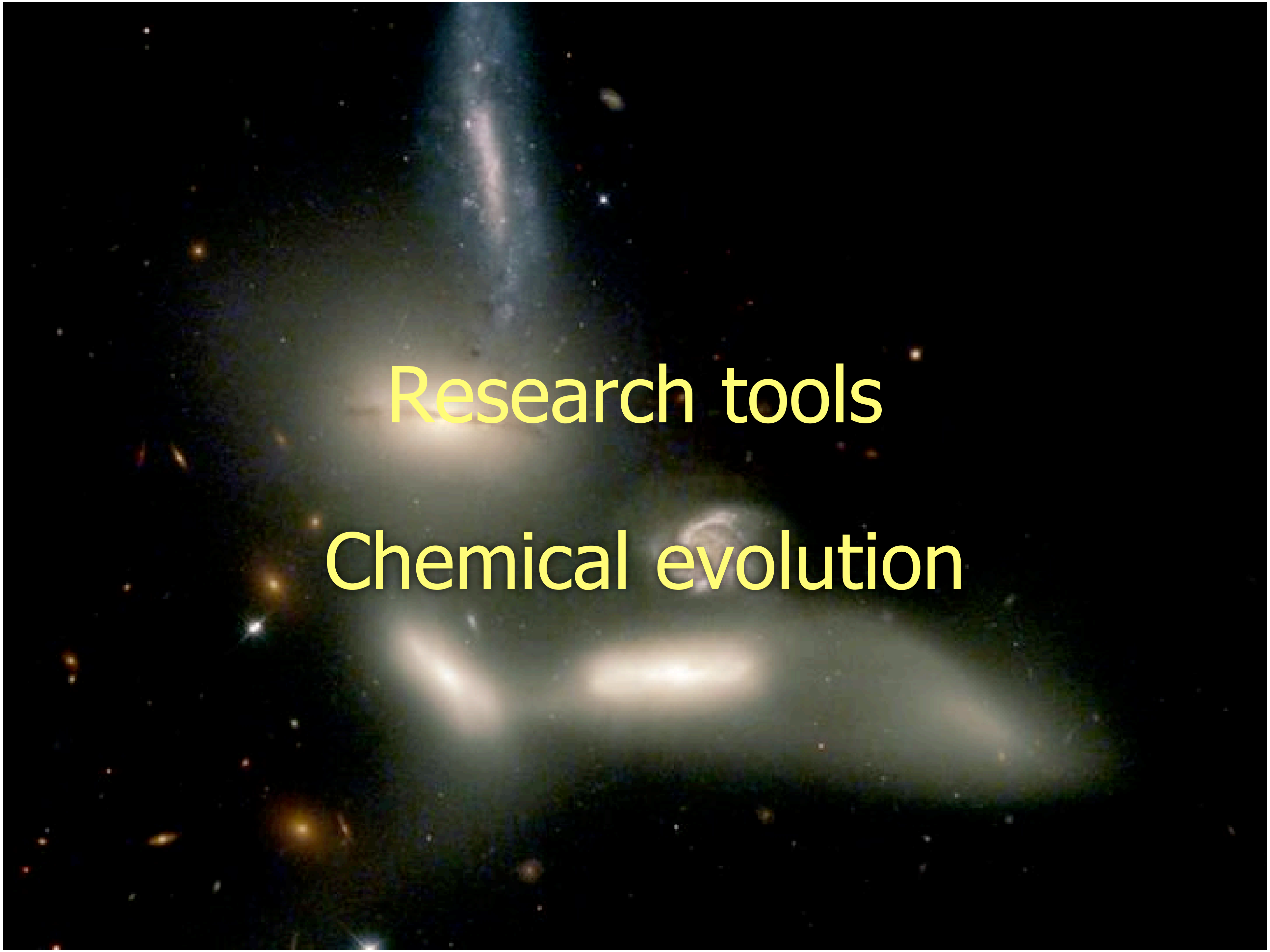

Research tools
Chemical evolution

Principles: formation

- Heavy elements made in nucleosynthesis
  - Most He made in Big Bang, otherwise all made as part of stellar evolution
  - Nucleosynthesis in stars (typically lighter elements)
  - S-process elements (slow addition of neutrons; made in AGB stars - pre-planetary nebula)
  - Supernovae products
    - Alpha elements (so-called because they're multiples of alpha particles/Helium nuclei)
    - R-process (rapid addition of neutrons)

- Pagel (1997) an excellent introduction…

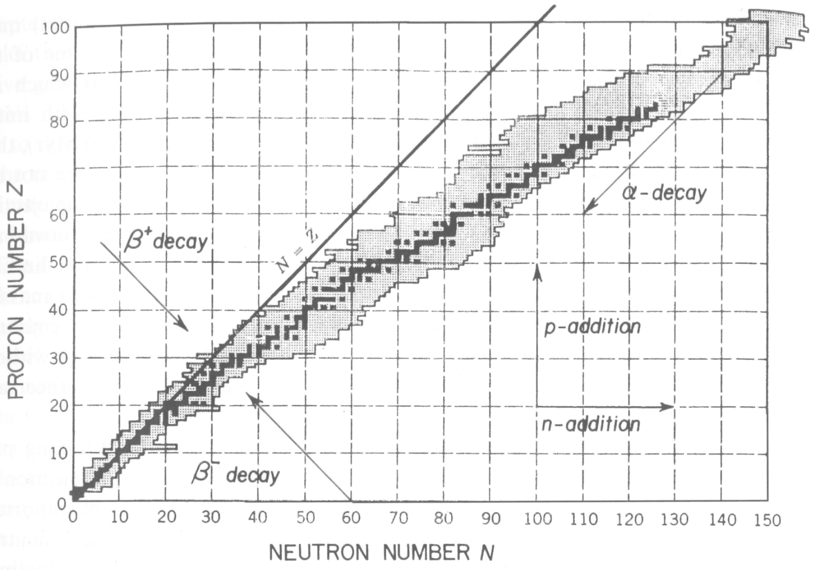


Fig. 1.2. Chart of the nuclides, in which Z is plotted against N. Stable nuclei are shown in dark shading and known radioactive nuclei in light shading. Arrows indicate directions of some simple nuclear transformations. After K.S. Krane, *Introductory Nuclear Physics*, ©1988 by John Wiley & Sons. Reproduced by permission of John Wiley & Sons, Inc.

nucleus outside the valley undergoes spontaneous decays, while in accelerators, stars and the early universe nuclei are transformed into one another by various reactions.

(2) The binding energy per nucleon varies with A along the stability valley as shown in Fig. 1.3, and this has the following consequences:

(a) Since the maximum binding energy per nucleon is possessed by ^{62}Ni, followed closely by ^{56}Fe, energy is released by either fission of heavier or fusion of lighter nuclei. The latter process is the main source of stellar energy, with the biggest contribution (7 MeV per nucleon) coming from the conversion of hydrogen into helium (H-burning).

(b) Some nuclei are more stable than others, e.g. the α-particle nuclei ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca. Nuclei with a couple of A-values (5 and 8) are violently unstable, owing to the nearby helium peak. Others are stable but only just: examples are D, ^{6,7}Li, ^{9}Be and ^{10,11}B, which are destroyed by thermonuclear reactions at relatively low temperatures.

(3) Nuclear reactions involving charged particles (p, α etc.) require them to have enough kinetic energy to get through in spite of the electrostatic repulsion of the

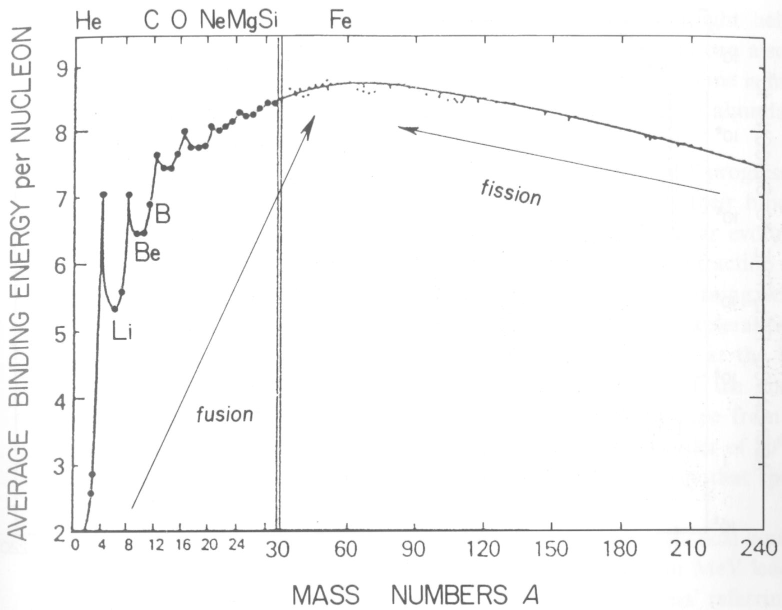


Fig. 1.3. Binding energy per nucleon as a function of mass number. Adapted from Rolfs & Rodney (1988).

target nucleus (the 'Coulomb barrier'); the greater the charges, the greater the energy required. In the laboratory, the energy is supplied by accelerators, and analogous processes are believed to occur in reactions induced in the ISM by cosmic rays (see Chapter 9). In the interiors of stars, the kinetic energy exists by virtue of high temperatures (leading to *thermonuclear* reactions) and when one fuel (e.g. hydrogen) runs out, the star contracts and becomes hotter, eventually allowing a more highly charged fuel such as helium to 'burn'.

There is no Coulomb barrier for neutrons, but free neutrons are unstable so that they have to be generated *in situ*, which again demands high temperatures.

