Astronomy 730

Interstellar Medium

Outline

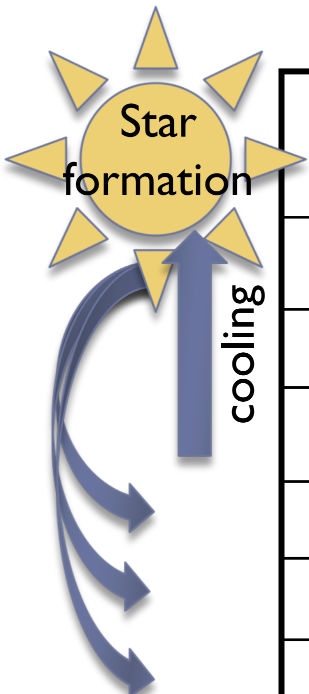
- Interstellar Medium (ISM) in galaxies
  - Phases
    - Atomic gas
    - Dust and molecular gas
    - Warm ionized gas
    - Hot ionized gas
  - Star-formation
  - Feedback

Interstellar Matter (ISM)

- Optically visible components
  - Dark band through center of the MW (absorption)
  - Diffuse emission regions
  - Reflection nebulae
- Verification
  - Cluster diameter vs luminosity distances
  - Non-varying absorption lines in binaries

NGC 891 – viewed edge-on

Phases of the ISM



Phase	Temp (K)	N (cm^{-3})	Filling factor	Diag.
Cold	10	10^4	low	CO, mid-IR
Cool	10^2-10^3	10^3	low	HI
Warm	10^3-10^4	10^2	high	HI
Warm	10^4	10	high	Hα
Hot	10^5-10^6	1	high	X-ray/FUV
Relativistic	?	?	High	Synch.

Neutral Hydrogen: 21 cm HI line

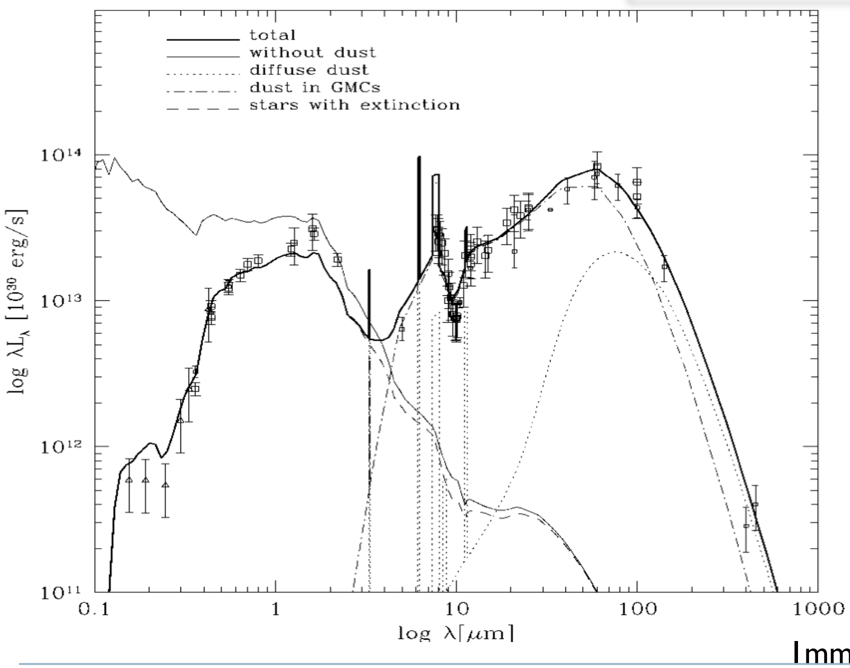
- Hyperfine transition in the ground state from the interaction between the spins of the electron and proton.
  - $\Delta E = 6 \times 10^{-6}$ eV → $\nu = 1.4204$ GHz
  - Lifetime of excited level is long (10^7 yr) so collisional excitation and de-excitation is fast compared to spontaneous decay. Level populations depend only on kinetic temperature of the gas.
- Useful relationships:
  - $N_H = 1.82 \times 10^{22} \int dV\, T_B$ (if optically thin)
  - $M_H = 2.36 \times 10^5\, M_\odot \times D^2 \int S(V)\, dV$, where $S(V)$ is in Jy km s^{-1}

Molecular Gas

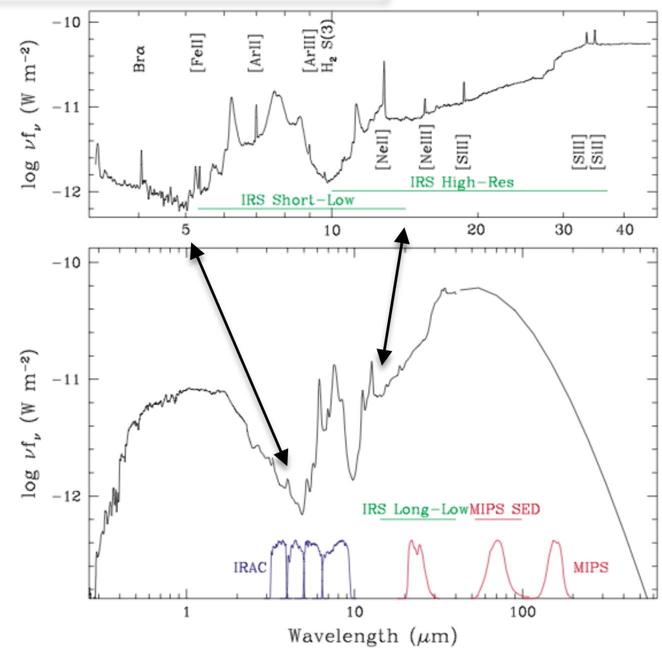
- Cold – molecular line spectroscopy with radio/mm wave telescopes.
  - H_2 most common molecule, but no dipole moment, so hard to detect
  - CO next most common molecule; has a dipole moment, transitions due to angular momentum quantum number (e.g. $J=1\rightarrow0$ at 2.6mm)
  - $I_{CO} = \int dv\, T_A$ (2.6mm line of ^{12}CO)
    - T_A is the antenna temperature so that $P = kT_A$
  - Conversion to H_2 :
    - $X_{CO} \equiv N(H_2)/I_{CO} \sim 2.3 \times 10^{24}$ (The *infamous* X factor)
    - (is this really the same everywhere???)
  - Other methods include UV spectroscopy to get H_2, even more complex molecules (e.g. HCN)

Dust: The Mid to Far Infrared Window

- What' the difference between dust and molecules?
- Key components:
  - multiple thermal components from 10 to 300 K (cool and cold)
    - 30 microns – 1 mm
  - molecular (PAH) emission
    - 3-30 microns
- Key instruments: IRAS, ISO, Spitzer, and Herschel satellites, SOFIA



