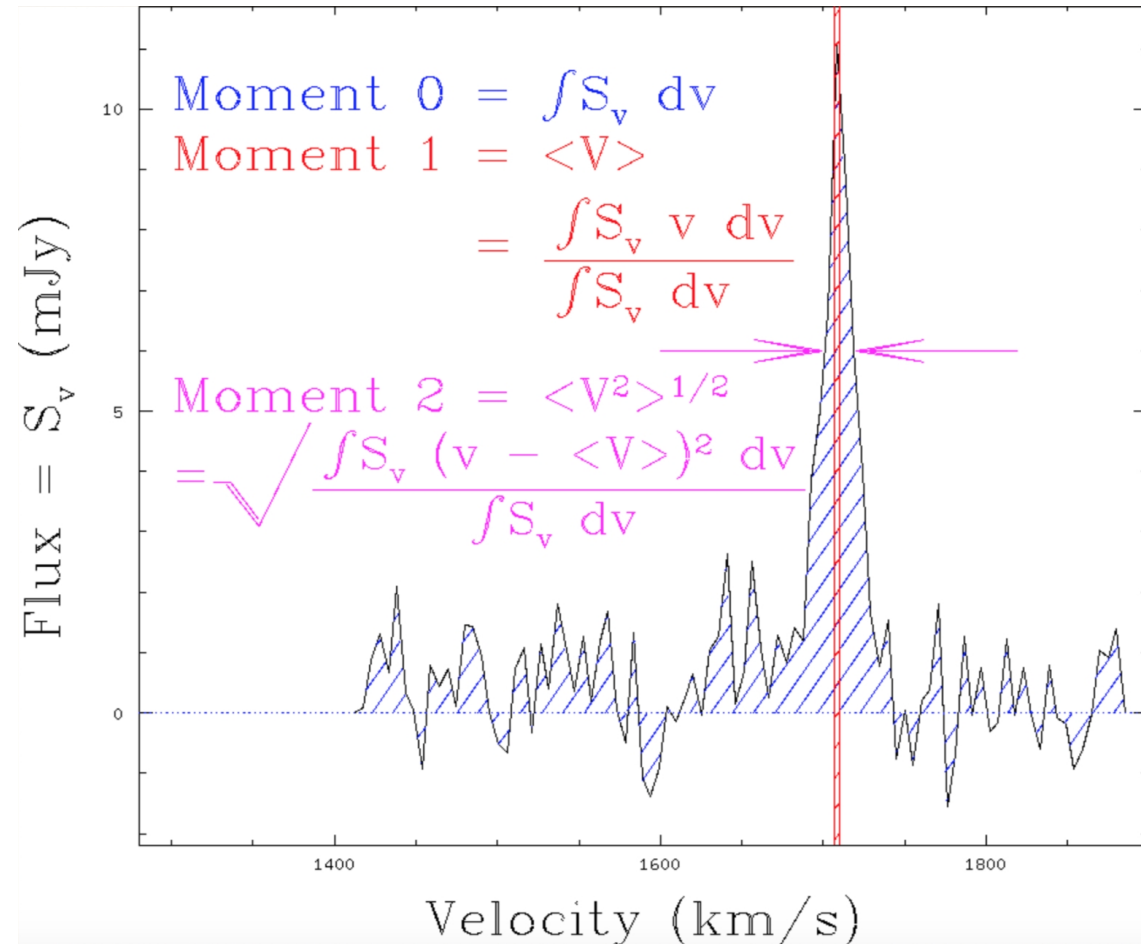
$$M_1 = \frac{\sum v A(v)}{\sum A(v)}$$

2 = IW velocity dispersion

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

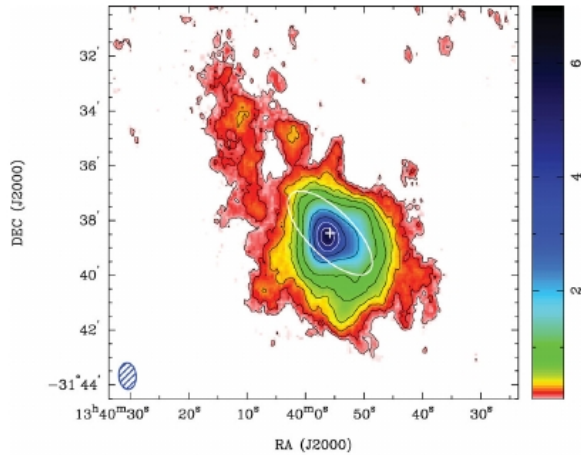
3 = skewness/line asymmetry

4 = kurtosis

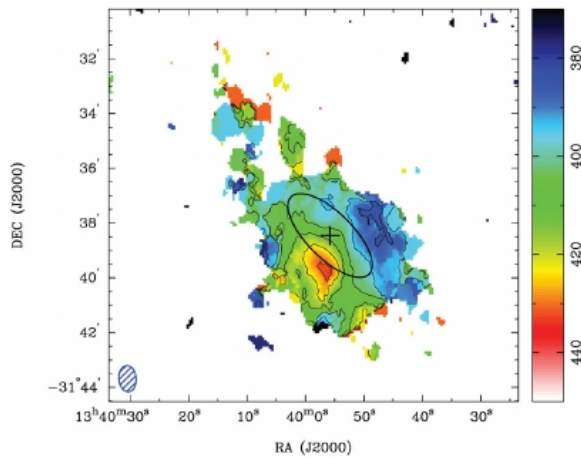


Example moment maps of NGC 5253

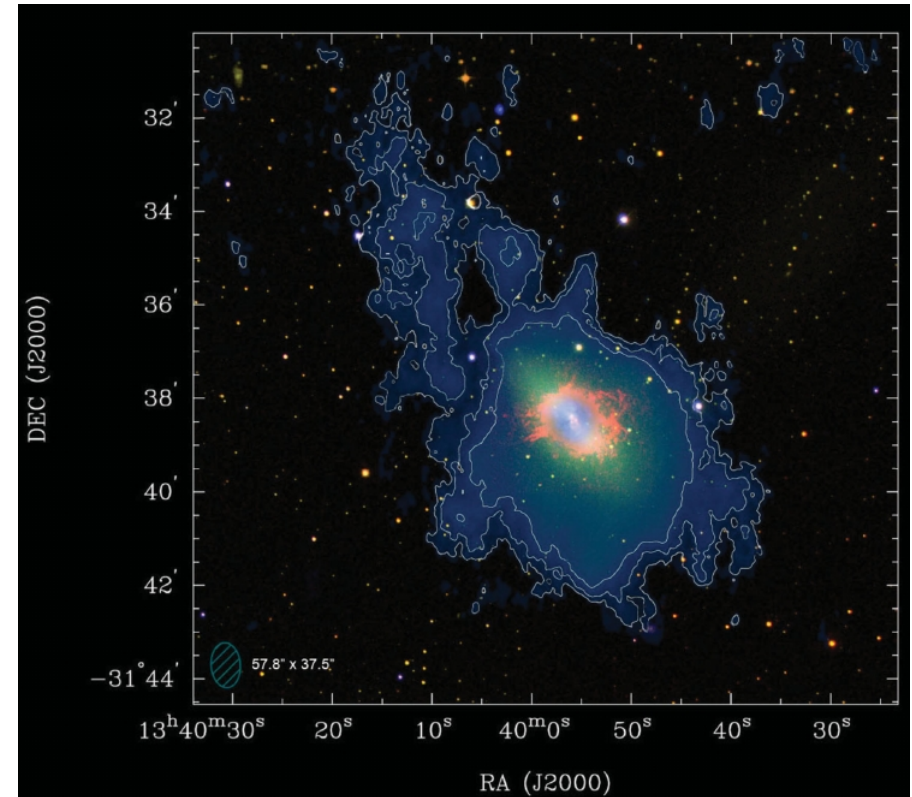
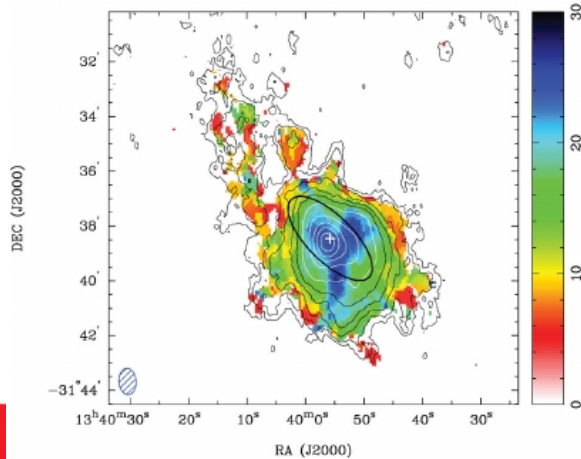
Moment 0



Moment 1



Moment 2





Tilted Ring Fitting Code

HOME

Input and Syntax

Modelling Strategy

Model Geometry

Model Fitting

Output

Parameter Index

Examples

GUI

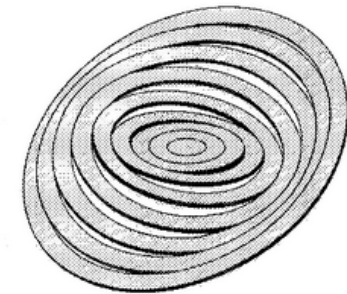
Bugs and Development

Download and Installation

Contact and Feedback

Credits

Tilted Ring Fitting Code (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 SPEKKENS⁴, PETER KAMPHUIS⁵ & BÄRBEL S. KORIBALSKI⁶
MNRAS, accepted