1.3 The local abundance distribution

Fig. 1.4 shows the 'local galactic' abundances of isobars, based on a combination of elemental and isotopic determinations in the Solar System with data from nearby stars and emission nebulae. These are sometimes referred to as 'cosmic abundances', but because there are significant variations among stars and between and across galaxies this term is best avoided. The curve shows a number of features that give clues to the origin of the various elements:

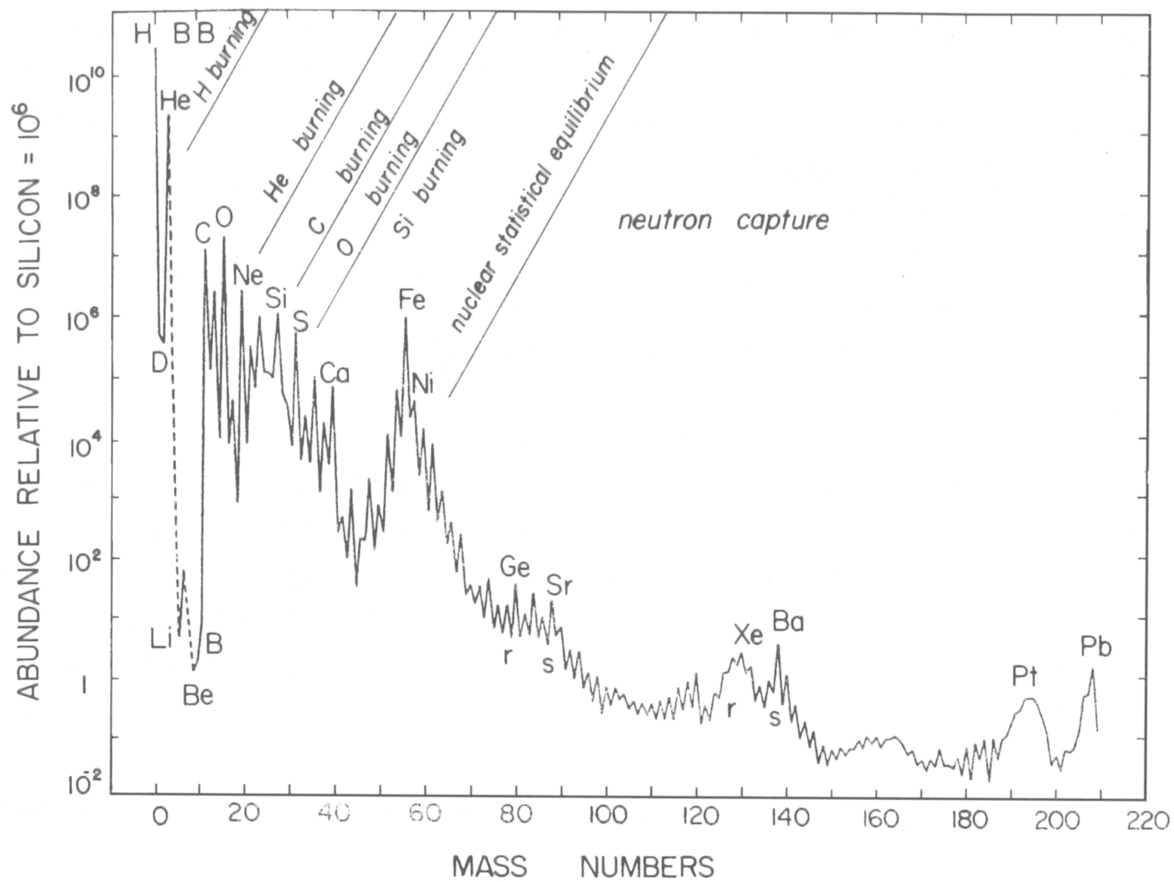
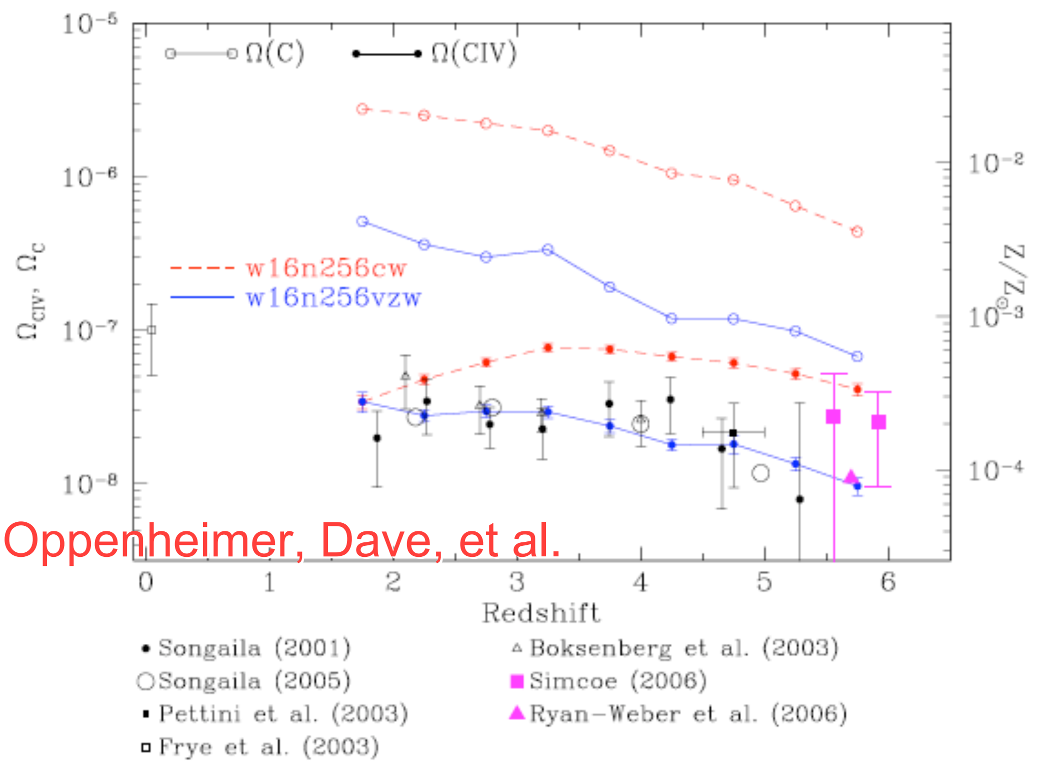


Fig. 1.4. The 'local galactic' abundance distribution of nuclear species, normalised to 10^6 ^{28}Si atoms, adapted from Cameron (1982).

Principles: redistribution

- Supernovae and stellar winds - redistributes these metals and can drive galactic winds….



Approximation : IRA

- Instantaneous Recycling approximation
  - Because much of enrichment is prompt (with enrichment timescale << Hubble time) can assume it happens instantaneously
    - Makes math simpler (tractable)
    - OKish for alpha elements
    - BAD for Iron, CNO, heavy elements

IRA world…

- dM_{met} = (y-Z)*SFR(1-R) - [metals in outflow] + [metals in infall]
- dM_{gas} = -SFR(1-R) - outflow + infall
- dM* = SFR(1-R)
- Z = Mmet/Mgas

- Here y=yield, R=recycled fraction (fraction of mass that was in stars that ends up back in the ISM)

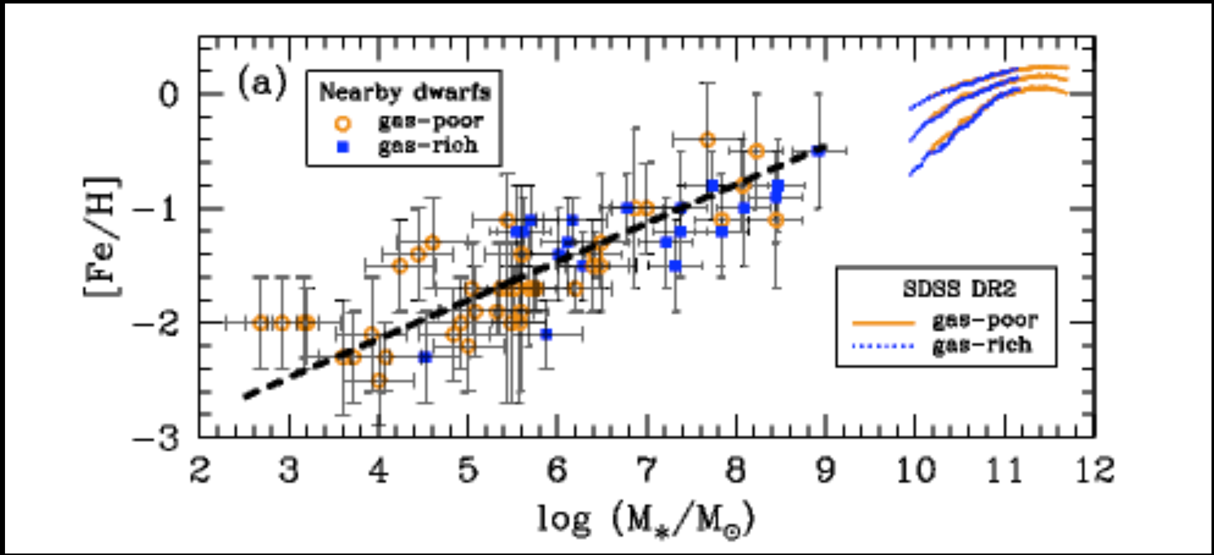
A closed box

- CLOSED BOX - no metals or gas in or out, full mixing in box
- Then
  - dg = -ds — gas conversion from astration
  - $g\ dZ/ds = -g\ dZ/dg = y_{true}$ — yield
  - Therefore, $Z = y_{true} \ln M/g = y_{true} \ln(1/f_{gas})$
- Can define $y_{eff} = Z/\ln(1/f_{gas})$

Yield that a system would have to get a metallicity at a given f_{gas}

Some key results

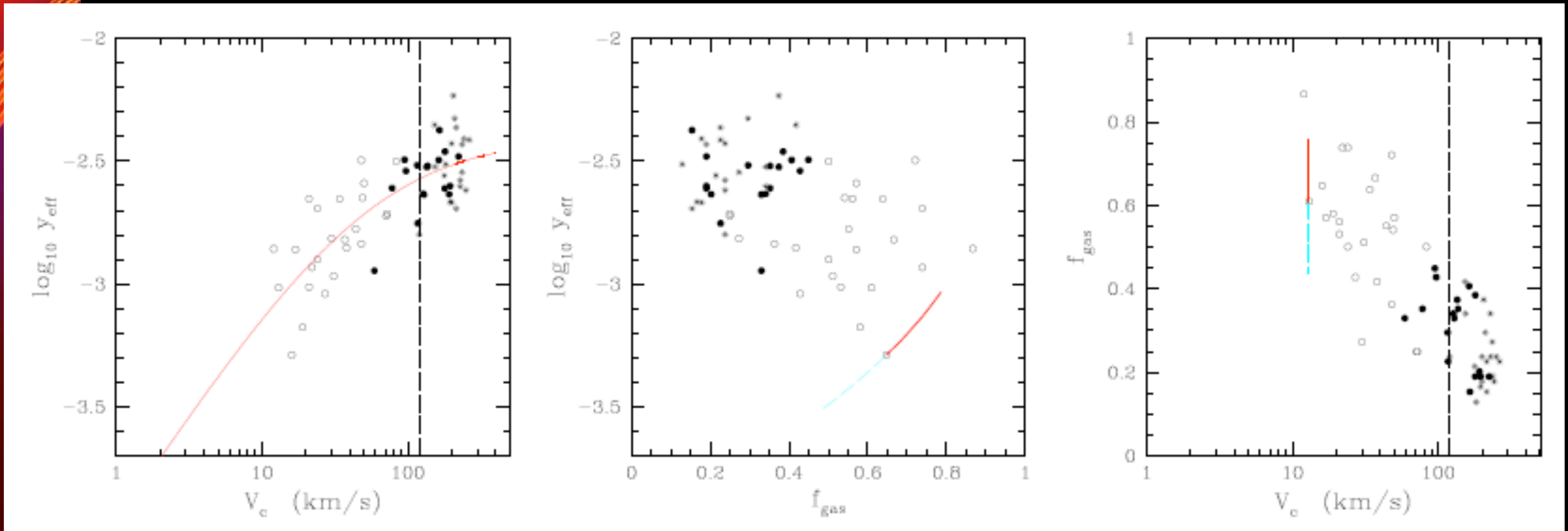
Lee, Bell, Somerville 2008



- Metallicity-mass relation
- Same for gas-rich and gas-poor galaxies
  - Can go from one to the other by just losing gas…

Key results II

- Metal-enriched outflows are ~only way of driving down yeff, but only in systems with a lot of gas…
- Main driver or metal-mass relation is low SFE, modulated by metal-enriched outflows.