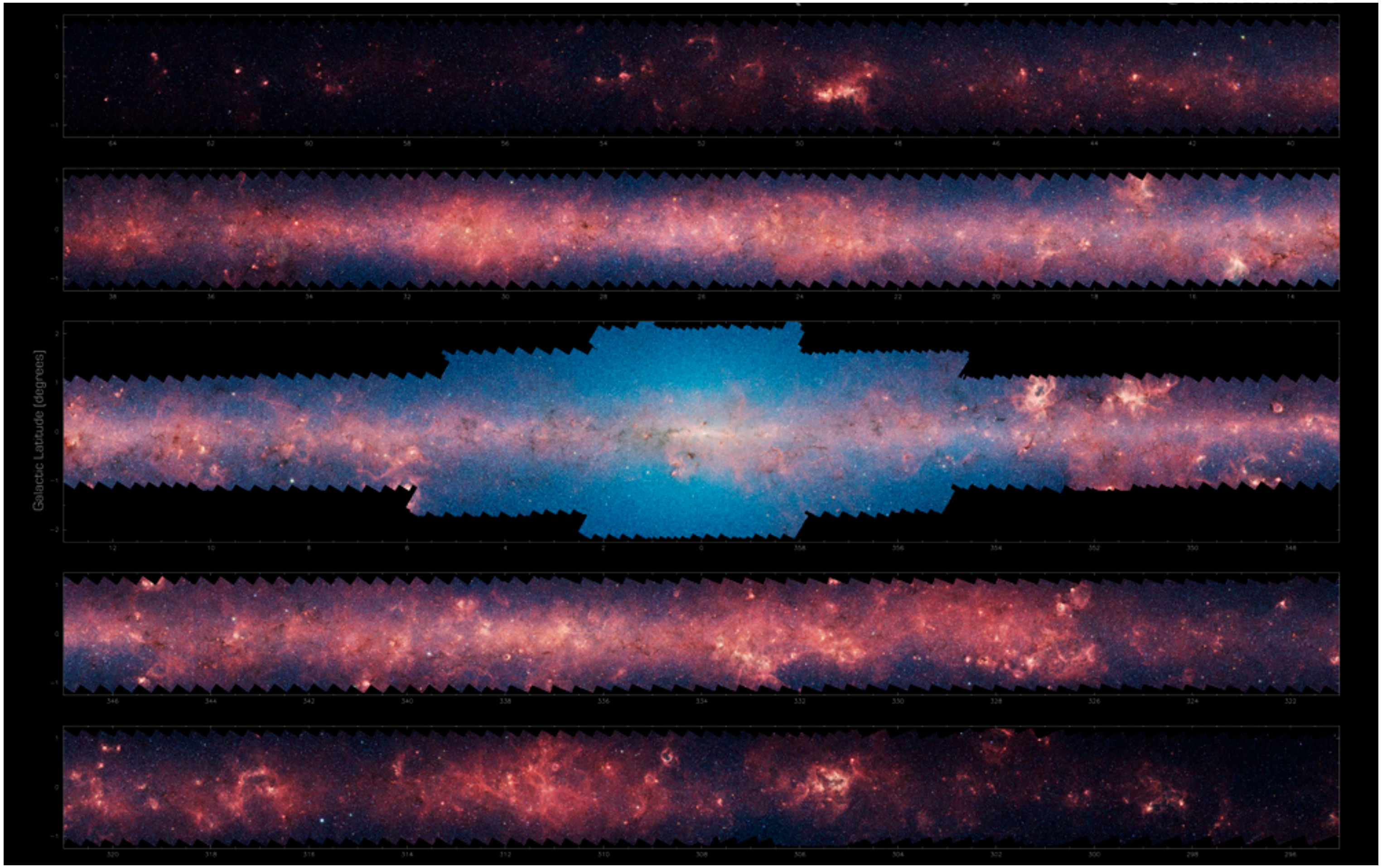
Silva 1998: ISO



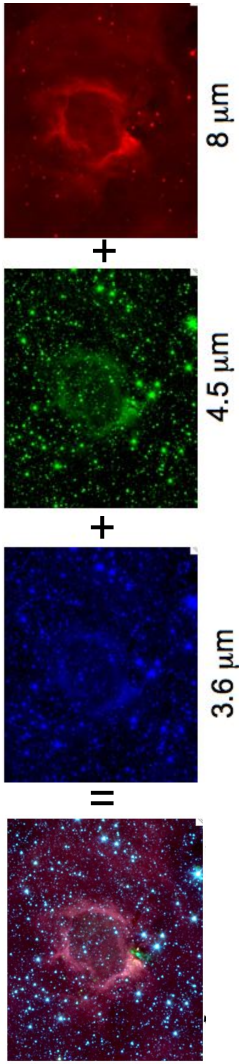
Kennicutt et al. 2003: Spitzer

GLIMPSE 3.6 to 8 microns: Stars vs PAH

Galactic Latitude

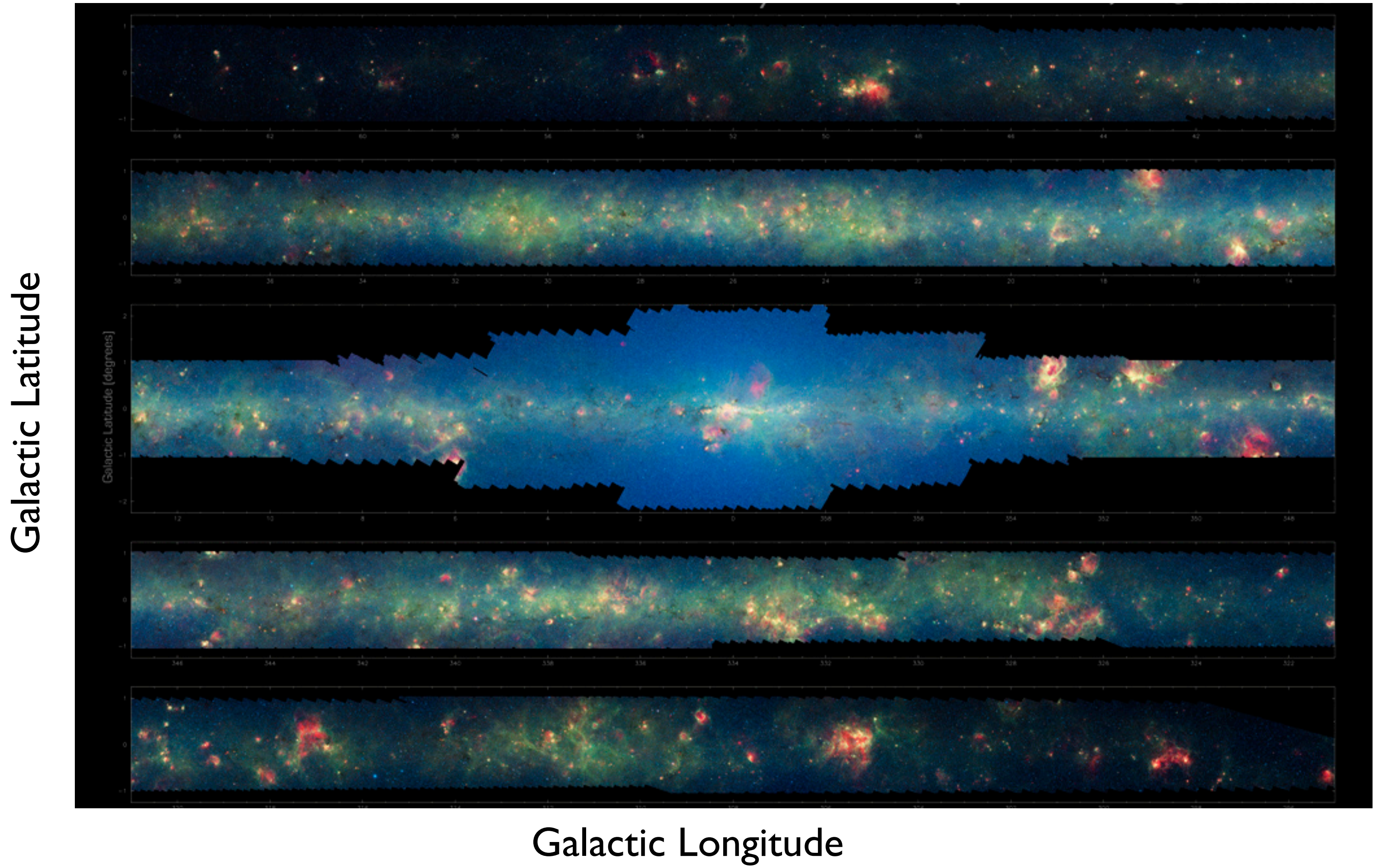


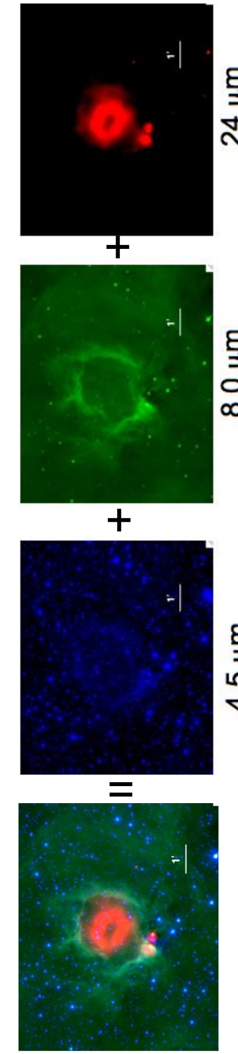
Galactic Longitude



Spitzer Galactic Plane Survey: PI E. Churchwell (U.Wisconsin)