ABSTRACT

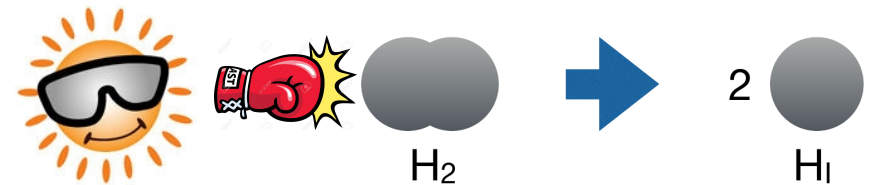
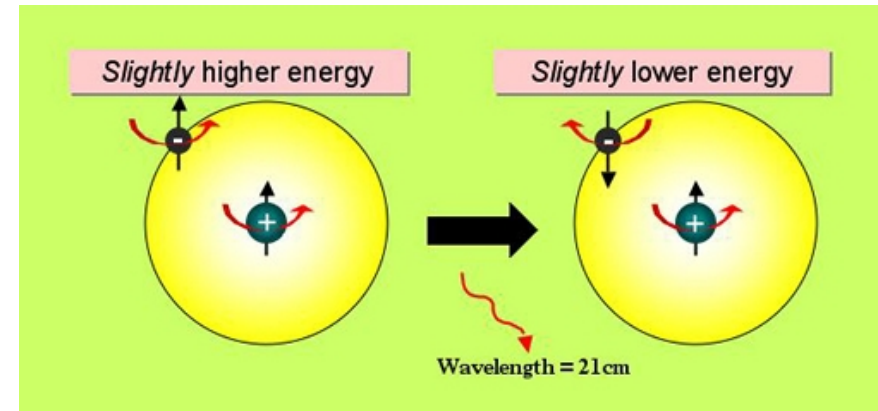
We present a novel algorithm based on a Bayesian method for 2D tilted-ring analysis of disk galaxy velocity fields. Compared to the conventional algorithms based on a chi-squared minimisation procedure, this new Bayesian-based algorithm suffers less from local minima of the model parameters even with 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-

Sep 2017

✓ Emission lines

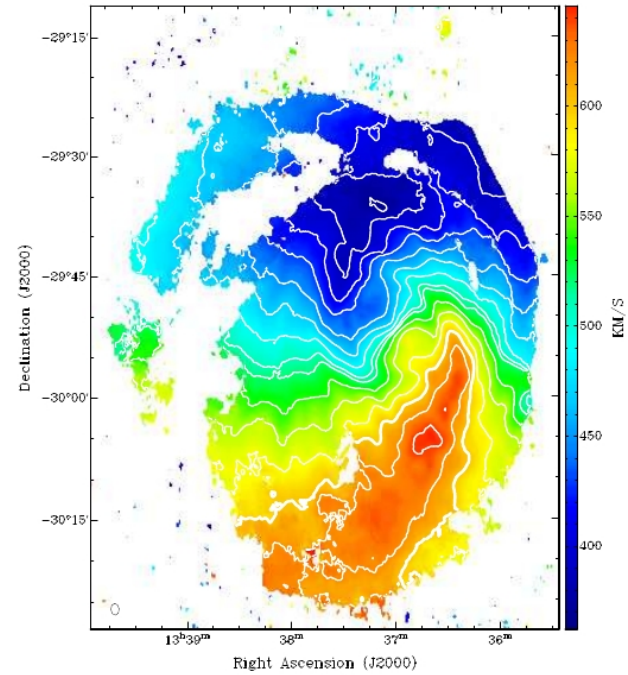
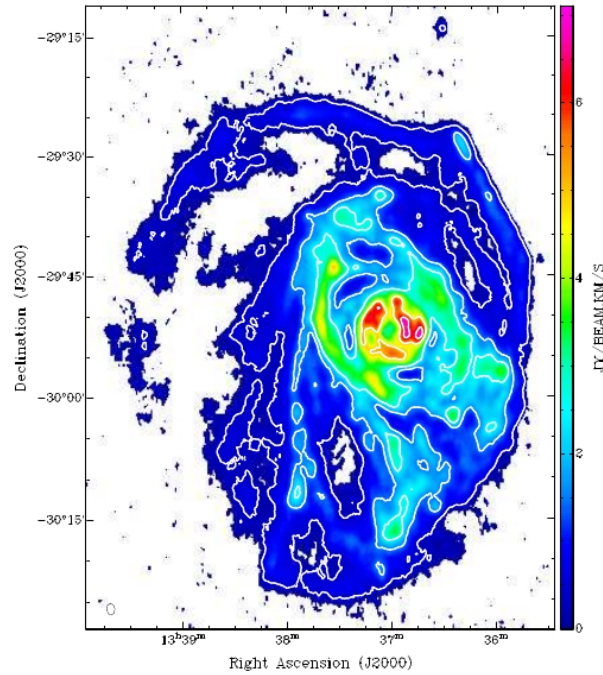
✓ Hyperfine / spin-flip transition

➤ HI → emission at 1.4204 GHz

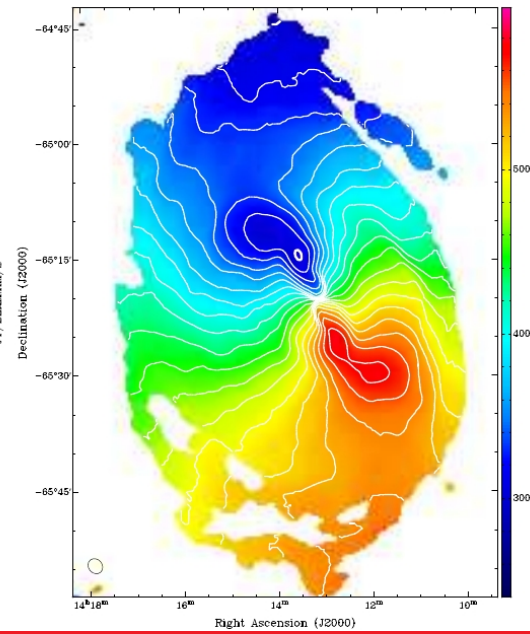
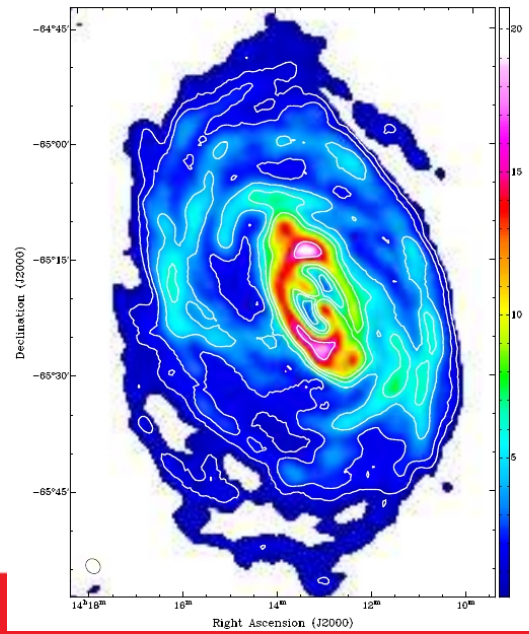


LVHIS finds giant HI halos in nearby galaxies

M83



Circinus





Calculating HI emission column densities

✓ Detecting HI in emission relies on HI column densities

Flux densities to brightness temps:

$$T_B = \frac{\lambda^2 S}{2k_B \Omega} \quad \rightarrow \quad T_B = \frac{1.36 \lambda^2 S}{a \times b}$$

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

Assuming that the gas is optically thin ($\tau \ll 1$),

$$N_{\text{HI}} = 1.823 \times 10^{18} \int T_B dv$$

Column density N_{HI} (cm^{-2}); v (km s^{-1})

✓ At $z \gg 0.1$,

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

specify widths at rest frame as ΔV_{obs} & observed frame as $\Delta \nu_{\text{obs}}$