Dalcanton 2007

Relative abundances as a cosmic clock…

- One of the key diagnostics of timescales of galaxy evolution is relative abundances
  - Alpha/Fe, N/O, etc…

Schiavon 2006

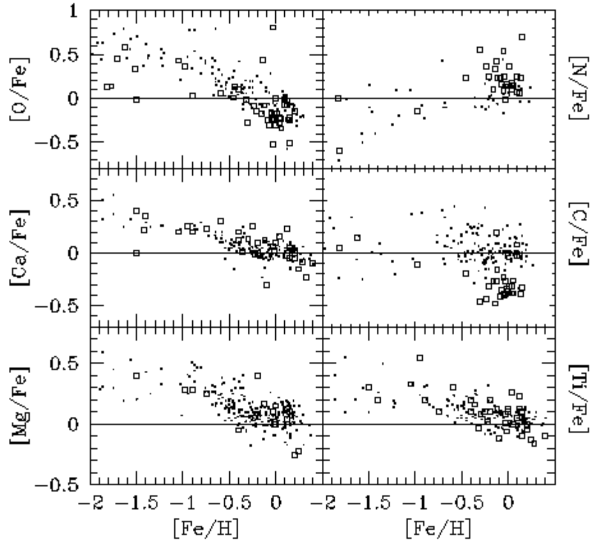


Fig. 3.— Abundance pattern of the input stellar library. Dwarfs and giants are marked by small dots and open squares, respectively.

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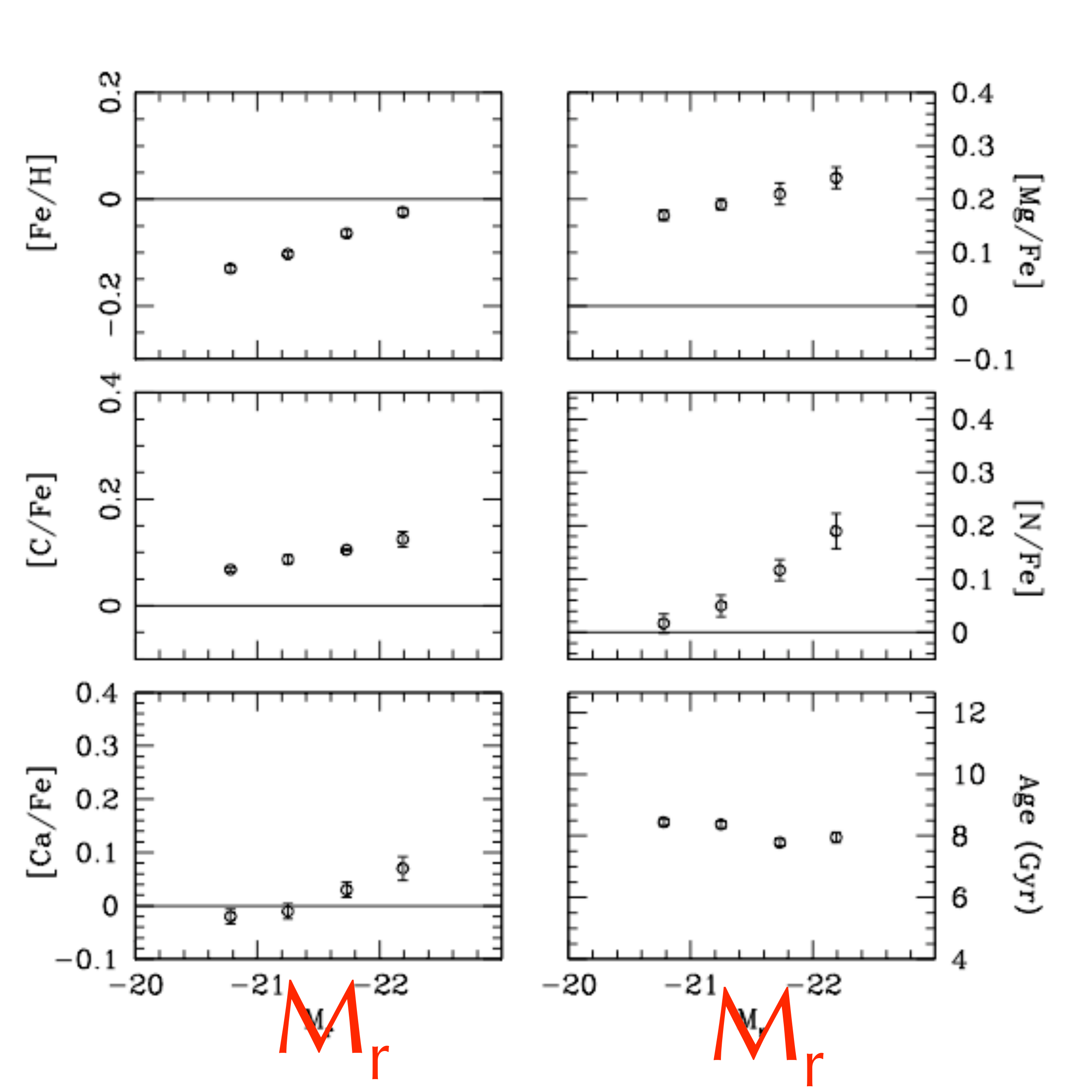
Abundance Pattern

Schiavon 2006



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Summary I

- Chemical Evolution
  - 'garbage' of stellar evolution,
  - does not go away (so valuable diagnostic),
  - but does get moved around (so not trivial to interpret)
  - Different origins of elements --> diverse chemical clocks (alpha elements, Iron, nitrogen, R-process, S-process) which need to be used with care
  - Key result : metallicity--mass relation, supports interpretation of this relation as evolutionary clock
  - Feedback : metals spread all over the intergalactic medium, so we know they get blown out, just where and when?


Research tools
Diagnostics of atomic and molecular ISM
Ionized gas and SFR calibrations

Gas

- Almost information from gas comes from emission lines…
  - As e^- fall through energy levels --> recombination radiation (radio through to optical/UV/X-ray)
  - Forbidden lines (long transition times, e.g., ~hours), denoted by [OIII]
  - Fine structure lines - coupling between the spin and orbital ang. Mom of an e^-
    - $1/137^2$ times as large as between main levels (~FIR), e.g., OI at 63 and 145um, CII at 158um are hugely important cooling lines (why sodium D is a doublet)…

Gas (cont)

- Hyperfine transitions
  - Nuclear spin and e- spin (2000x smaller still)
  - HI when flips from parallel to antiparallel, 21cm radiation, timescale ~10Myr
- Molecules
  - Vibrational transitions (few um for common molecules e.g., HCN, CO, CS)
  - Rotational transitions (mm regime), excited by collisions with H_2 molecules (e.g., CO at 1.3 and 2.6mm CO1-0; excited at $n(H_2) \sim 10^3 cm^{-3}$ and T~10-20K for excitation); higher transitions need larger densities / higher temperatures

Gas (cont)

- Larger dipole moments
  - Faster decays back to ground state, and denser gas reqd. to cause emission.
    - E.g., ammonia, HCN, CS (10,100,1000x denser than CO), SiO requires densities higher still
- Symmetric molecules
  - E.g., H_2, rotational transitions 137^2 times slower (least energetic transition is at 20um, only shocked gas at T~1000K can emit at all)
  - Absorption lines in the UV, need an absorber…

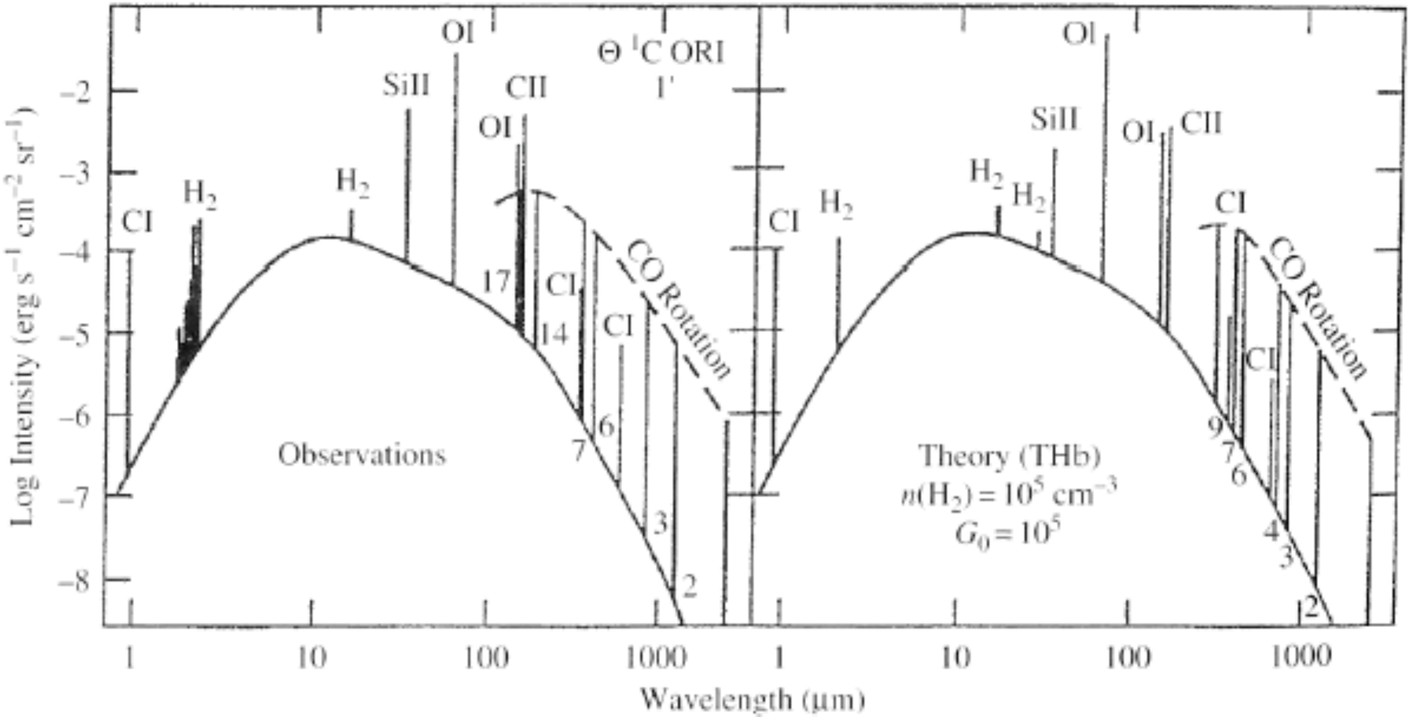
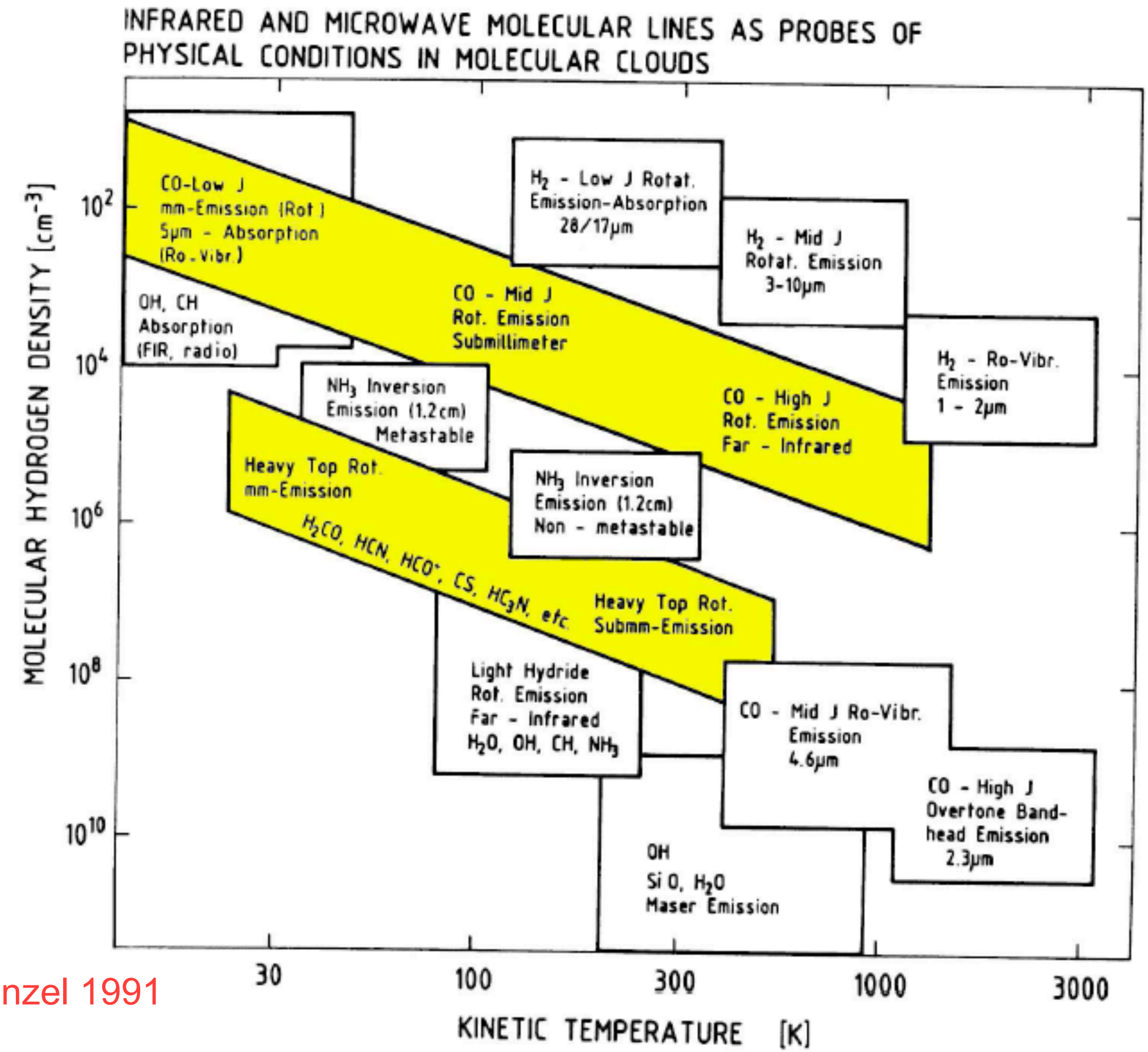