GLIMPSE 3.6 to 24 microns





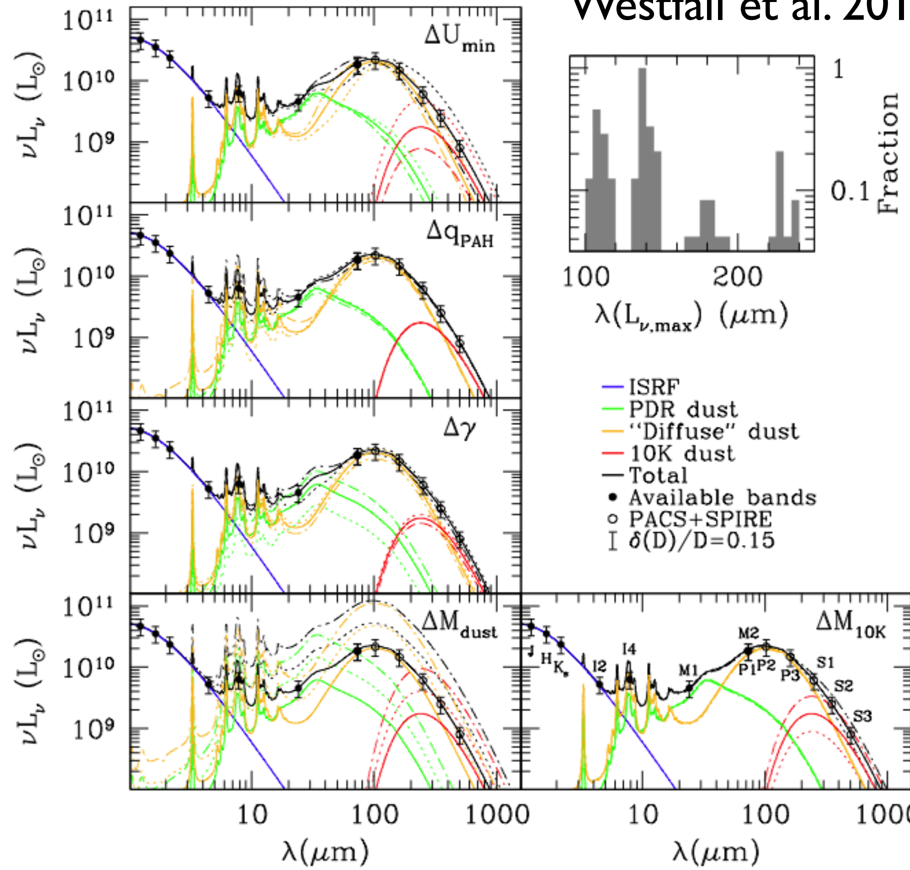
- Dust sub-structure: photo-disassociation regions (PDRs), shocks

Spitzer Galactic Plane Survey: PI E. Churchwell (U.Wisconsin)

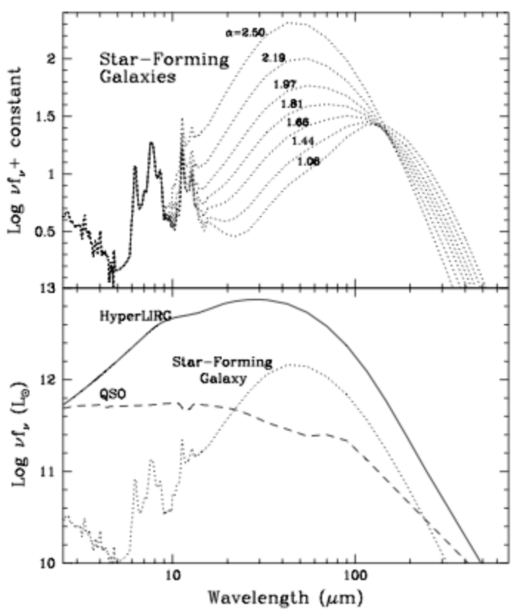
Dust continued

- What drives the detailed shape of the spectrum?
- Radiation field: U
- Composition:
  - PAH abundance q_{PAH}
- Dust Masses: diffuse, PDR
- Temperatures: diffuse, PDR

Westfall et al. 2010



Herschel



Dale et al 2001

Models: Draine & Li 2007

Dust and Molecules

- Can we estimate molecular gas content from studying the dust?
  - Unsurprising to find tight correlation between I_{CO} and MIR flux, e.g., $I_{24\mu m}$
  - Higher degree of correlation likely to be found by considering broader range of MIR and FIR colors
- Why would we want to do this?
  - CO measurements are hard
  - The conversion from CO to H_2 is frought
  - Detailed modeling of 3-300 micron SEDs* should yield molecular/chemical composition and radiation field:
  - Link to CO measurements to understand X_{CO}
- Research project waiting to happen

*SED = spectral energy distribution

Warm Ionized Gas

- Emission from
  - Photoionization
    - We largely see H emission lines via recombination into various primary quantum levels. e.g.,
      - Hα (656.3nm) arises from transition from n=3 to n=2.
      - See example from M33
  - Collisional excitation
    - Forbidden lines
    - C, N, O, Ne, S, Si, Fe

- Line-strengths of H
  ➔ star-formation rates
- Line-ratios of H and forbidden lines ➔ estimates of
  - redenning
  - metallicity
  - T_e = electron temperature
  - n_e = electron density
  - Shocks vs photo-ionization