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



Calculating HI masses

✓ In nearby galaxies,

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

✓ At $z \gg 0.1$,

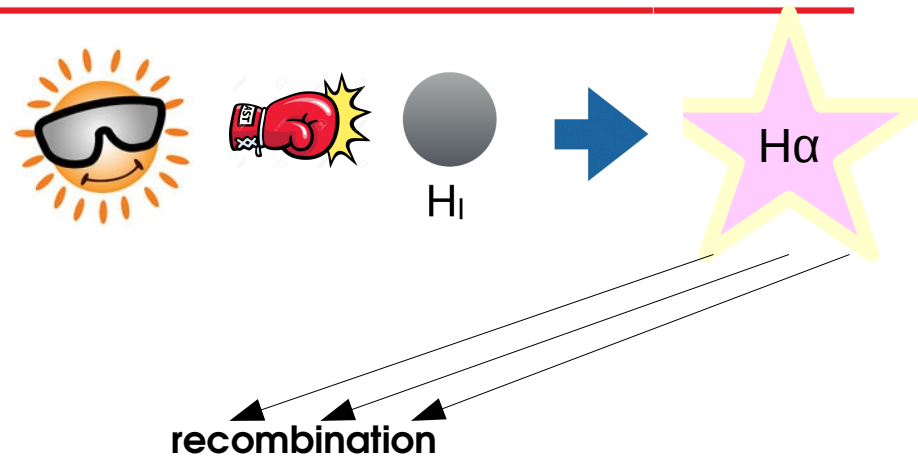
$$S = \frac{L}{4\pi D_L^2}$$

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

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

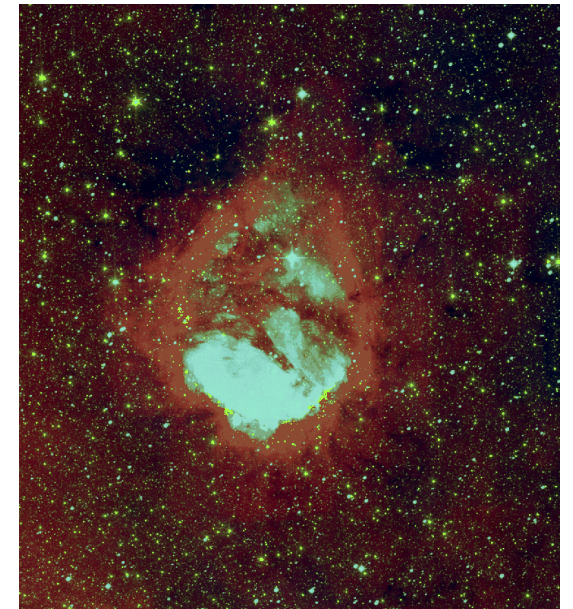
$$\left(\frac{M_{\text{HI}}}{h_C^{-2} M_{\odot}} \right) \simeq 49.7 \left(\frac{D_L}{h_C^{-1} \text{Mpc}} \right)^2 \left(\frac{S}{\text{Jy Hz}} \right)$$

Types of spectral lines



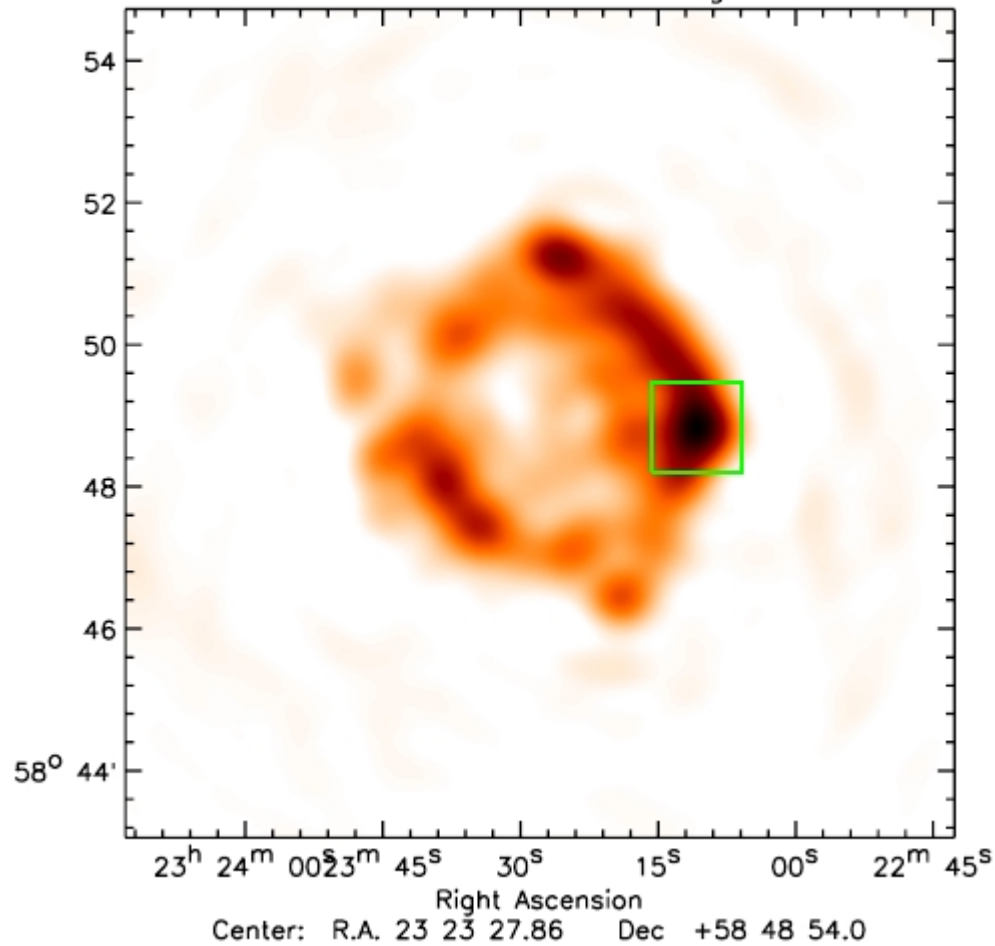
✓ Radio recombination lines

- $H40a \rightarrow \sim 100 \text{ GHz}$
- $H109a \rightarrow 5 \text{ GHz}$
- $H600a \rightarrow 30 \text{ MHz}$
- $C538a \rightarrow 42 \text{ MHz (Asgekar+2013)}$

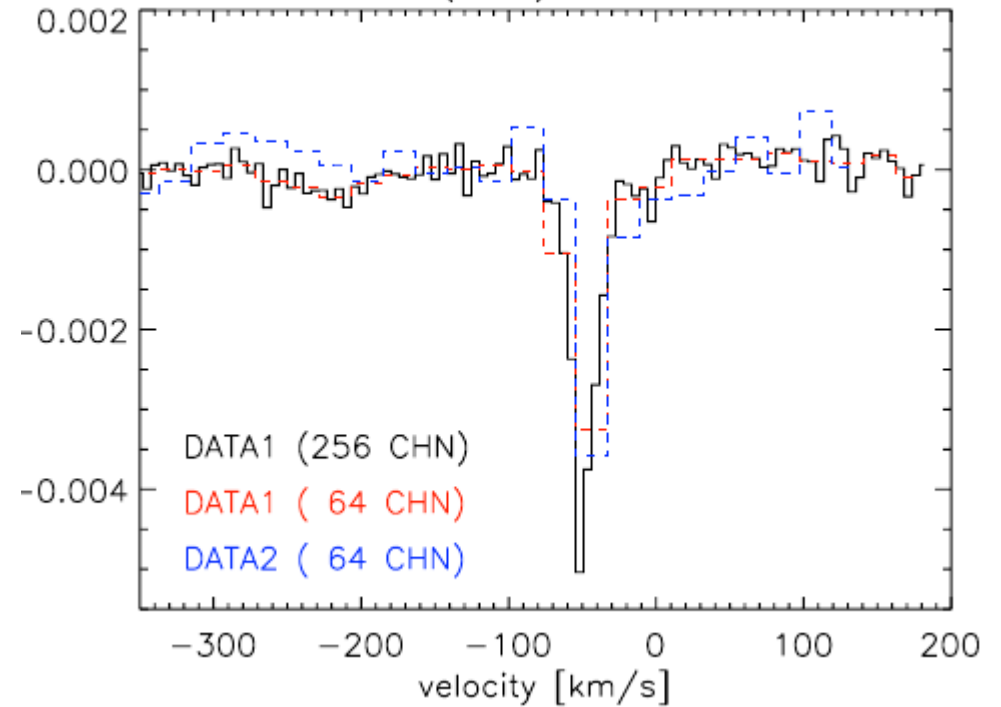


C538 RRL in absorption from Cas A using LOFAR

Cas A: Continuum Image



Cas A: C(538) COMPARISON

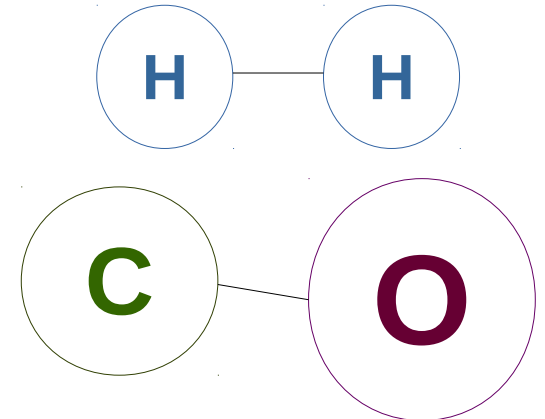


Types of spectral lines (2)

✓ 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, $A \propto \nu^3 \rightarrow$ lines more prominent at higher ν