Figure 1.2: Observed IR spectrum (*left*) and model calculations (*right*) for Orion, a dense, star-forming region (Hollenbach & Tielens 1999). The most prominent emission lines are those of CO, C I, C II, and O I, responsible for the cooling of the neutral atomic and molecular ISM.



Genzel 1991

ell

^{12}CO lower dens

^{13}CO, CS, HCN traces progressively denser phases

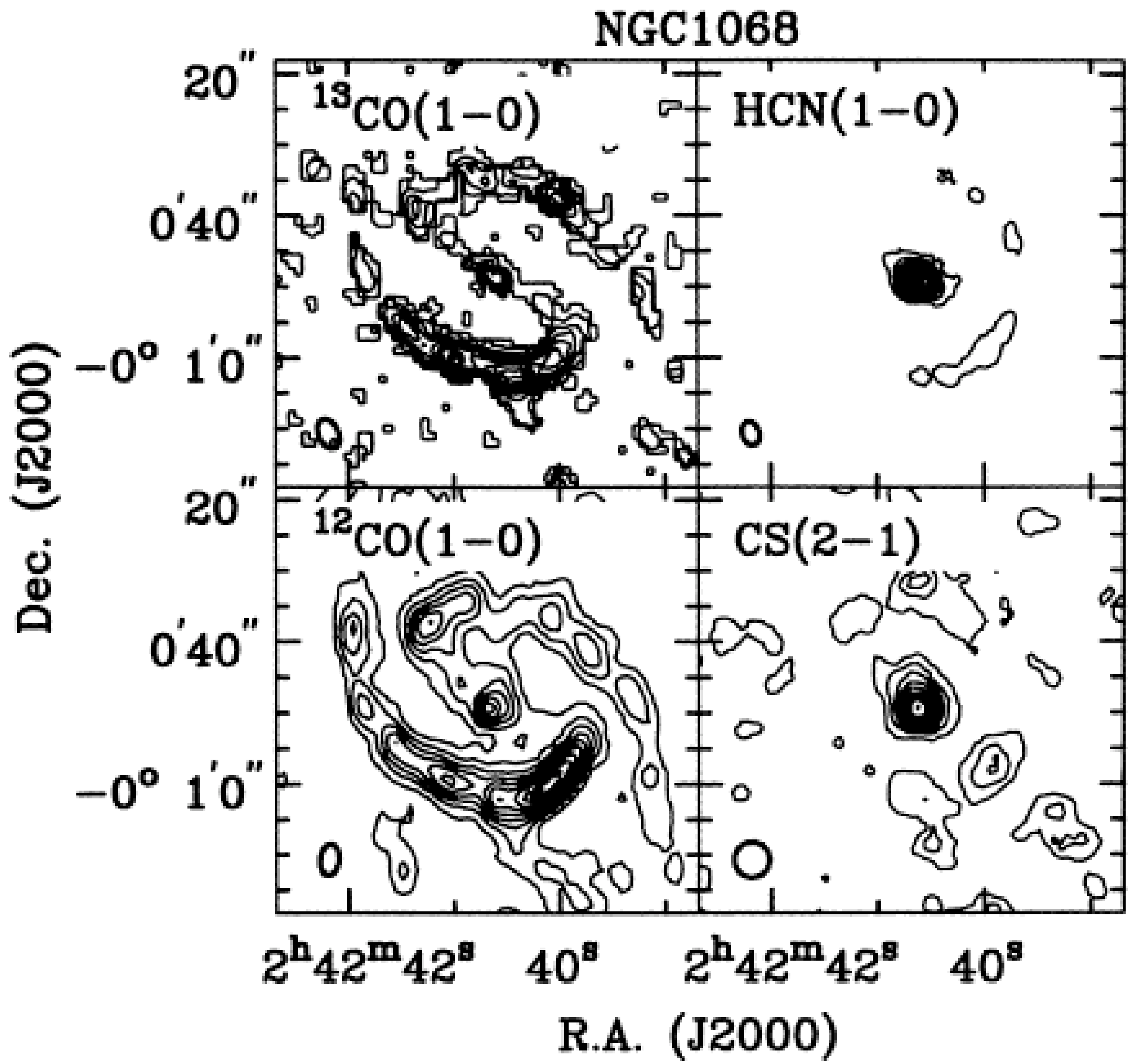


Figure 4. ^{12}CO 1–0 (left, 4″ resolution) and HCN 1–0 (right, 2″.5 resolution) mm-interferometer maps of NGC 1068, taken with the Plateau de Bure mm-interferometer (Tacconi et al. 1994, 1996).

How does one turn that into H_2 mass?

- Virial estimator
  - Gravitational mass of cloud from sigma^2 r vs. luminosity in CO, CS, HCN, etc…
  - Have to have confidence that you're looking at an area where sigma^2 and r reflect just support of one cloud
- Dust-to-gas method
  - Calibrate HI to dust mass ratio (dust mass from long wavelength emission).
  - Assume that H_2 to dust mass ratio same as HI / dust ratio
  - Then can use dust mass to estimate H_2 mass in that region, then calibrate CO-to-H_2 ratio…
- Gamma Rays from protons interacting with cosmic rays…
  - Proton to CO ratio --> CO-->H_2…

HI and H_2 (from CO)

- $M_{HI} = 2.36 \times 10^5 D^2(Mpc) \int S(Jy)dv(kms^{-1})$
- $M_{mol} = 1.61 \times 10^4 D^2(Mpc) S_{co}$ Wilson & Scoville 90
- Often CO is given as a surface brightness (in Kelvins), and one needs to integrate over the beamsize oneself or integrate over the galaxy (if larger than the beam)

5. DISCUSSION

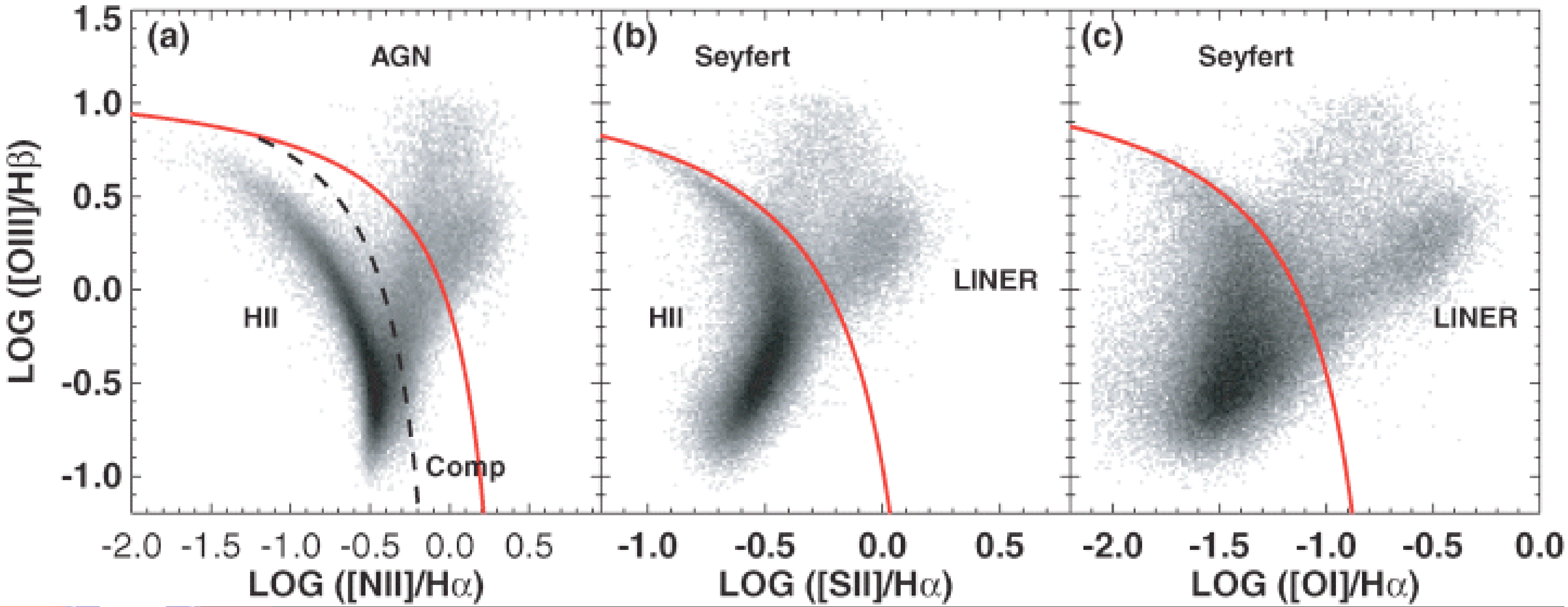
We estimate the total mass of molecular hydrogen within the 55″ telescope beam (Table 3) from

$$M_{H_2} = 4.78[\pi/(4 \ln 2) I_{CO} d_b^2]\epsilon^{-1} \ (M_\odot), \qquad (2)$$