HII regions: ionizing radiation from OB stars


M33

Line diagnostics

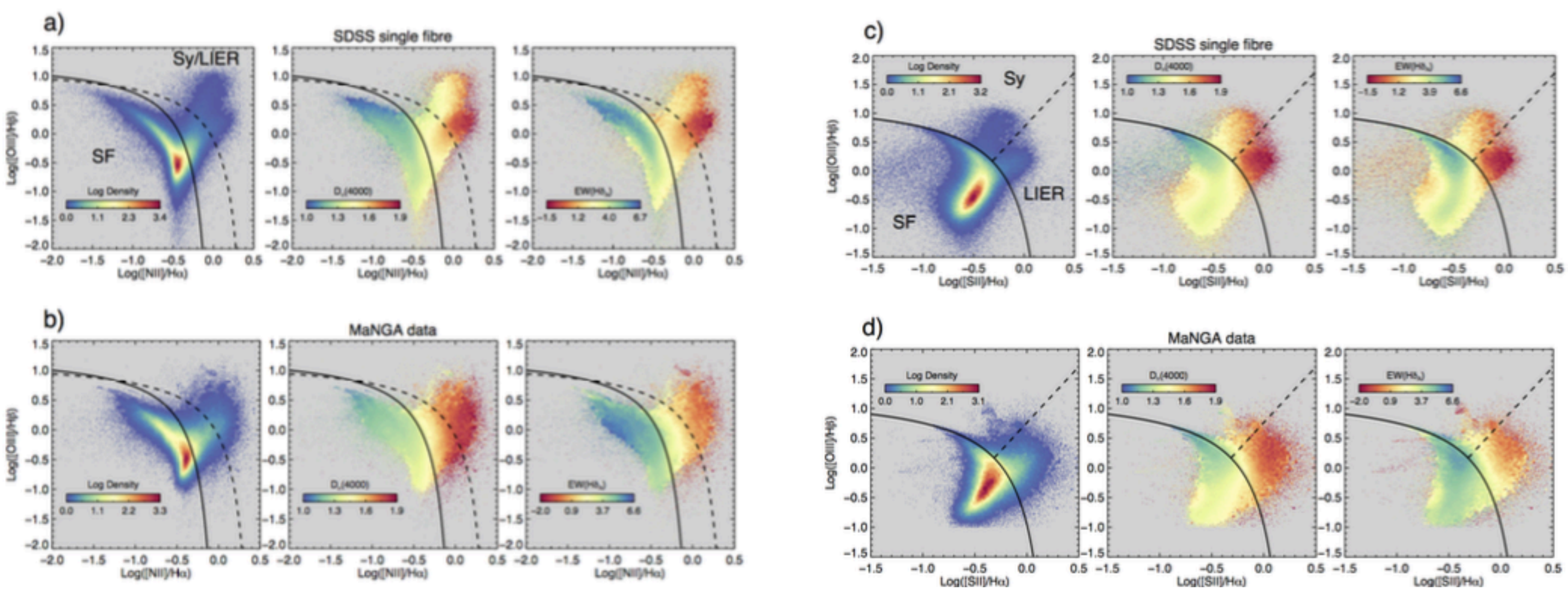
- Redenning:
  - Use recombination coefficients for different lines compared to measured flux ratios, e.g., Hα/Hβ
    - Recombination coefficients depend in detail on knowing T_e and n_e
    - Must correct emission for stellar photospheric absorption which is, e.g. larger in Hβ than Hα
- Temperature: T_e
  - Flux ratios of forbidden-lines from ions with different ionization potentials, e.g.,
    - H+,S+,N+,O+,O++
    - Metallicity and shock-heating effects
- Density: n_e
  - Flux ratios of some forbidden-line doublets, e.g.,
    - [OII]λλ3726,3727 , [SII]λλ6717,6731
    - Limited sensitivity to large dynamic range in density

Missing topics

- QM fixed line-ratios
- BPT diagram
- T_e/Z issues and estimating gas-phase metallicity

Line diagnostics: BPT

- BPT = Baldwin, Phillips & Terlevich (1981)
  - Use redenning-insensitive line-ratios that probe different conditions of ionizing radiation:
    - [OIII]λ5007/Hβ, [NII]λ6584/Hα or [SII]$\lambda\lambda$6717,6731/Hα
  - Identify regions consistent with star-formation (SF, e.g., HII regions), AGN, or so-called Low Ionisation Nuclear Emission-line Regions (LINERS).
  - LINER-like ratios are found NOT just in nuclear regions and probably do not have anything to do with AGN activity but more associated with old stellar populations, hence LINER➔ LIER. See Belfiore et al. papers (2014, 2016ab)



Belfiore+ (2016a) - MaNGA

Figure 3. The BPT diagnostic diagrams based on [NII]/Hα (top) and [SII]/Hα (bottom) for the galaxies in the MPA-JHU legacy SDSS sample and MaNGA sample used in this work. The three panels in each row show respectively the density of galaxies (left), the average $D_N(4000)$ (middle) and EW(Hδ_A) (right) across the BPT diagram. The demarcation liens are discussed in Sec. 4. For each plot, both axes have been divided in 100 intervals thus creating small bins in the 2D space. Bins containing more than 20 galaxies are represented by the average value of the quantity (or total number density). For bins containing less than 20 galaxies, the individuals values of each galaxy are shown. For the SDSS legacy data, emission line fluxes and stellar population indices are taken from the MPA-JHU catalogue (Brinchmann et al. 2004; Tremonti et al. 2004).

BPT vs stellar populations

Belfiore+2014

This addresses the point Concerning the origin of 'LIER'-like BPT-diagram line ratios.

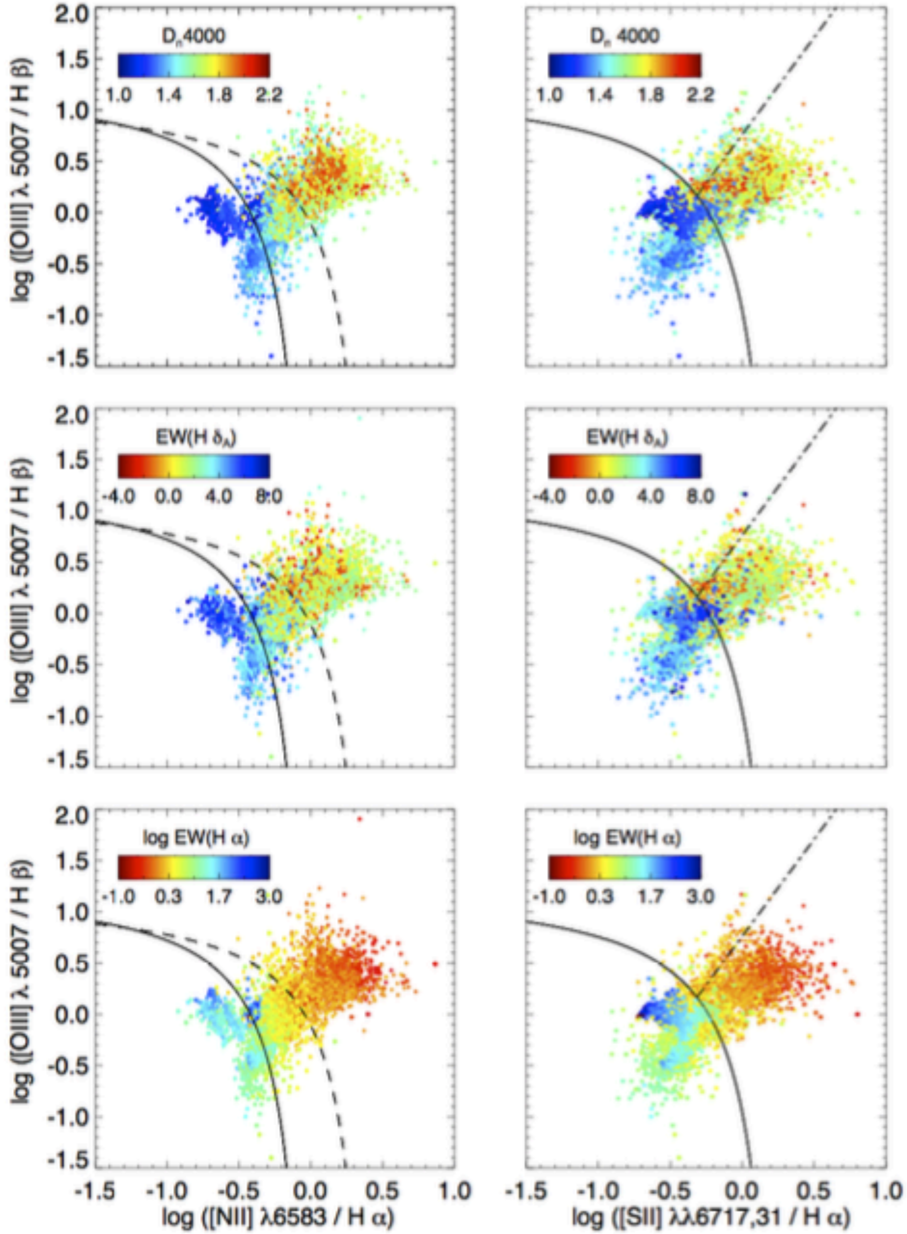


Figure 5. [NII] (left) and [SII] (right) BPT diagnostic diagrams colour-coded by $D_n(4000)$ (top), EW($H\delta_A$) (middle) and log EW($H\alpha$) (bottom). Each points corresponds to a Voronoi bin in one of the 14 galaxies considered. Note that, since single spaxels oversample the PSF, not all data points are statistically independent.