In molecular clouds, spontaneous emission time \gg collisional time

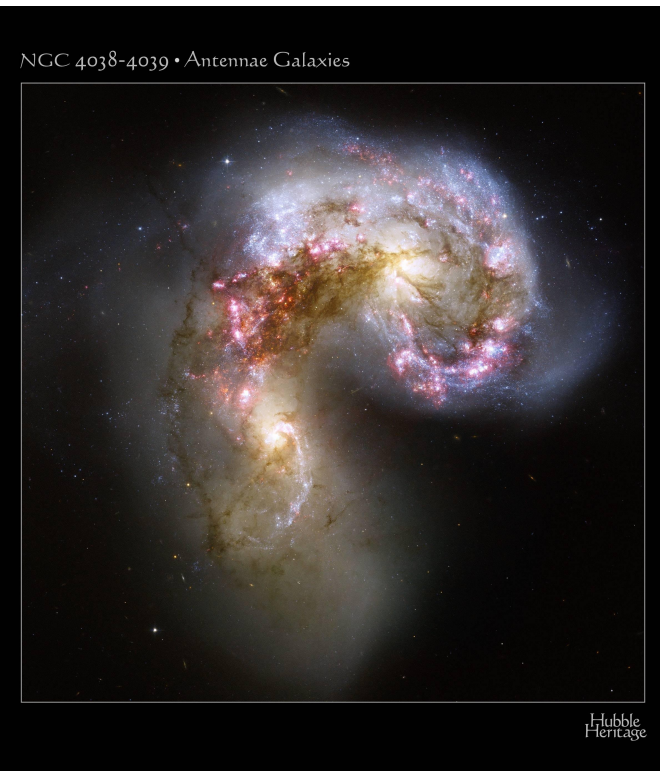
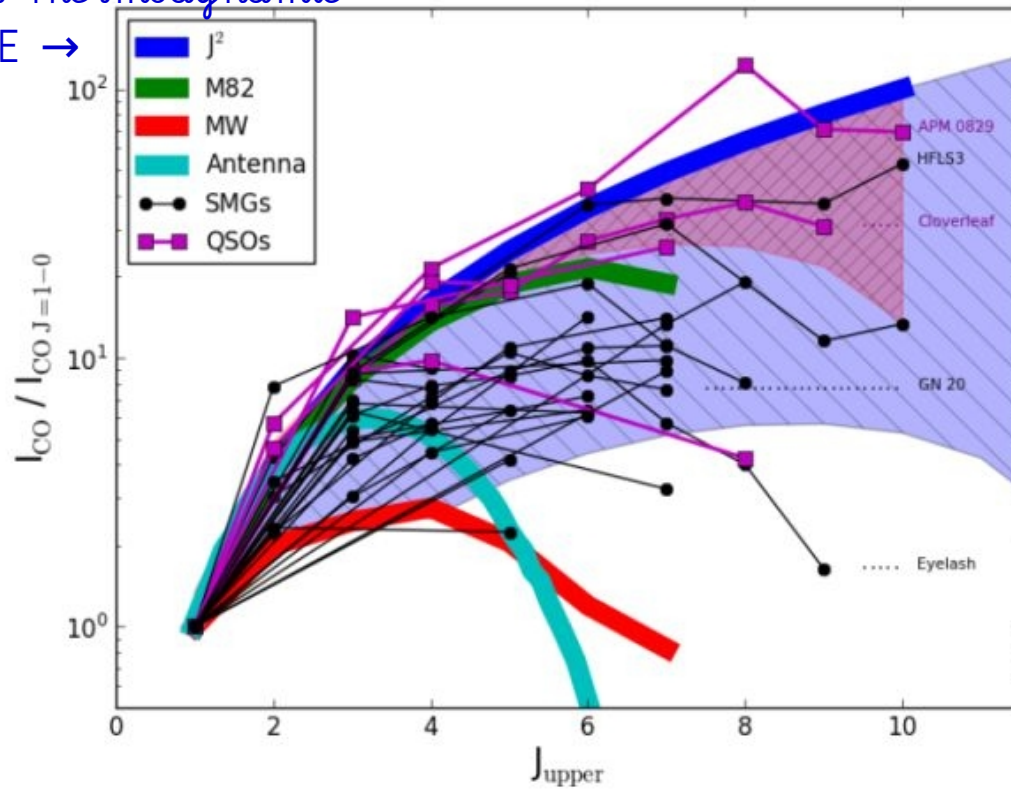
- when collisional rate equals $A \rightarrow$ critical density, $n^* \approx A/\sigma v$ *cross section σ (cm^2); v (cm s^{-1})*

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

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

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

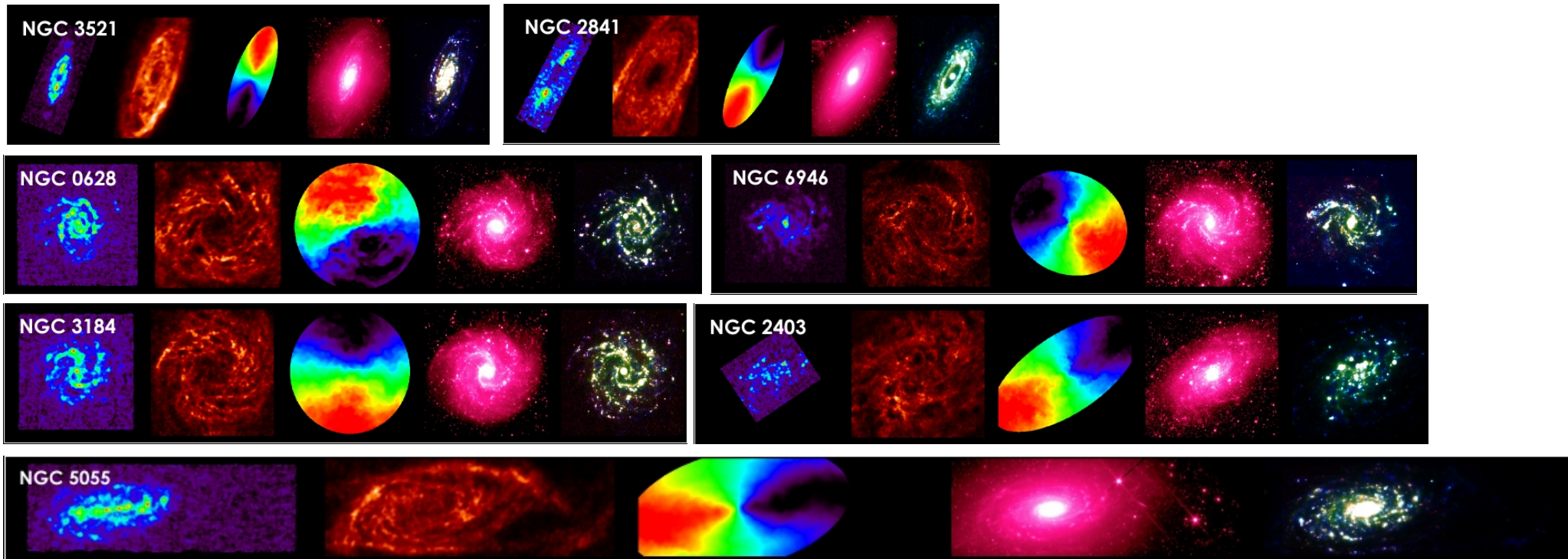
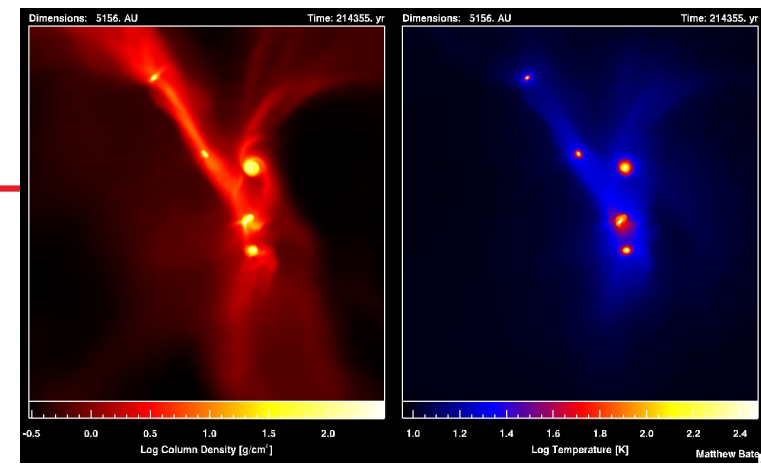
Assuming Local Thermodynamic Equilibrium, LTE \rightarrow