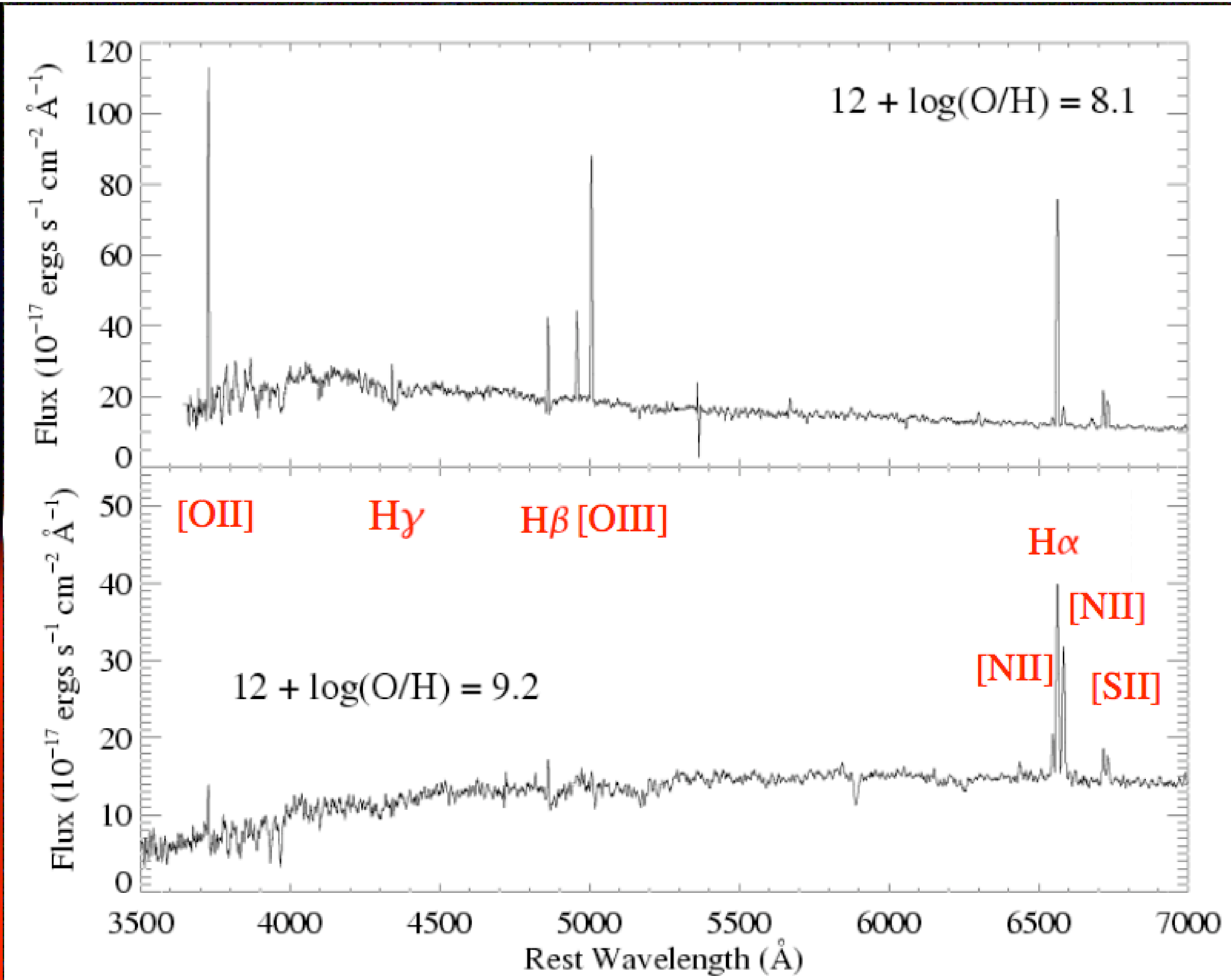
where I_{CO} is the integrated CO line flux in units of K km s^{-1} (T_R^* scale), d_b^2 is the telescope beam diameter in units of parsecs at the distance of the galaxy, and ε is the main-beam efficiency of the telescope (0.84 at 115.3 GHz for the 12 m telescope as of 2000 January). This formula assumes a Gaussian beam and a standard Galactic value of the CO-to-H_2 conversion factor $X = N(H_2)/\int T(CO)dV = 3.0 \times 10^{20}$ cm^{-2} (K km $s^{-1})^{-1}$, [where $T(CO) = T_R^*/\epsilon$; e.g., Young & Scoville 1991], which is applicable to molecular clouds at virial equilibrium. For galaxies where data were obtained at off-center pointings, the total H_2 mass was estimated by summing the individual spectra according to equation (3) of Sage (1993a).

Ionised gas

- Ionised gas
  - Low-energy lines (<few keV) from SF
  - Higher-excitation lines (>10 keV) collisions and AGN



Kewley et al. 2006

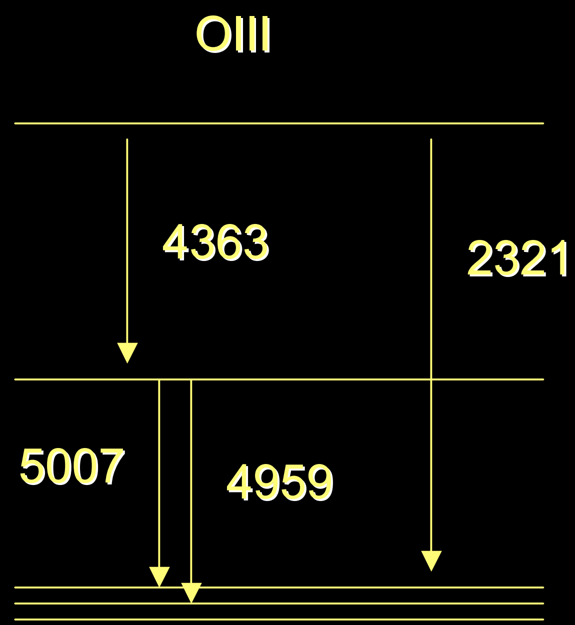

12 + log(O/H) = 8.1
12 + log(O/H) = 9.2
[OII]
Hγ
Hβ [OIII]
Hα
[NII]
[NII]
[SII]
Flux (10^{-17} ergs s^{-1} cm^{-2} $Å^{-1}$)
Rest Wavelength (Å)

Overview of methods

- Physical parameters from
  - Effective temperature method
    - Have different lines from same species, allows estimate of electron temperature and number density, so can model HII region directly
  - Photoionization model
    - Lack this information, use strong lines + a model of how stars ionize and HII regions work to figure out metallicity + ionization

Electron temperature

Ratio of 4363
to 4959+5007
gives a measure
of electron temperature



4959+5007 / 4363 =

$$7.73\ e^{33000/T} / (1 + 0.00045\ N_e/\mathrm{sqrt}(T))$$

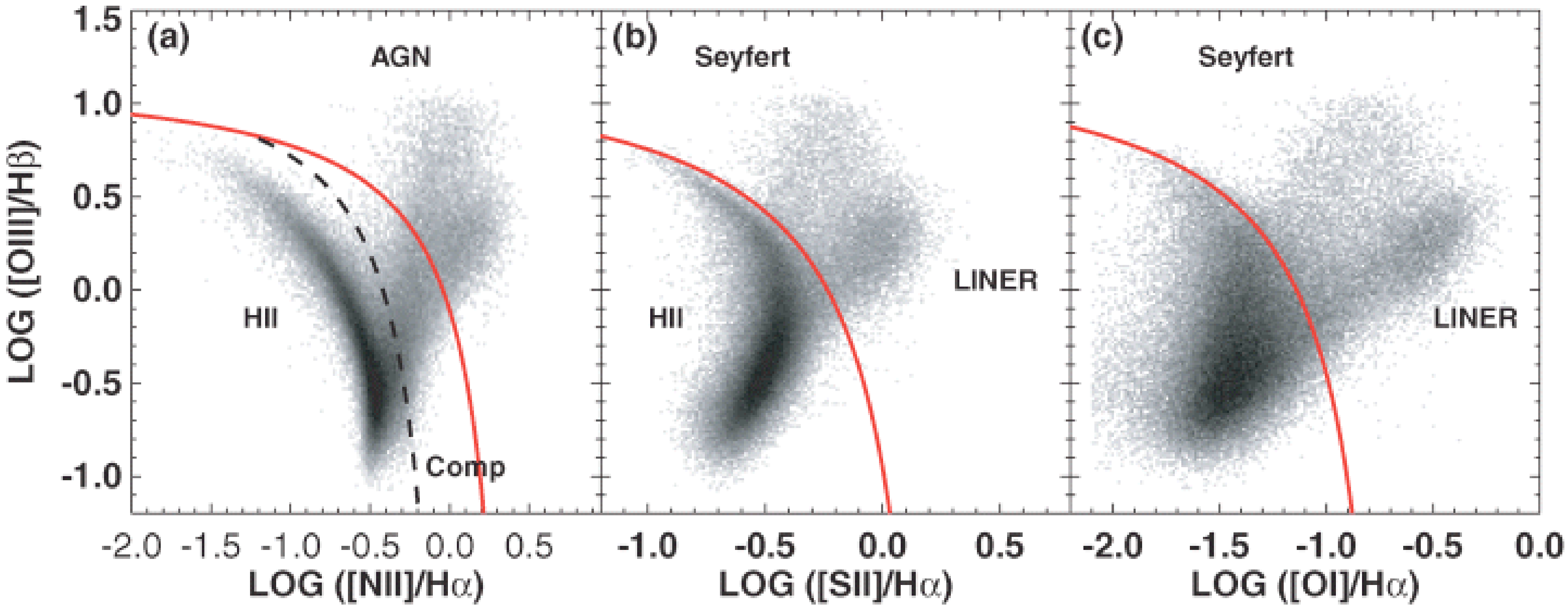
Gas conditions, continued

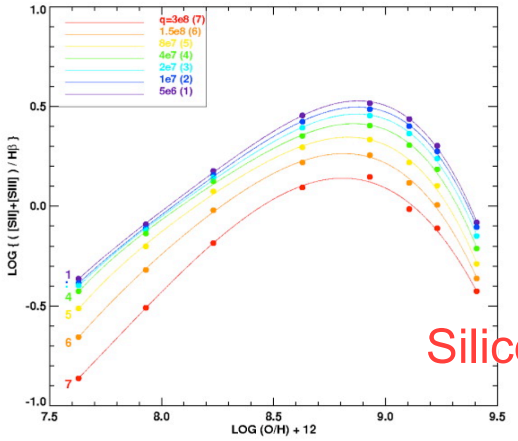
- Electron density (e.g., OII)…
  - Two levels with almost same energy difference but different angular momenta and different radiative transition probabilities.
  - At low N_e, every excitation has to de-excite with a photon, so transition probabilities don't matter
  - At high Ne, most de-excitations are from collisions, so transition probabilities matter very much indeed…