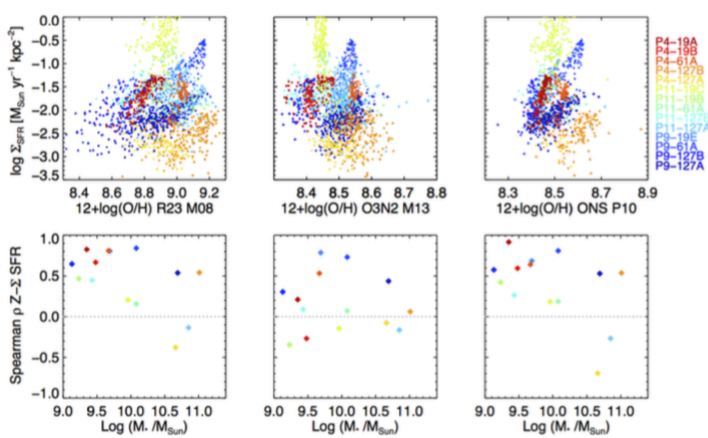
Ionized gas-phase metallicity

- Need to control for reddening, T_e , n_e, relative abundances, ionization parameter, shape of ionizing continuum
- Insufficient information from strong lines alone, but attempts have been made to calibrate strong lines using very deep observations that include weak auroral lines to break these degeneracies (e.g., see CHAOS papers, Berg et al. 2015)

Some common (but inconsisent) Methods:

- R23 = ([OII] 3726,29 + [OIII] 4959 + [OIII] 5007)/Hβ (see Tremonti 2004, Maiolino et al. 2008,)
- O3N2 method uses [OIII]/[NII], mediated by Hα, Hβ (Marino et al. 2013)
- ONS method: uses OII, OIII, NII, SII (Pilyugin, Vilchez & Thuan 2010)
- NII/Ha method

An example of the mess:



Belfiore+ 2014 (MaNGA)

Belfiore+ 2016 (MaNGA)

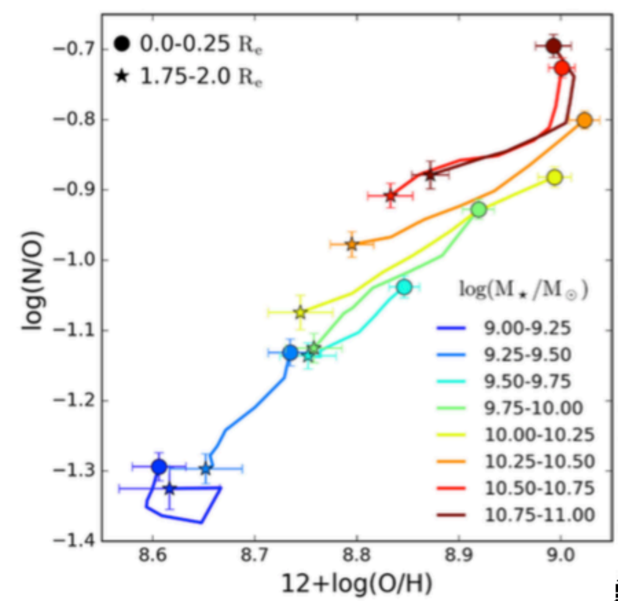


Figure 8. The relation between log(N/O) and metallicity [12+log(O/H)] as a function of both stellar mass and radius. The radial profiles in both metallicity and N/O are stacked in stellar mass bins of width 0.25 dex. The coloured solid lines represent the location of the stacked radial profiles in the log(N/O) versus 12+log(O/H) plane, with circles representing the innermost radial bin (0.0–0.25 R_e) and the stars representing the outermost radial bin (1.75–2.0 R_e).

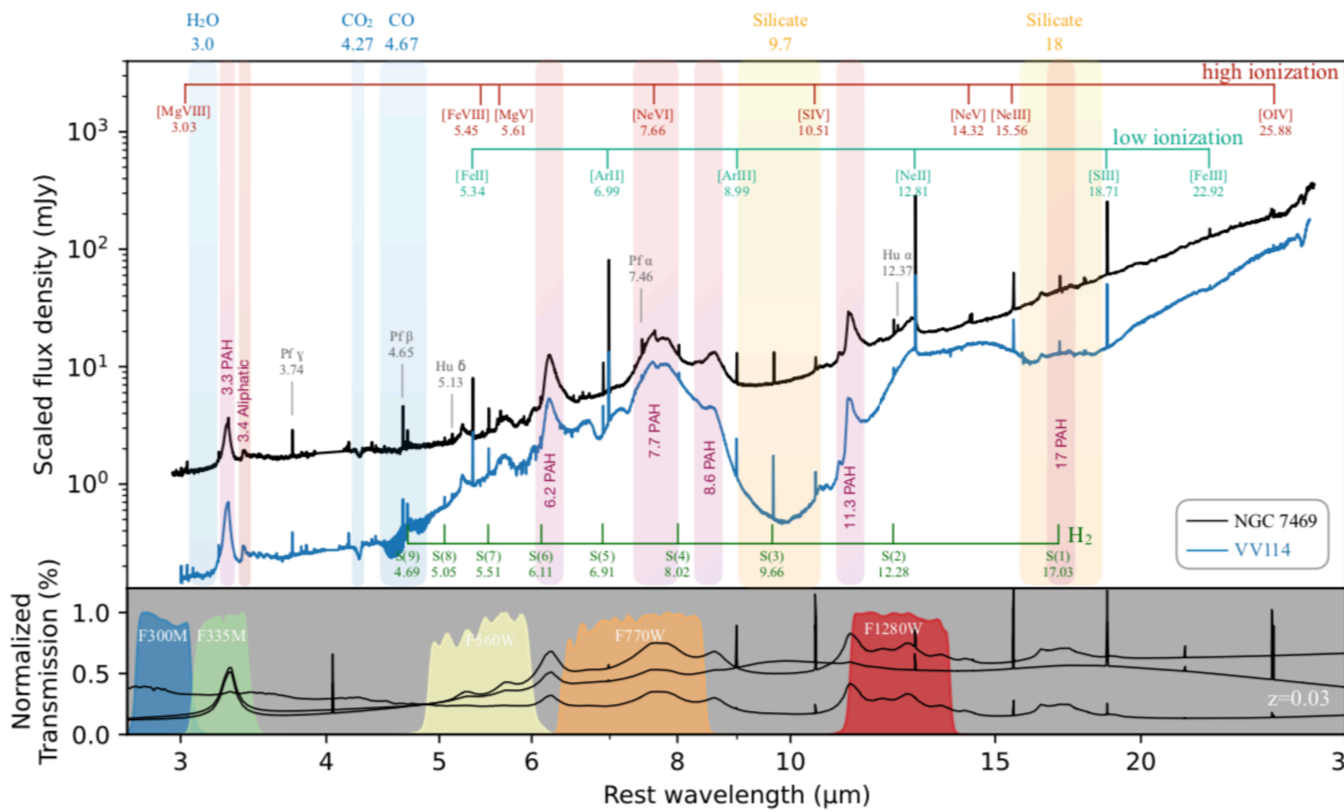
Ionization potential energies

- In principle, ionized gas fluxes of different elements with different ionization potentials and known recombination rates provide insights into the total amount of ionizing radiation and shape (e.g., hardness) of the ionizing radiation field.
- The interpretation is subject to uncertainties in the relative abundances and the detailed geometry of the nebular regions, i.e., the ions are not necessarily (and often certaintly not) spatially coextensive.
  - Na+ 5.1 eV – no optical line (NaD $\lambda\lambda$5892 Å is Na I, neutral)
  - Na++ 47.3 eV – no optical line
  - **S+ 10.4 eV [SII] $\lambda\lambda$6716,6731 Å**
  - **S++ 23.3 eV [SIII] $\lambda\lambda$9069,9532 Å**
  - **H+ 13.6 eV (Balmer: Hα, Hβ, etc.)**
  - **O+ 13.6 eV [OII]$\lambda\lambda$3727 Å**
  - **O++ 35.1eV [OIII] $\lambda\lambda$ 4959,5007 Å**
  - **N+ 14.5** eV **[NII] $\lambda\lambda$ 6548,6584 Å**
  - N++ 29.6 eV [NIII] – no optical line
  - Ar+ 15.8 eV [ArII] λ7130 Å - weak
  - He+ 24.6 eV HeI λ5876 Å - moderate
  - He++ 54.4 eV HeII λ4686 Å - weak
  - Ne++ 62.7 eV [NeIII] λ3869 Å - weak