Casey, Narayanan & Cooray 2014

Typical location of CO

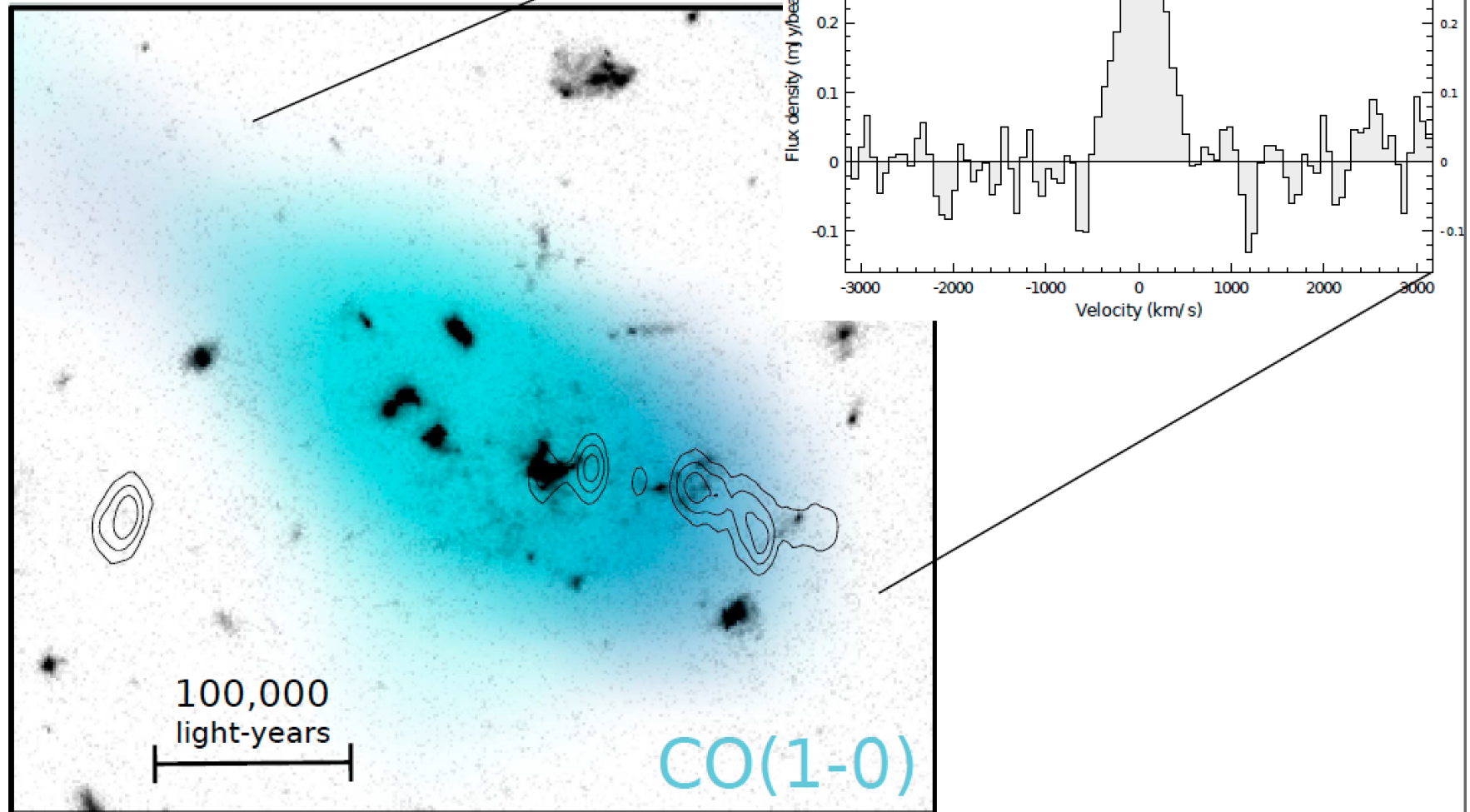
✓ Heracles survey of 18 THINGS galaxies

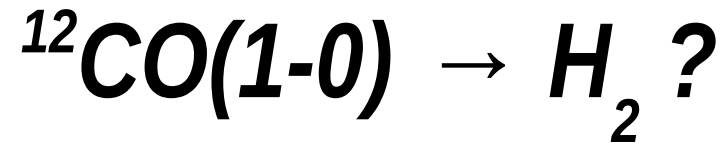


✓ CO usually found in strongly star-forming regions within optical disk

Stop Press – CO found between galaxies!

Cold gas in the Spider-web Galaxy ($z=2$)





$$N_{\text{H}_2} = X_{\text{CO}} I_{\text{CO}}$$

$$\Sigma_{\text{H}_2} = \alpha_{\text{CO}} I_{\text{CO}}$$

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

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

Types of spectral lines (3)

✓ Absorption lines

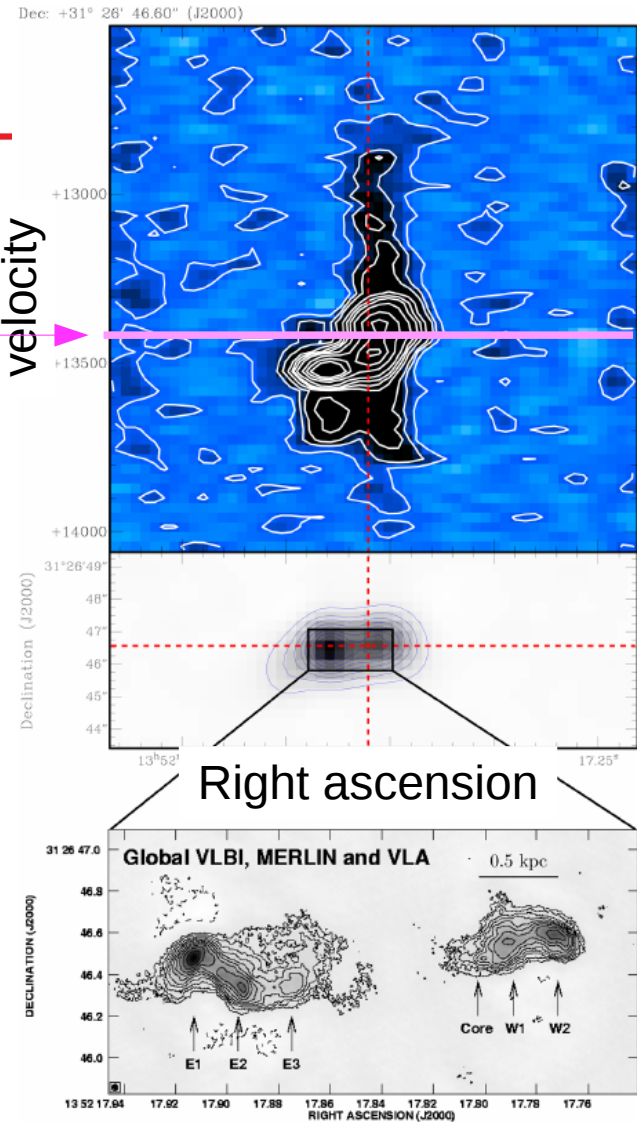
✓ against bright AGN → HI abs can be from host galaxy or intervening absorber

✓ If associated with host, this is the colder gas component

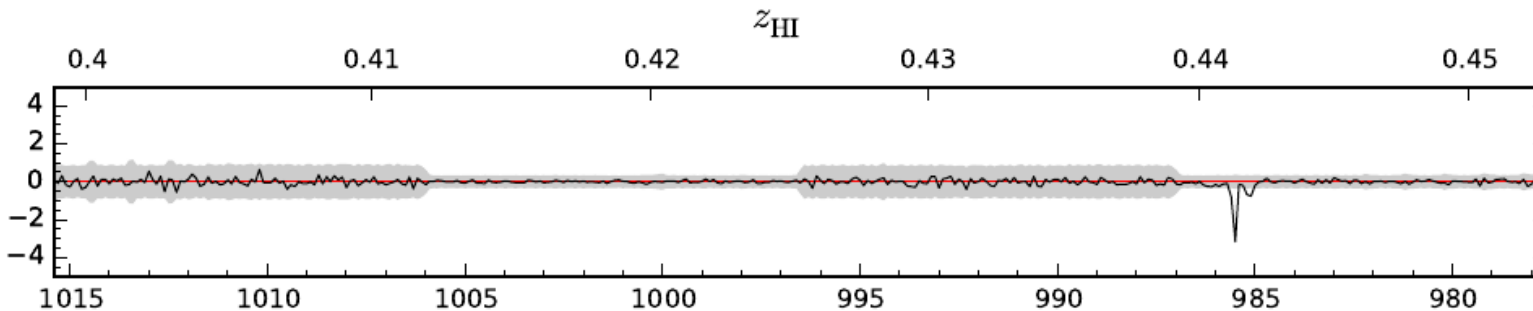
→ eg. Interaction btw radio AGN & circumnuclear ISM

systemic velocity

velocity



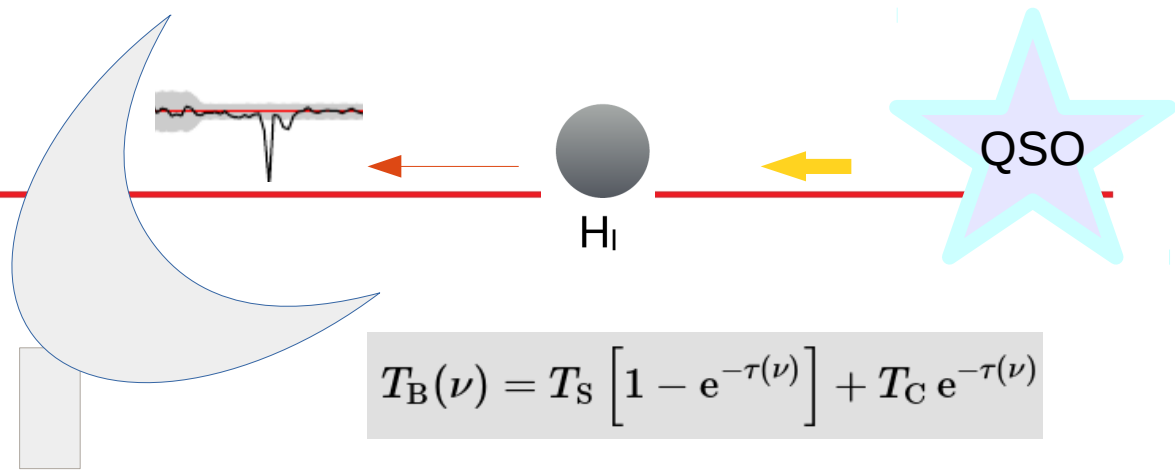
Mahony+ (2013)