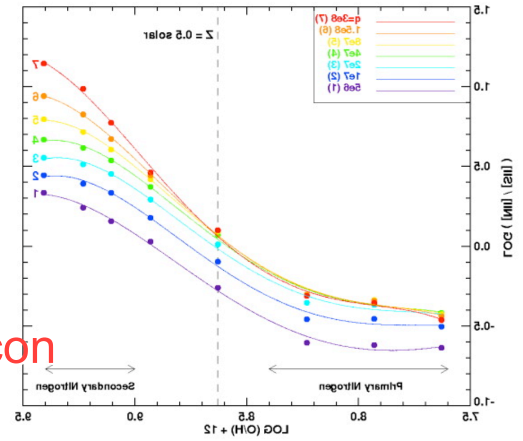
$$\frac{j_{\lambda 3729}}{j_{\lambda 3726}} = \frac{N_{^2D_{5/2}}}{N_{^2D_{3/2}}} \frac{A_{\lambda 3729}}{A_{\lambda 3726}} = \frac{3}{2} \frac{4.2 \times 10^{-5}}{1.8 \times 10^{-4}} = 0.35 \quad (4.1)$$

Photoionization modeling

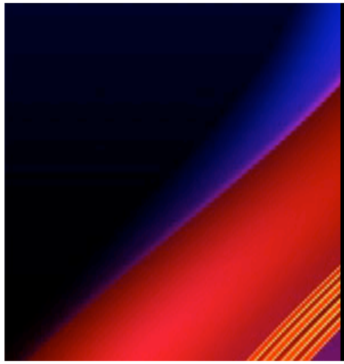
- For faint systems, high metallicity systems, can't get OIII 4363
  - Must do photoionization modeling

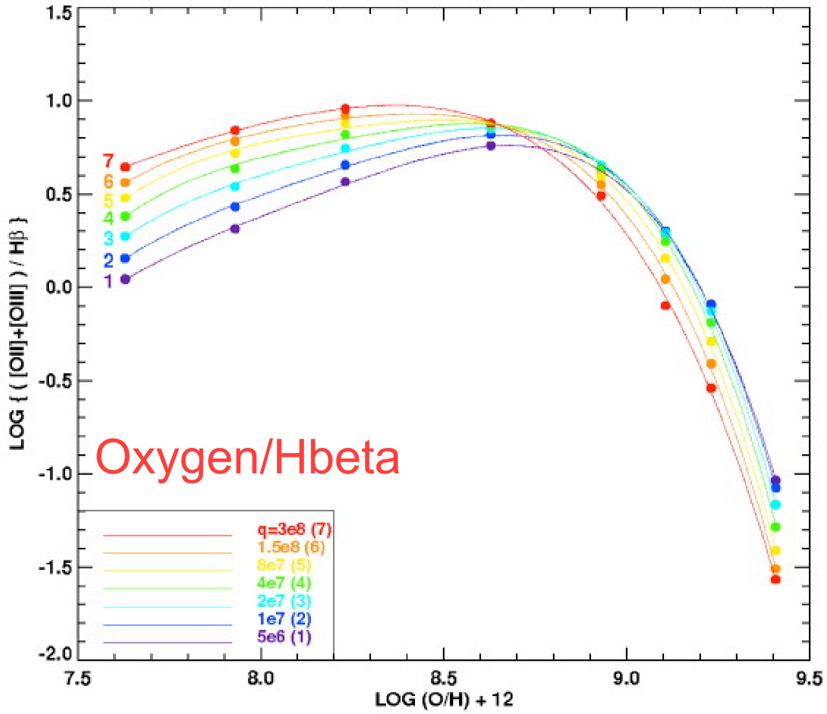






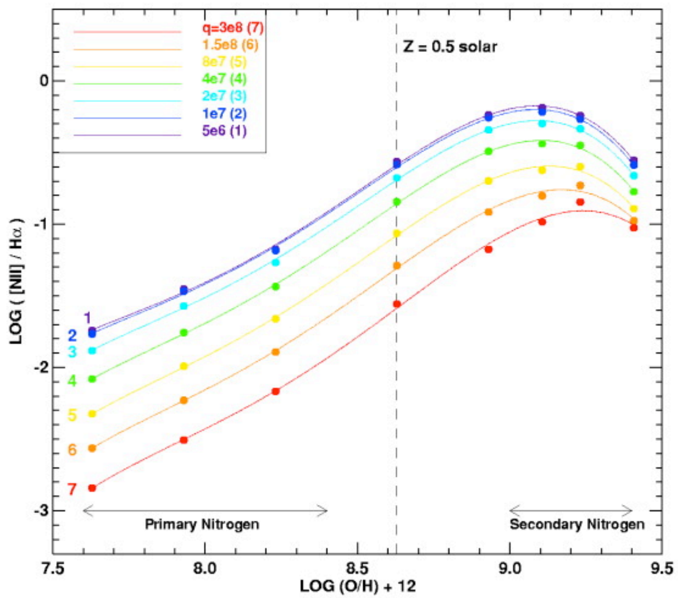
Silicon

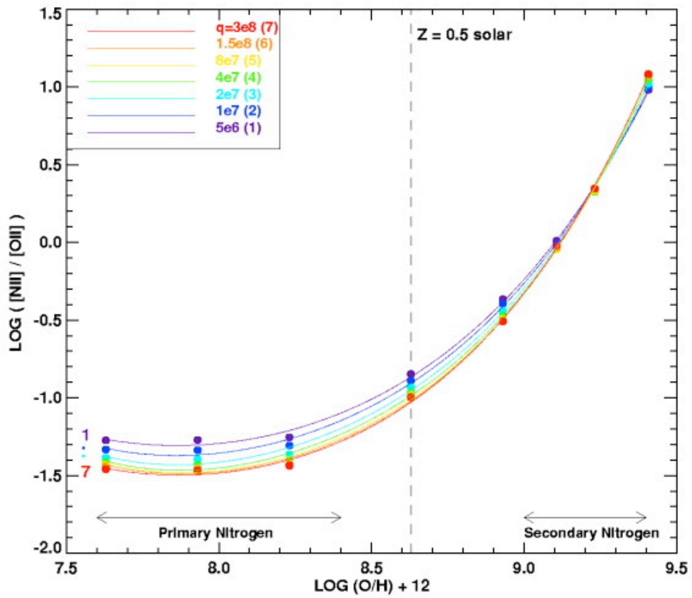




Oxygen/Hbeta

Kewley's photoionization models





~same ionisation so just met. Sensitive Can ~use for AGN!

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Nitrogen II

Gas metallicities

Some discrepancies between
Different sets of strong lines
~some idea of systematics…

Strong line methods -
R23 = (OII + OIII)/Hbeta

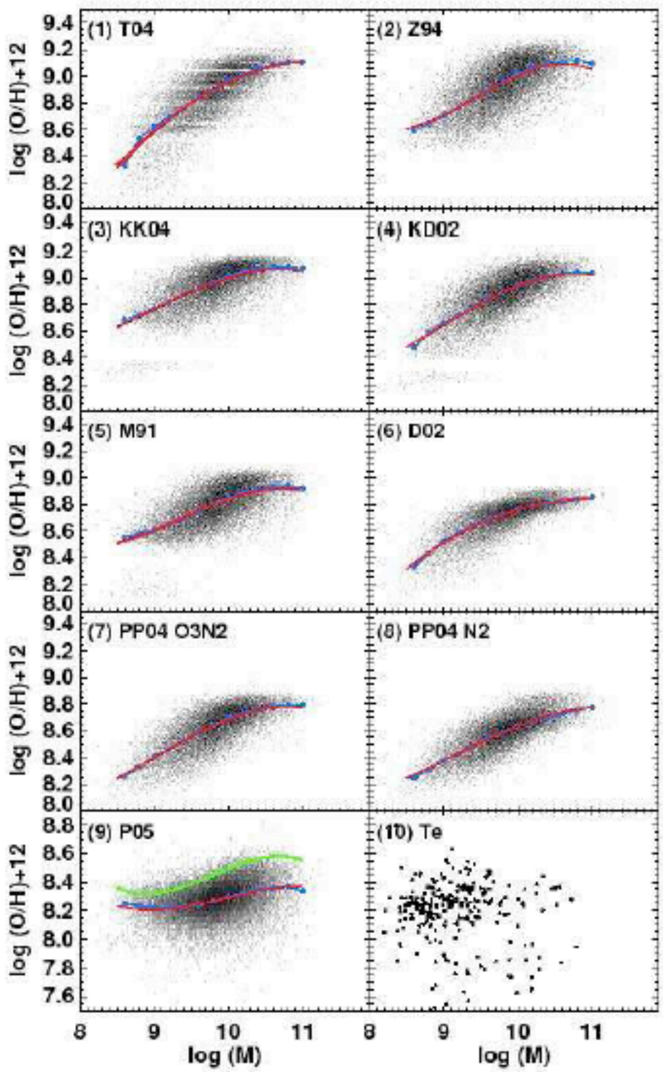


FIG. 1.— The mass-metallicity relation using the 10 different metallicity calibrations listed in Table 1. The red line shows the robust best-fitting 3rd-order polynomial to the data. The blue circles give the median metallicity within stellar mass bins of $\Delta \log(M/M_\odot) = 0.2$, centered at $\log(M/M_\odot) = 8.6, 8.8, ..., 11$. We use the updated calibration of P05 given by Pilyugin & Thuan (2005) in panel 9. The original P01 calibration is shown as a solid green line in panel 9.