Strong optical lines in the visible wavelength regime where Si-based detectors are efficient. ***NIR and MIR has a wealth of additional lines.***

Ionization potential energies

- The richness of JWST spectroscopy: NIRSpec + MIRI



- Low ionization: Ar+ 15.8eV [ArII] λ6.99μm, Ar++, Fe+ λ5.34μm, Fe++ λ22.92μm, Ne+ [Ne II] λ12.81μm, Ne++ 62.7eV [Ne III] λ15.56μm
- Intermediate ionization: [O IV] 54eV, Ne++ 62.7eV [Ne III] λ15.56μm
- Ultra-high ionization lines: [Ne V] 97eV, [Mg V] 109eV, [Fe VIII]124eV, [Ne VI] 126eV, [Mg VII] 187eV

Emission-line modeling

- Two parameter models as a function of metallicity (Z) and ionization parameter (q)
- $q=Q_{ion}/4\pi r^2 n_e$
  - Q_{ion} = number of ionizing photons emitted per sec
  - r distance from source
  - n_e is electron density
- Therefore need q to get Z even in this limited parameter space.
- (more complicated when you consider abundance variations and shape of the ionizing spectrum)

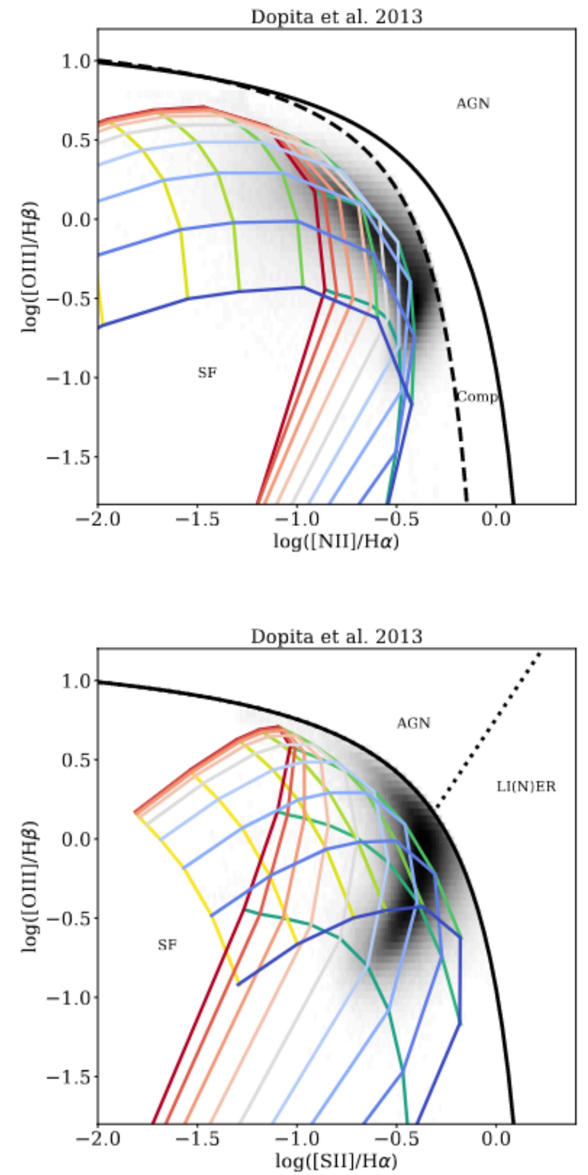
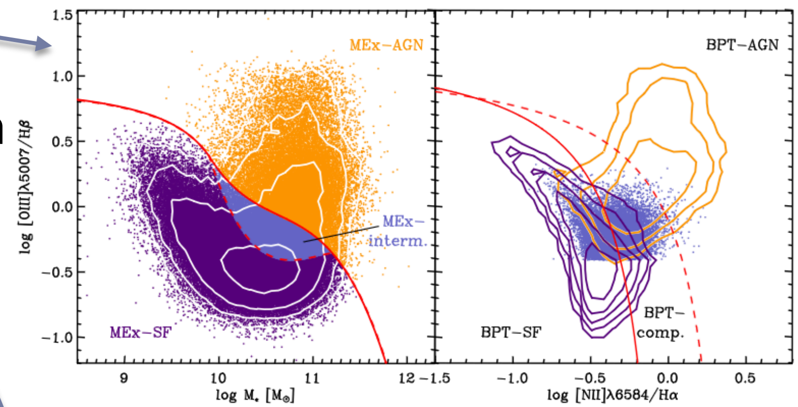
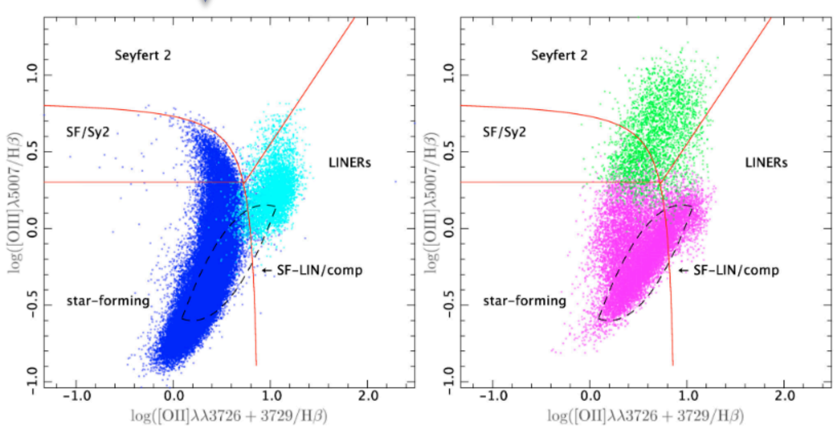


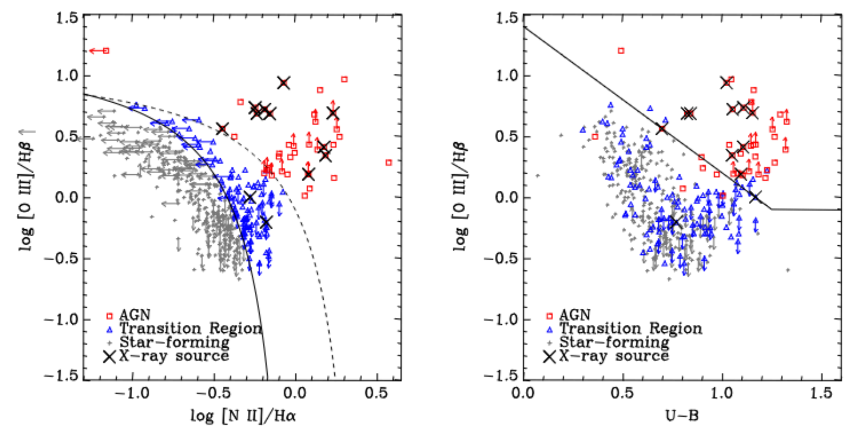
Fig. 2. [N II]- and [S II]-BPT diagrams for our sample of MaNGA spaxels compared with D13 models, for metallicities in the range [7.39–9.39] (increasing from yellow to green) and ionisation parameters in the range [6.5–8.5] (redder means higher log(q) and bluer lower log(q)). The models of D13, in general, accurately reproduce the observed line ratios in MaNGA spaxels as ensembles.