Allison+ (2015)



HI absorption lines



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

$$T_B(\nu) = T_S \tau(\nu) + T_C [1 - \tau(\nu)]$$

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

$$\tau(\nu) = \frac{T_L(\nu)}{T_C - T_S}$$

Extracting column densities from optical depth:

$$N_{\text{HI}} = C T_S \int \tau(\nu) d\nu$$

for $T_S \ll T_C$

$$N_{\text{HI}} = C T_S \int \frac{T_L(\nu)}{T_C} d\nu$$

rel strength of absorption line

*** Homework: estimate N_{HI} for $z \sim 0.3$



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

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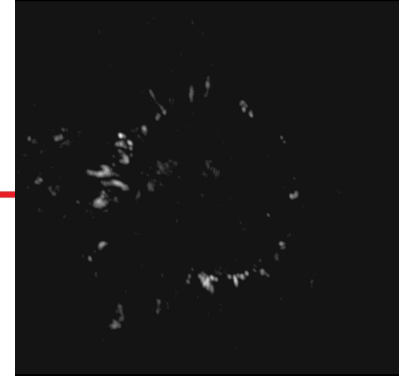
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Types of spectral lines (4)



SiO maser (TX cam)

✓ Stimulated emission

✓ Maser = Microwave Amplification by Stimulated Emission Radiation

- like lasers, involve population inversion from higher → lower levels but 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_2O maser kinematics
(Miyoshi+1995)

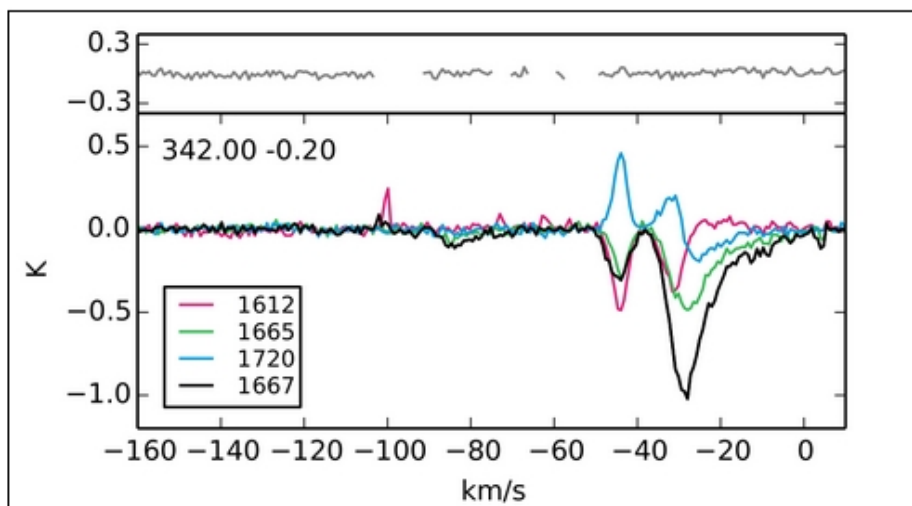


Figure 3. Example spectra showing primarily diffuse OH. The grey spectra above each panel show $[T_b(1612) + T_b(1720)] - [T_b(1667)/9.0 + T_b(1665)/5.0]$, with voxels in the vicinity of maser emission flagged out (blank ranges). The diffuse OH lines show their characteristic pattern – main-line signal 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} .

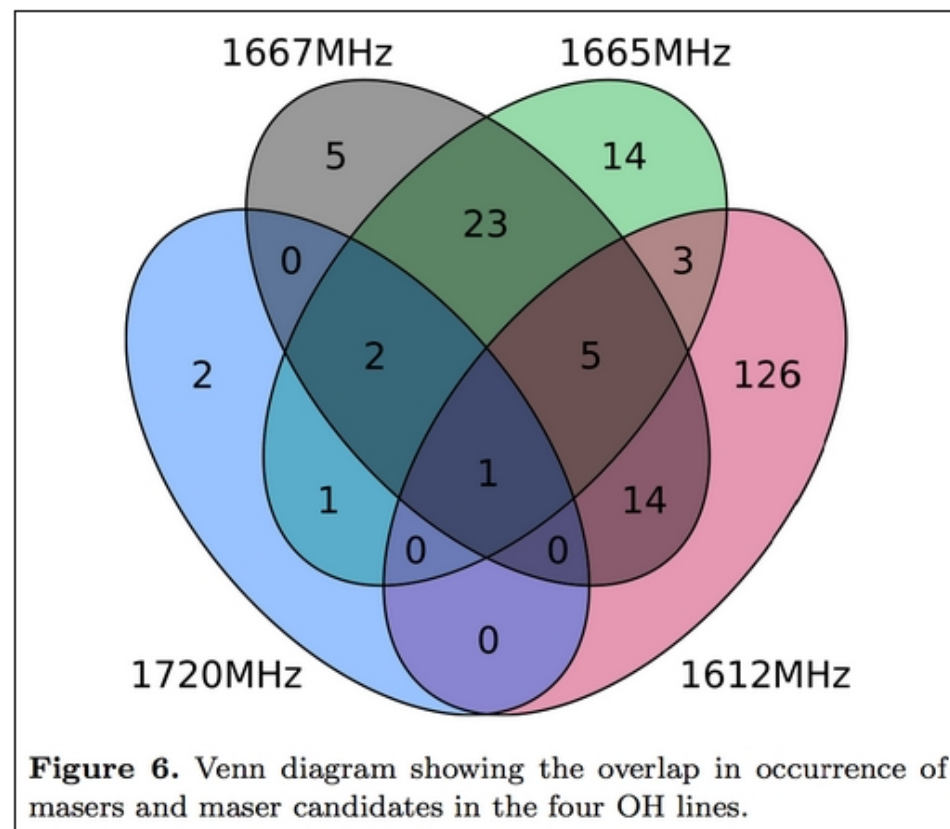
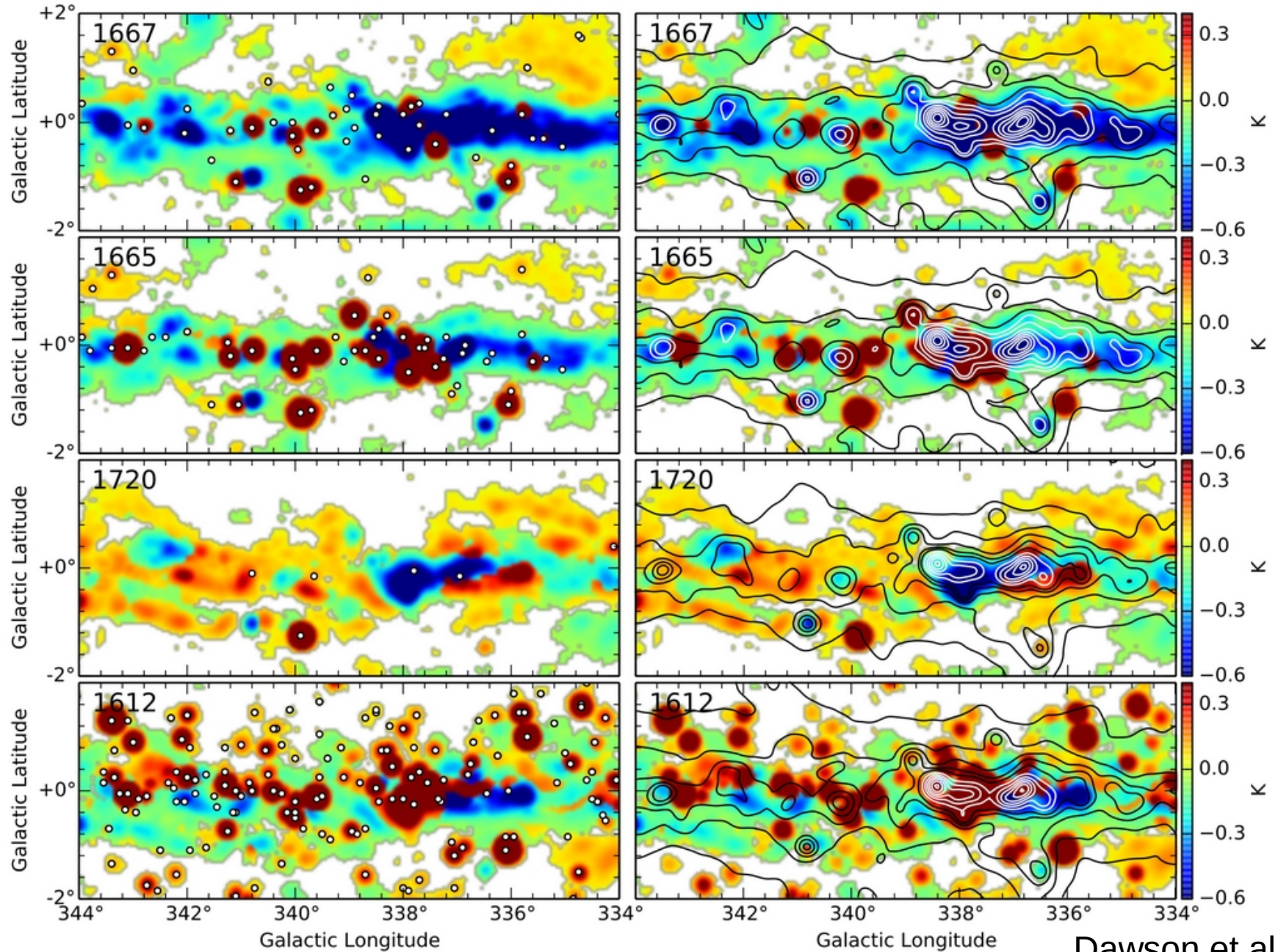