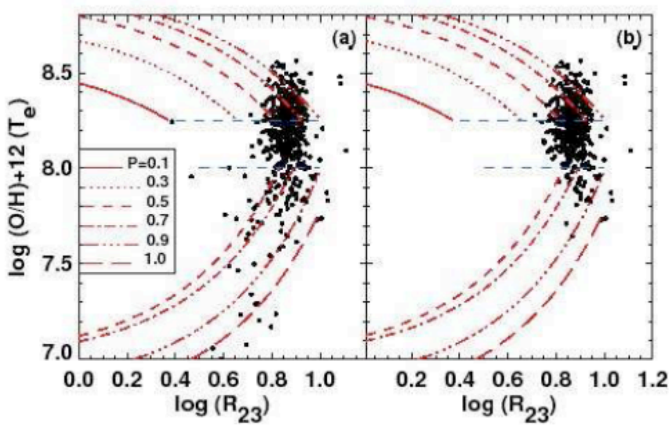


FIG. 11.— The observed relationship between the metallicities derived using the T_e method and the R_{23} line ratio for (a) all SDSS galaxies in our sample with measurable (S/N> 3) [O III] λ4363 fluxes, and (b) for the SDSS galaxies in our sample with measurable [O III] λ4363 lines that lie above the lowest 95 percentile line in the PP04 O3N2 calibration (Figure 10).

Eric Bell

March-April 2008

Kewley & Ellison 2008

Star formation rates

- UV / reprocessed UV light (IR; can be heated through light from older stars)
- Measuring rate of decrease of number of free electrons (ionising flux from v. hot stars)
  - Recombination lines Halpha, Pa alpha, etc. [number transitioning]
  - Thermal radio flux [energy losses]
  - Turn into SFR by requiring that loss of energy is compensated by new energy input (steady state)
- Synchrotron (indirect; measures cosmic ray density and mag. field strength)

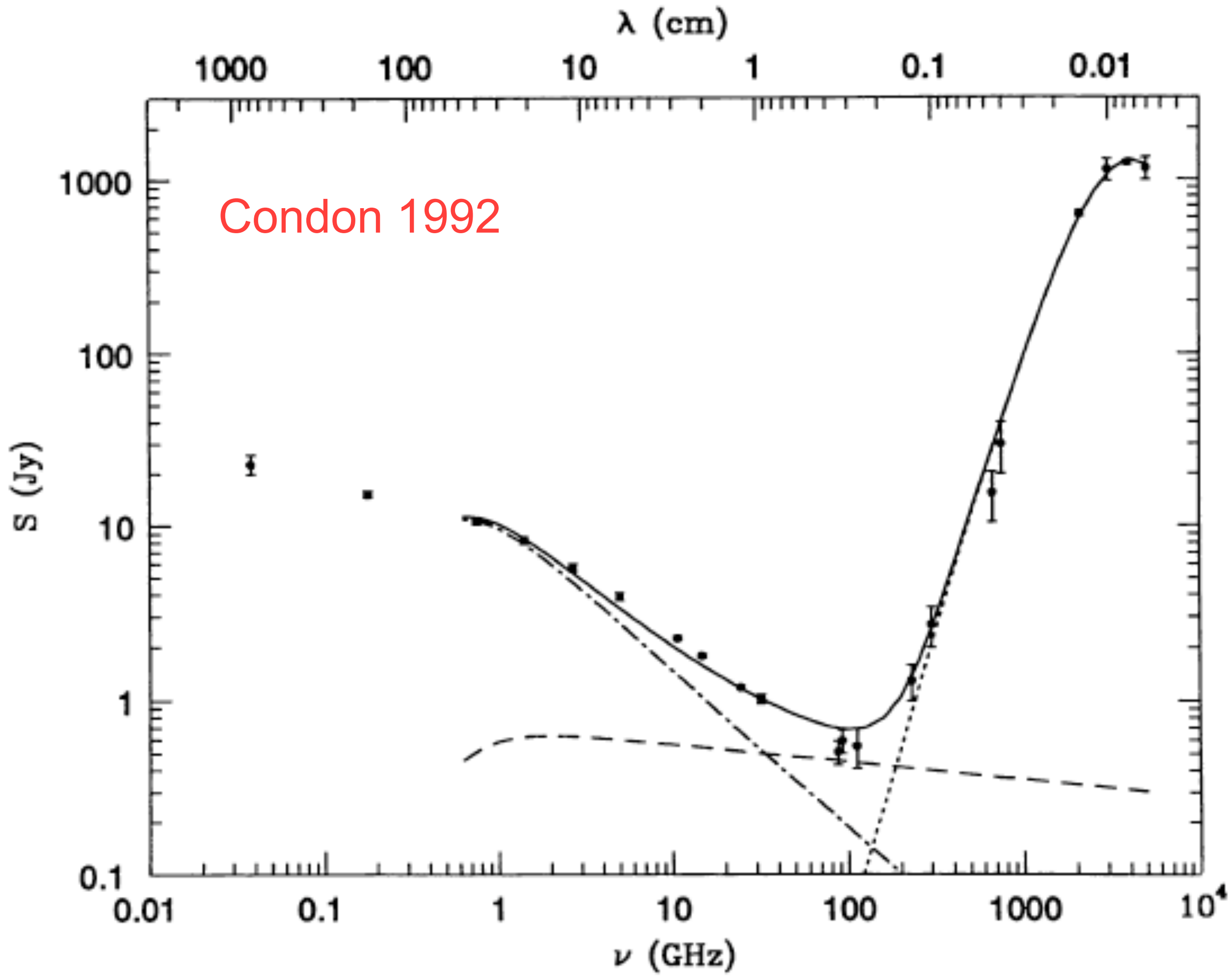
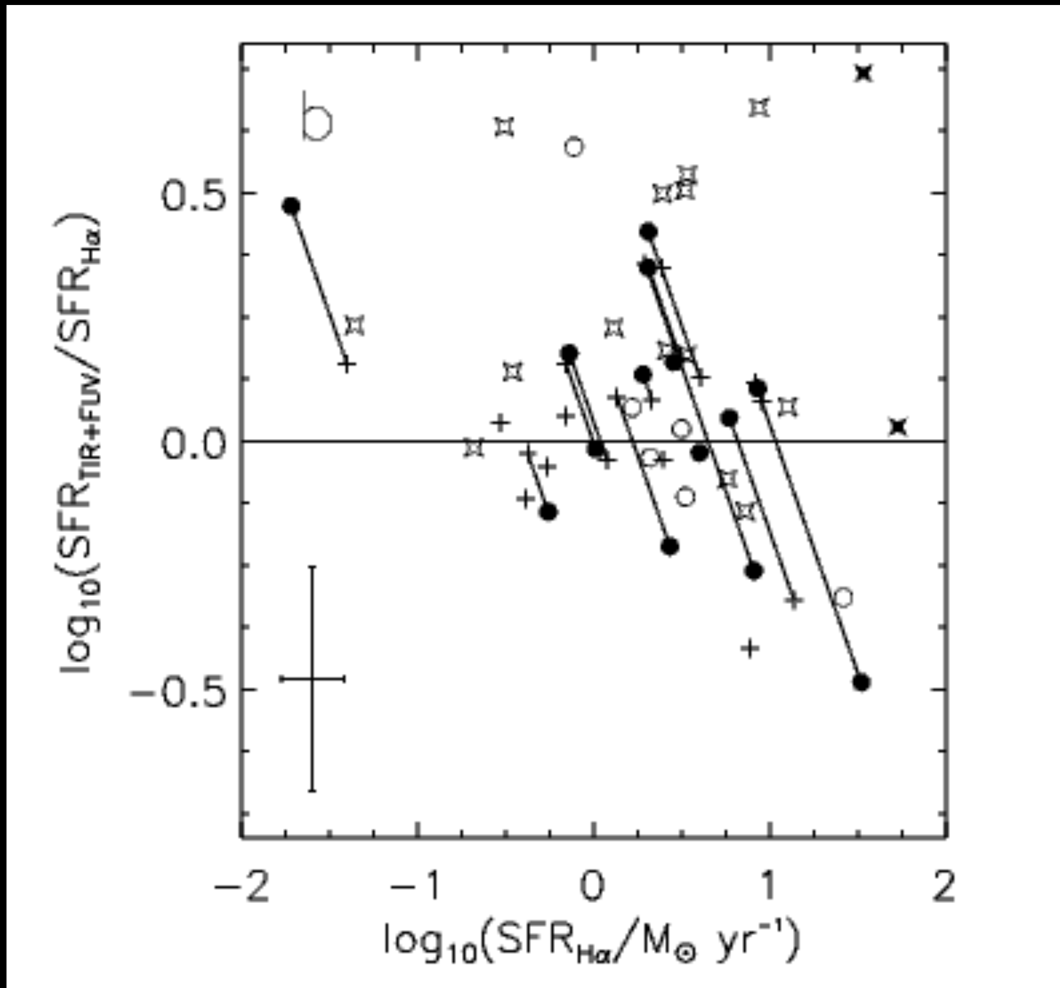
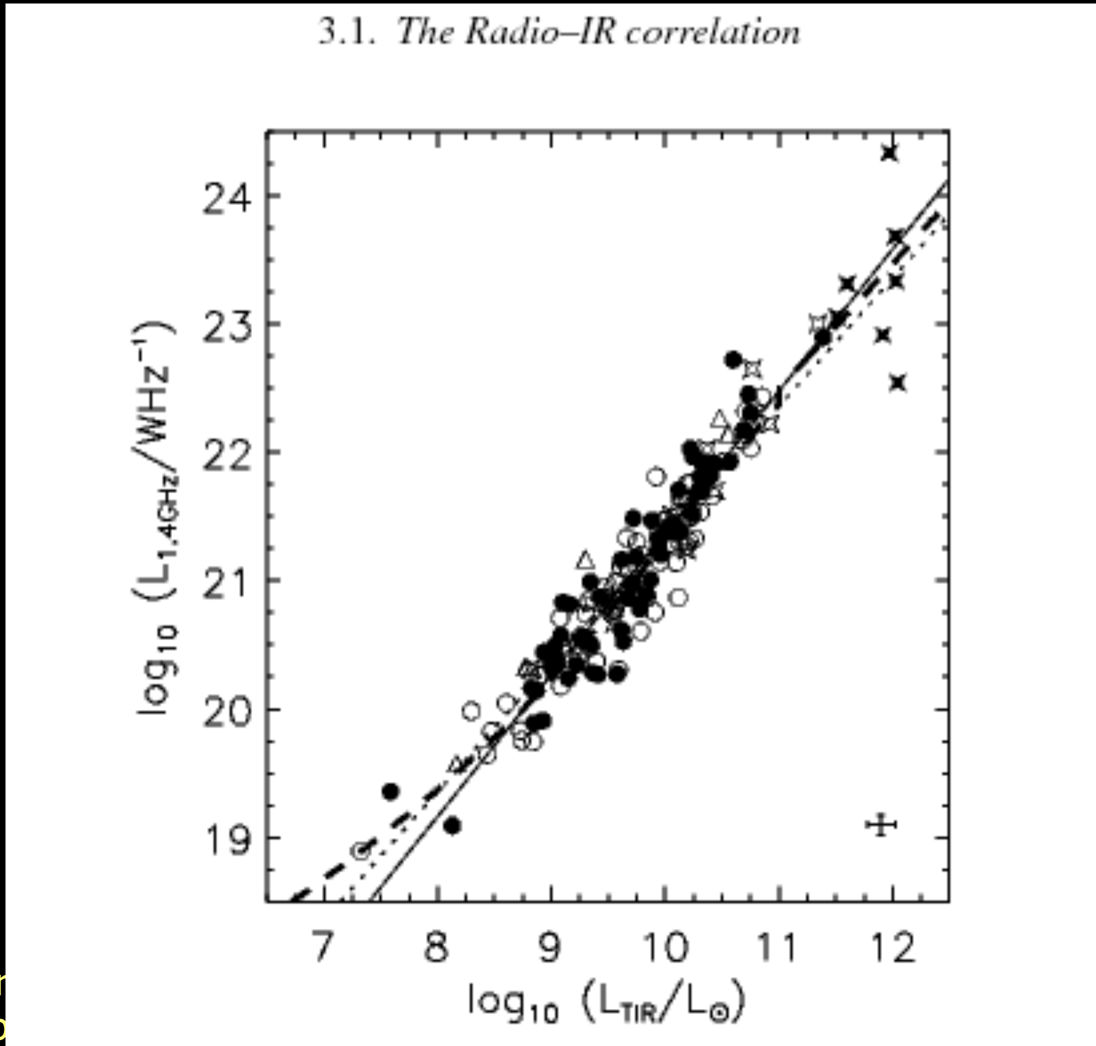