AGN diagnostics: optical spectra-1

- Standard BPT using either NII, SII, or OI
- **Mass-Excitation (MEx) diagram** (Juneau et al. 2011; 2014)
- **Color-Excitation (CEx) diagram** (Yan et al. 2011)
- **Blue** diagram (Lamareille 2010, Lamareille et al. 2004)

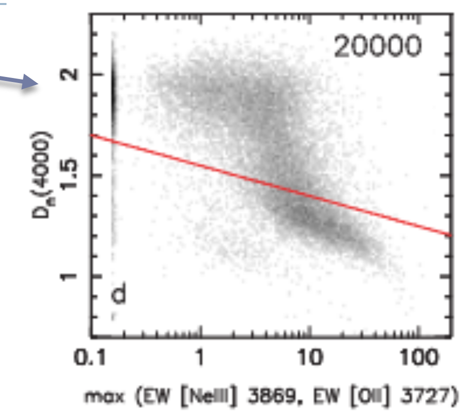


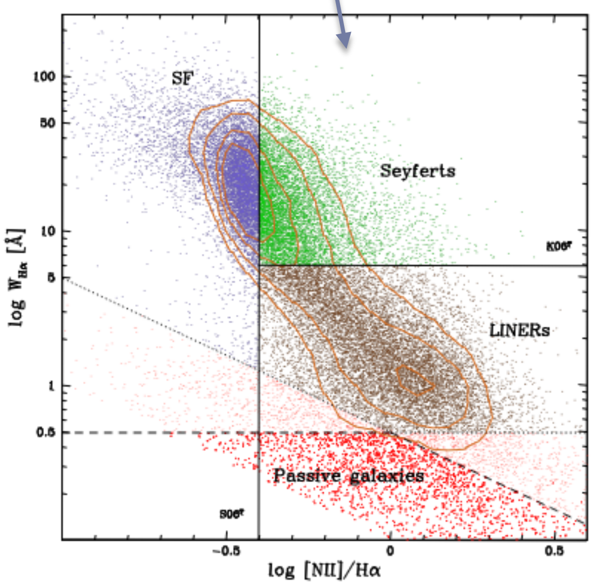


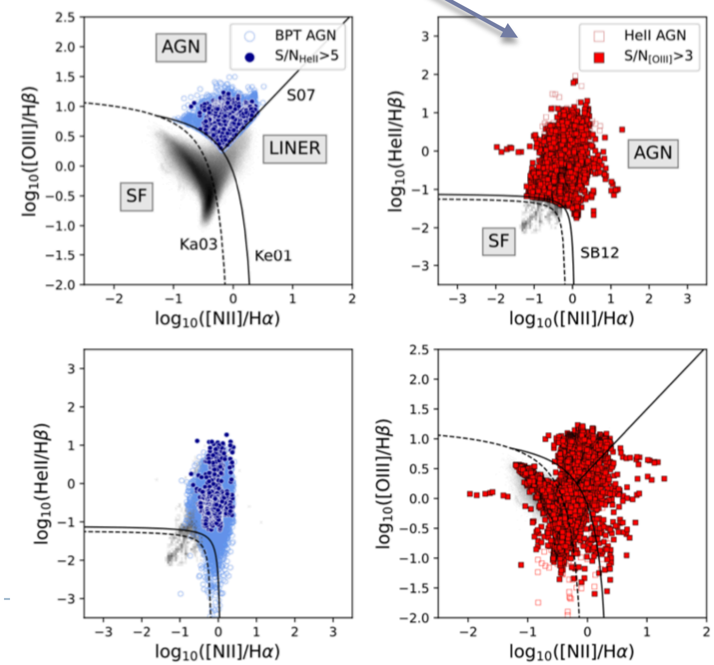


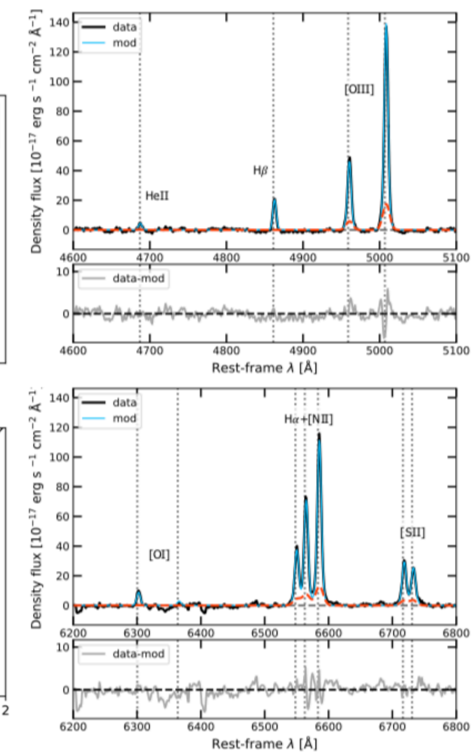
AGN diagnostics: optical spectra-2

- **DEW** diagram (Stasinska et al. 2006): $D_n(4000)$ against max(EW[OII],EW[NeIII])
- **WHAN**: (Cid Fernandes et al. 2011) Hα equivalent width vs [NII]/Hα. Useful also to classify weak-lined galaxies that lack bluer diagnostic lines (e.g., [OIII]5007/Hb).
- "BPT" in HeII (Tozzi et al. 2023)









Hot Gas

- Gas heated to 10^6 K (probably by SNe)
  - Powerful probe of mass distribution in galaxy clusters
- Detected via X-ray emission
  - Point source population
  - Diffuse hot gas
- Emission via
  - Brehmstrahlung
  - Emission lines of highly ionized species

Diffuse Hot Gas: Soft X-Ray Background

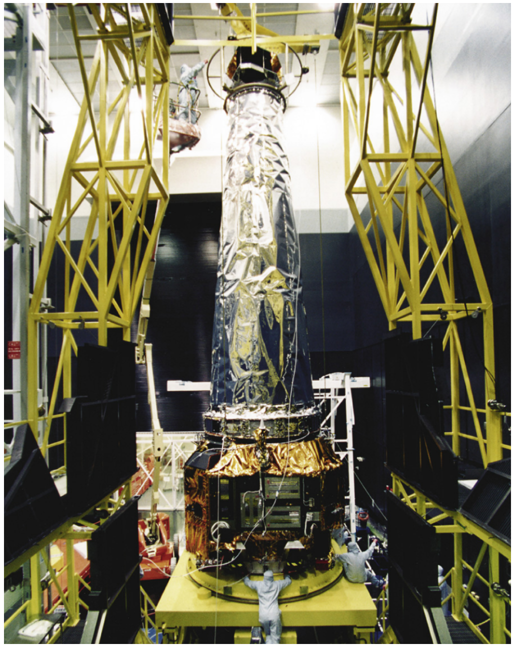
- McKee & Ostriker (1977): diffuse hot phase of the ISM with a filling factor of ~100%
- Early detection of X-ray emitting "superbubbles" in the Milky Way: Sco-Cen, Orion-Eridanus (McCammon et al. '83, McCammon & Sanders '90)
- Origin of Soft X-Ray background
  - MWG: local ISM + hot galactic halo
  - Local Group: hot intergalactic medium
  - Extragalactic: (un)resolved AGN + E galaxies

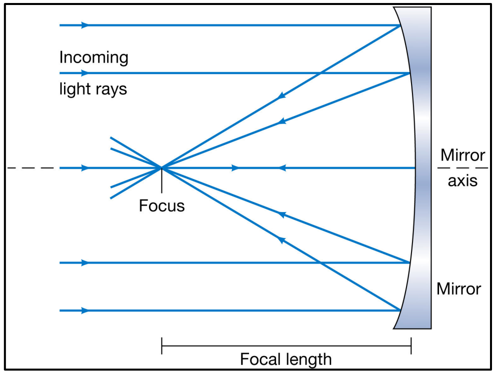
The Local Bubble

- Radius: 100-200 pc
- Temperature: ~2×10^6 K
- Thermal pressure: $p/k = 10^4$ cm^{-3} K
- N(HI) = 6×10^{18} cm^{-2} (derived from soft X-ray absorption)
- Origin of the Local Bubble
  - hot gas w/ 100% filling factor?
  - diffuse gas reheated by recent SNe?
  - a series of 2-5 SNe a few million years ago?
  - an extension of nearby superbubble?