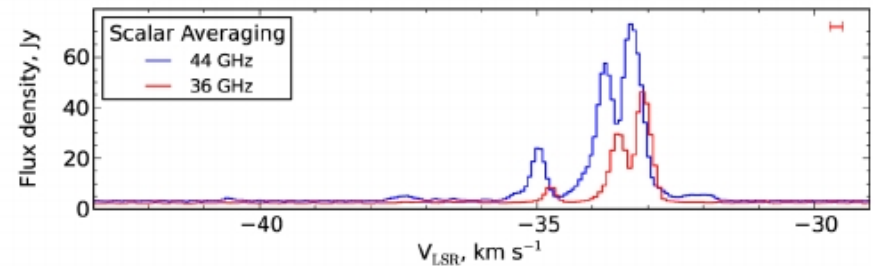
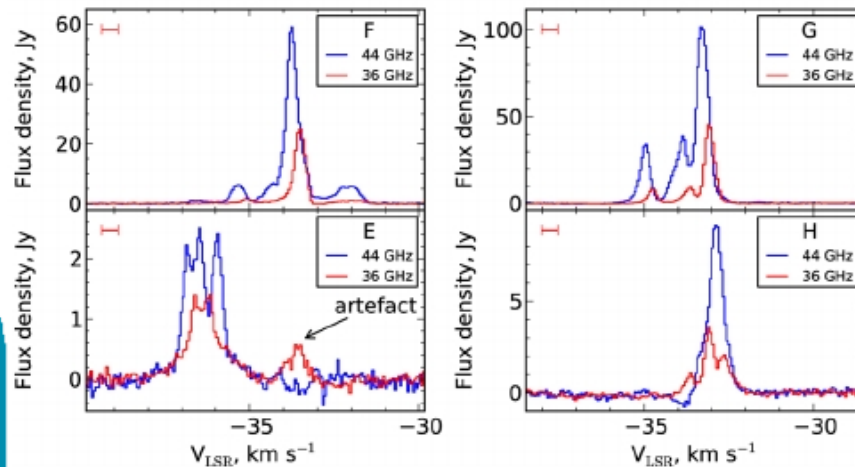
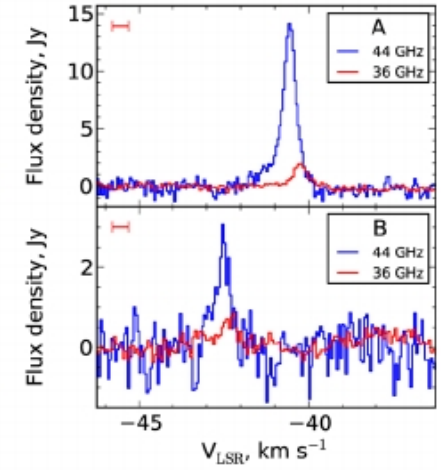
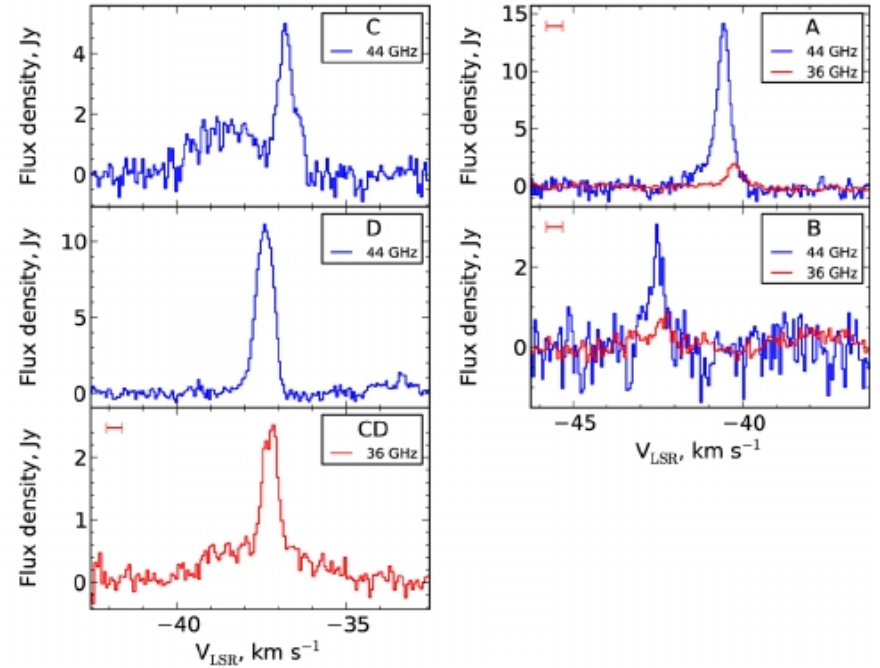
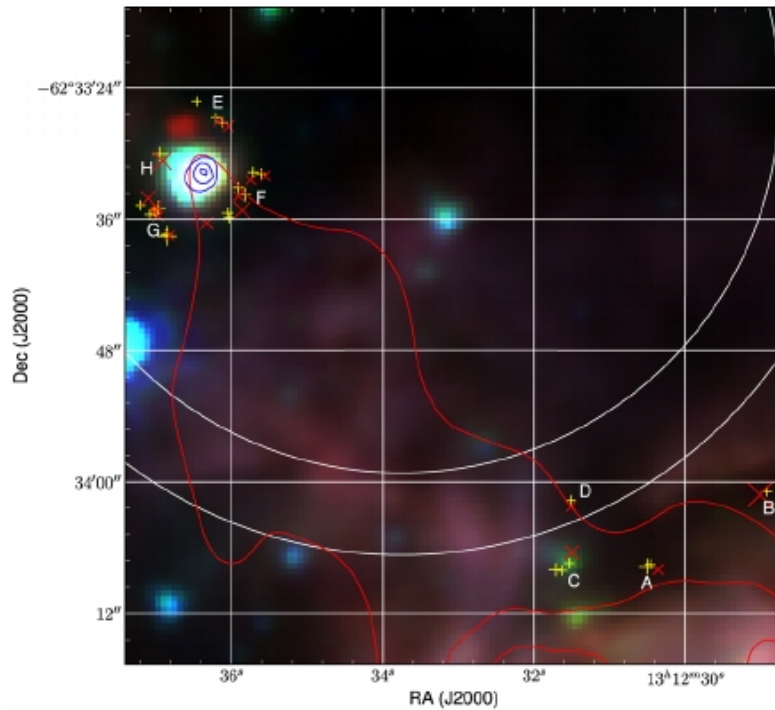
Figure 6. Venn diagram showing the overlap in occurrence of masers and maser candidates in the four OH lines.