Figure 1 The observed radio/FIR spectrum of M82 (Klein et al 1988, Carlstrom & Kronberg 1991) is the sum (*solid line*) of synchrotron (*dot-dash line*), free-free (*dashed line*), and dust (*dotted line*) components. The H II regions in this bright starburst galaxy start to become opaque below $\nu \sim 1$ GHz, reducing both the free-free and synchrotron flux densities. The free-free component is largest only in the poorly observed frequency range 30–200 GHz. Thermal reradiation from $T \sim 45$ K dust with opacity proportional to $\nu^{1.5}$ swamps the radio emission at higher frequencies. Lower abscissa: frequency (GHz). Upper abscissa: wavelength (cm). Ordinate: flux density (Jy).

intercomparison

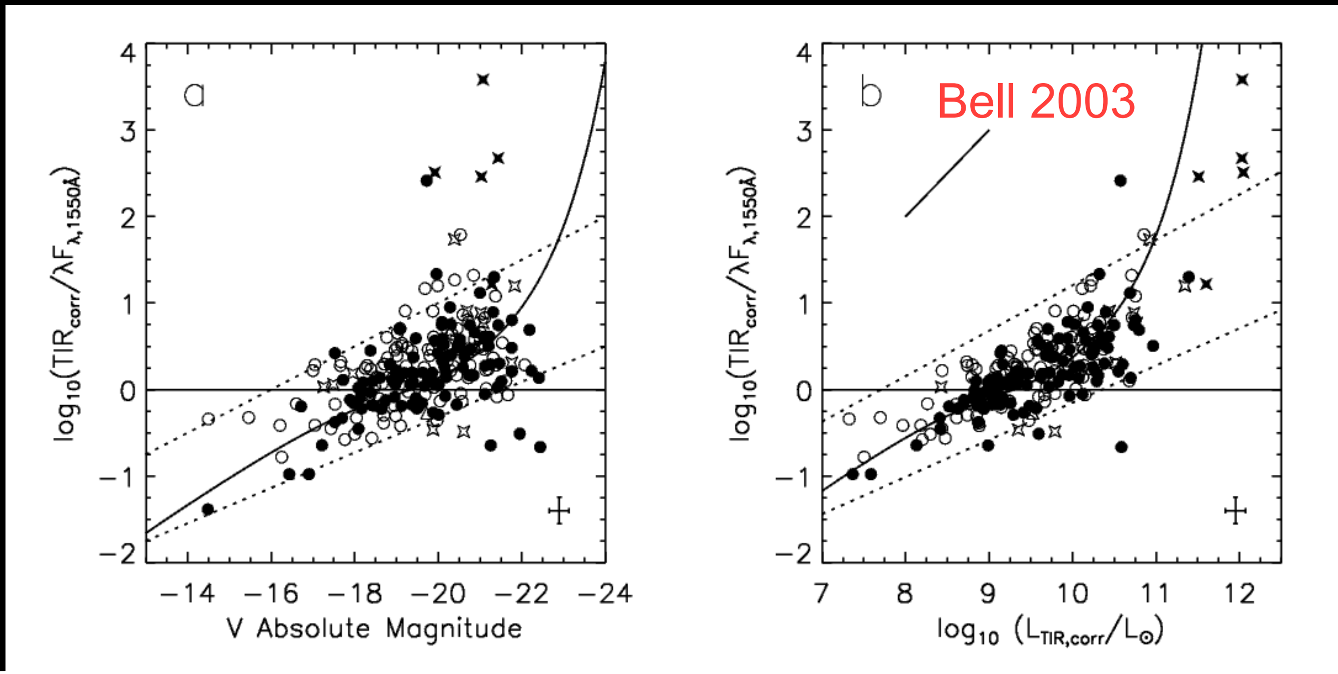


Radio-FIR correlation



Simple toy model consideration

- Optical depth ∝ gas surface density * metallicity
  - Motivation - dust/gas ∝ metallicity
  - Total dust column ∝ gas column



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Linear radio-FIR correlation: a conspiracy

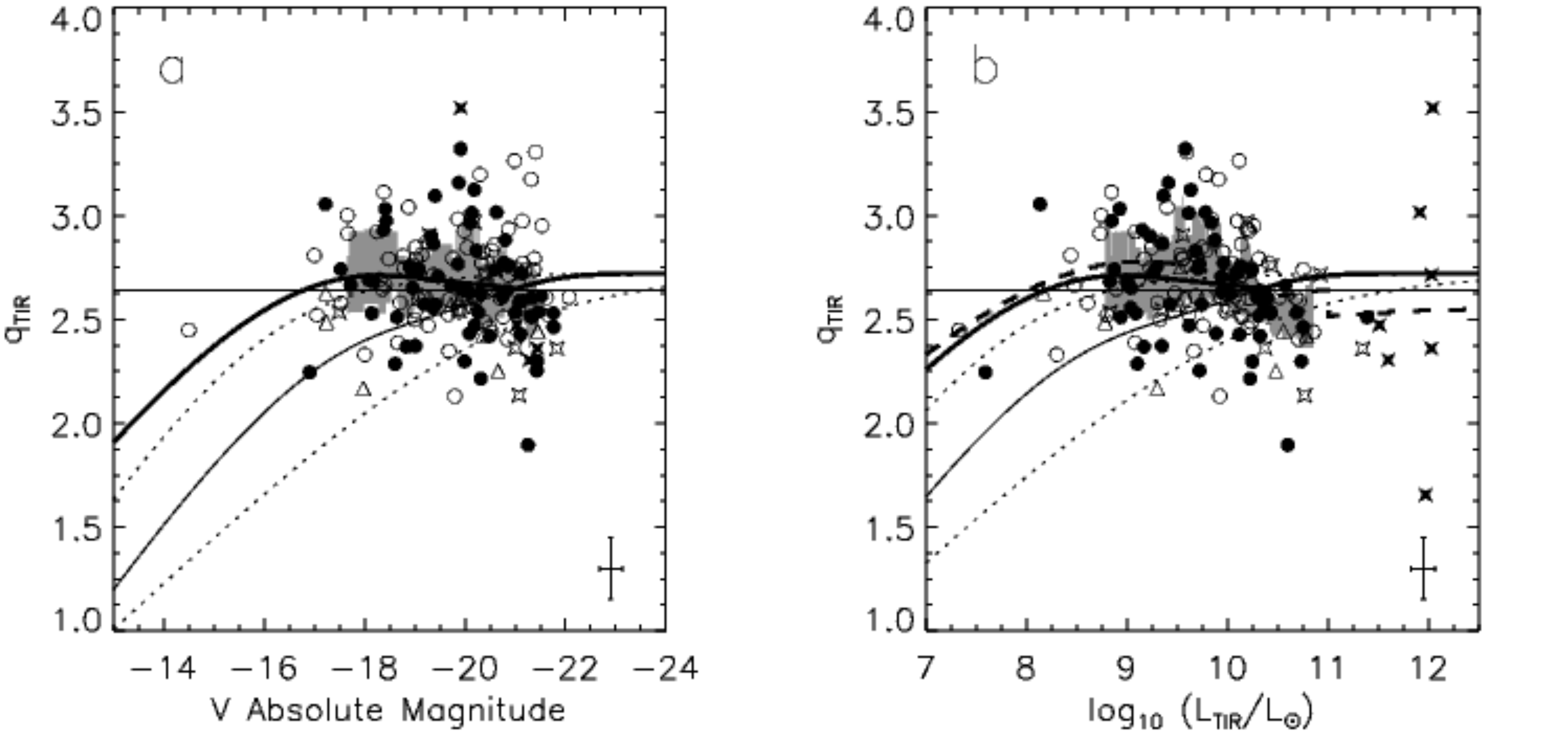

FIG. 4.— Trends in q_{TIR} with galaxy luminosity. Panel *a)* shows q_{TIR} against *V*-band absolute magnitude, and panel *b)* shows q_{TIR} against TIR luminosity. Symbols are the same as in Fig. 2. The shaded area shows the upper and lower quartiles as a function of luminosity: this shows, in a less noisy fashion, any trends between q_{TIR} and galaxy luminosity. The effect of trends in TIR/FUV with luminosity are plotted as thin dotted (the limits on TIR/FUV as a function of luminosity) and thin solid (the model TIR/FUV with luminosity) lines. If radio SFR were a perfect SF rate indicator, there should be a trend in q_{TIR} which follows the general trend of the thin dotted and solid lines. The thick solid line shows the final model presented in §5. The thick dashed line in panel *b)* shows the trend predicted by the final SF rate calibrations (see §6.1).

Calibrations; Kroupa 2001 or Chabrier 2003 IMF

- SFR ~ 9.8d-11 * (IR + 2.2UV) Bell+05
- SFR ~ 9.8d-11 * IR (1+sqrt[1d9/IR]) IR-only, Bell 03
- SFR_radio ~ pi d-22 * L_1.4GHz [L> Lc = 6.4d21 W/Hz]
- SFR_radio ~ pi d-22 * L_1.4GHz / (0.1+0.9*(L/Lc)^0.3)   [L<Lc]
- SFR_Ha = 5.3d-42 L_Ha (ergs/s) Calzetti+07

Summary III

- Gas
  - Atomic hydrogen easy
  - Molecular hydrogen no dipole moment, so indirect probes (CO, HCN, etc) only which are calibrated to molecular hydrogen
- Ionised gas
  - Different lines of one element with different energies gives insight into Electron Temperature
  - Different transitions with ~energy but diff. AM give density (because of degree of collisional de-excitation is measured)
  - Then can measure metallicity

Summary III (cont…)

- Star formation rates
  - Hydrogen recombination (==> Ionising Luminosity)
  - UV/IR (luminosity of young stars/reprocessed)
  - Radio synchrotron (cosmic ray electron density ~ SNR)
  - Comparably good if careful/use in appropriate regime, can calibrate to x2