SPLASH

The Southern Parkes Large-Area Survey in Hydroxyl



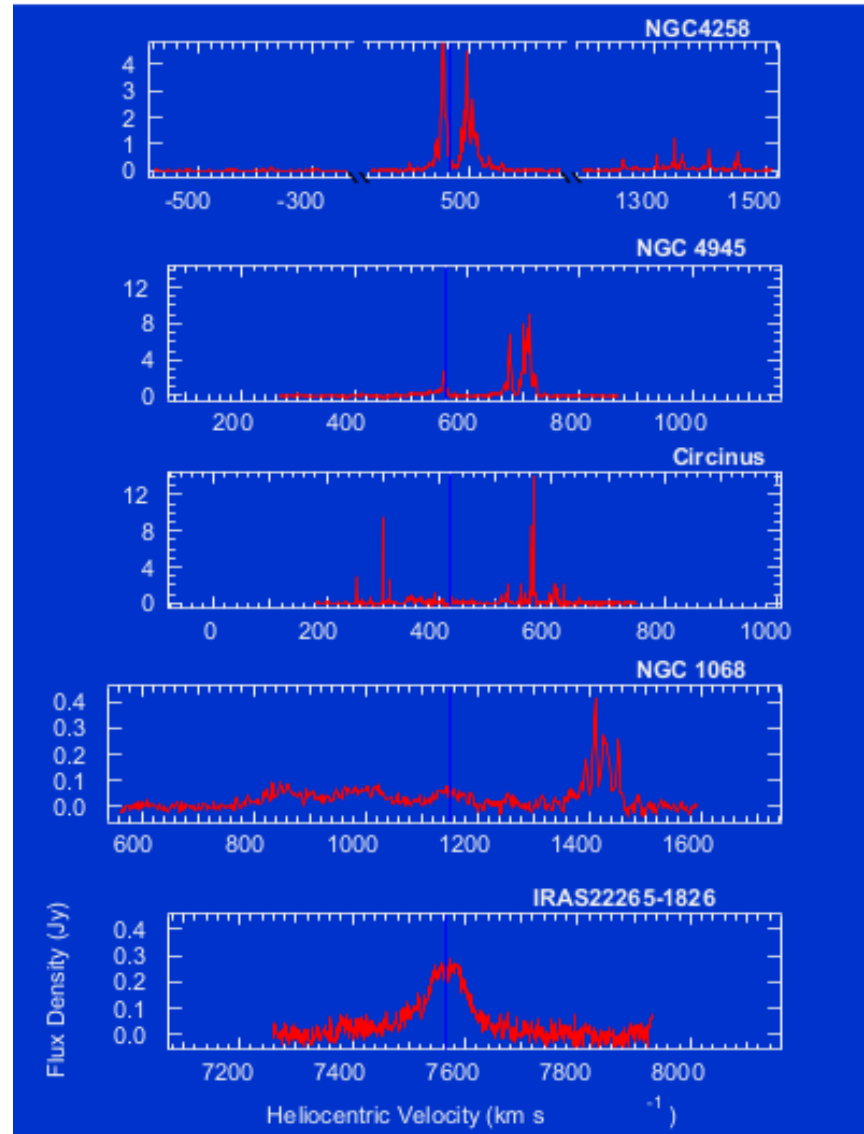


ATCA follow-up of MMB: 0.4 arcsec localisation of 71 Galactic Plane Cls 1 Methanol masers @36 & 44 GHz (Voronkov +2014)

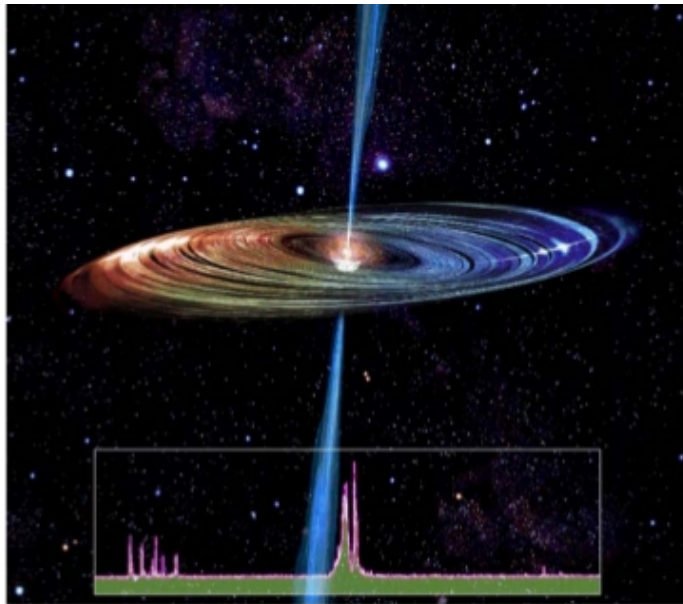
Taxonomy

Velocity symmetry,
narrow-lines dominate

Single-emission feature,
broad-hump dominates



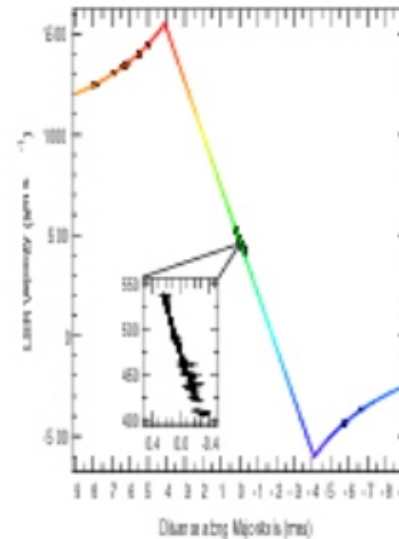
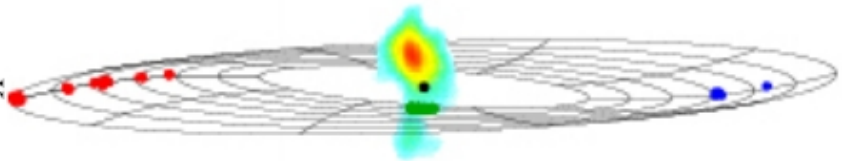
Water masers → most accurate mass estimator of SMBH



Kagoya/Inoue

NGC4258: The archetypal accretion disk maser

0.15 pc



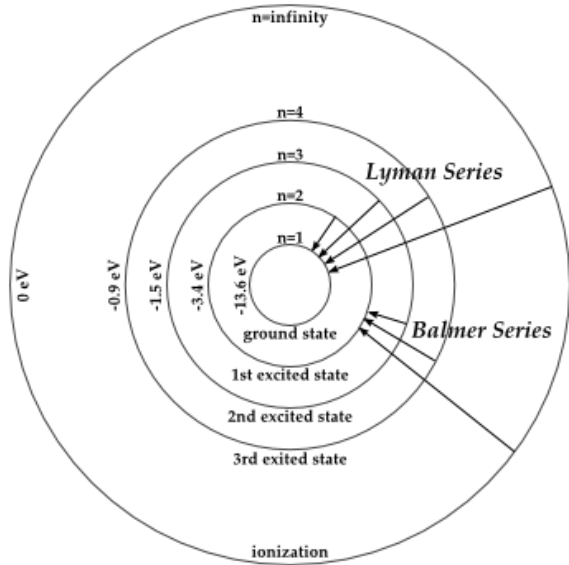
Review

- 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 × 10⁶ M_{sun}

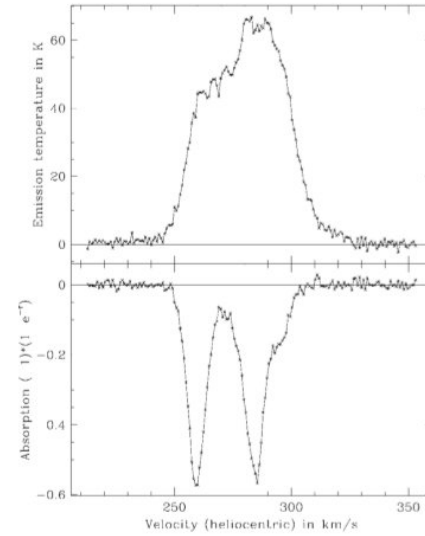
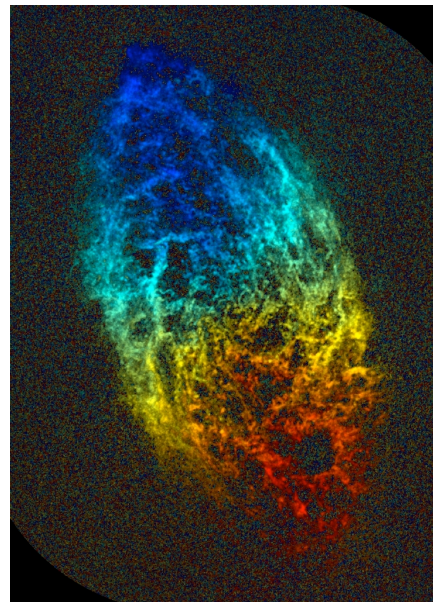
NGC 4258

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

Radio recombination lines

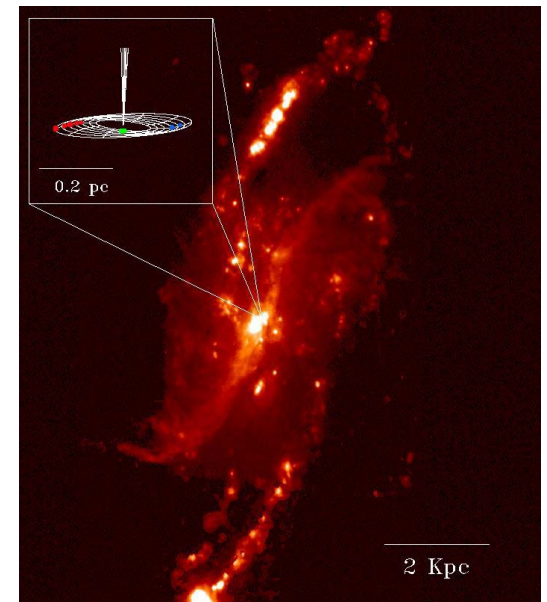
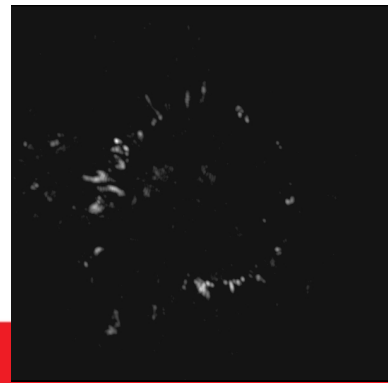
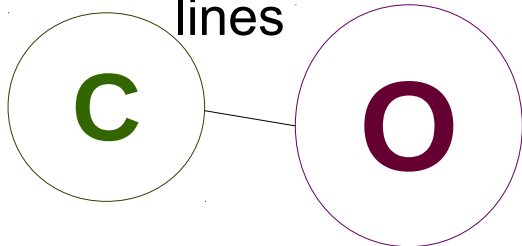


HI emission and absorption



Optical depth

Molecular lines



Masers

























ANY QUESTIONS?



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