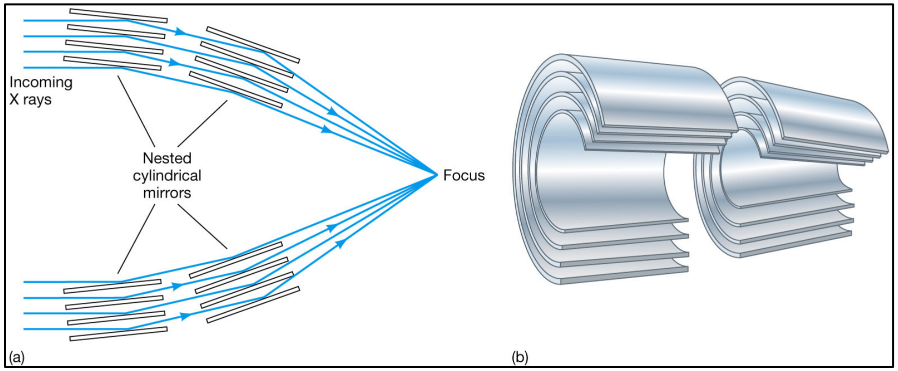
Comparison of X-Ray Observatories

- Einstein: 1' resolution
  - M101 (McCammon & Sanders 1984)
  - L_X(diffuse) ~ 10^{38}-10^{40} erg s^{-1}
- ROSAT (PSPC): 1.'8 resolution, 0.1-2 keV
  - M101, N3184, N4395, N5055, N4736 (Cui et al. 1996)
- CXO (Chandra): <1" over 8 arcminutes
- XMM/Newton: 15" over 30 arcminutes

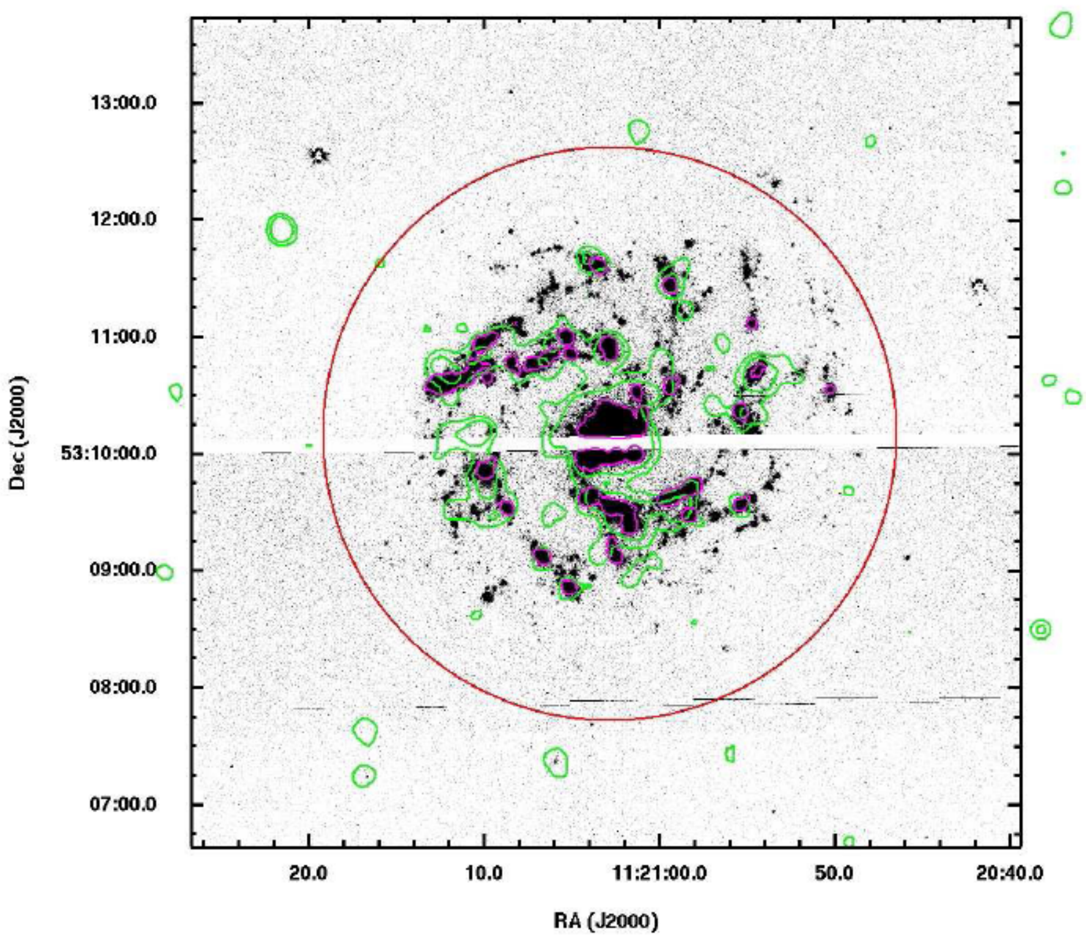




Mirrors:
←Optical
X-ray→



X-ray vs HII region comparison NGC 3631



X-ray emission

Hα emission (WIYN)

(Doane et al. 2007)

Temperature Comparison (10^6K)

- LMC Superbubbles: 1.7-9
- Orion-Eri.: 3.3
- N. P. Spur: 3.0
- Sco-Cen: 4.6

- NGC3631: 1, 3
- NGC6946: 2, 7
- M101: 2 ,8
- N253(halo): 4
- M82(halo): 3, 4

Spirals are best fit with two temperature models of hot gas, but there is variation in the high temperature and surface brightness.

Summary of X-Ray Results

- Diffuse emission is highly correlated with both spiral arms and HII regions
- Bulk of the diffuse emission arises from less than 25% of the area of the disk
- X-ray spectra are best fit with a two temperature model
- There is variation in the surface brightnesses between galaxies and variation in the temperature of the hot component

Star formation

- Basic raw materials:
  - Molecular mass at some critical density
    - recall instabilities to gravitational collapse: the Jean's length
  - Spiral arms collect gas into shocks, accelerating collapse
- On a large enough scale, clouds should make stars according to the initial mass function (IMF) and do so largely in clusters
  - there are interesting deviations from this

- Whatever factors give rise to spiral structure, this is where most of the star-formation occurs.
- What we do see: Massive stars and the effect of their radiation
- What we don't see (directly): low-mass stars
  - How can we detect them?

Tracers of massive stars: UV to Mid-IR

- UV luminosity
  - Directly traces the massive stars and their supply of ionizing photons
  - Susceptible to extinction!
  - Requires UV telescope (GALEX)
- Emission lines arising from ionized gas
  - Not as susceptible to extinction (at least Hα)
  - Measures the number of recombinations

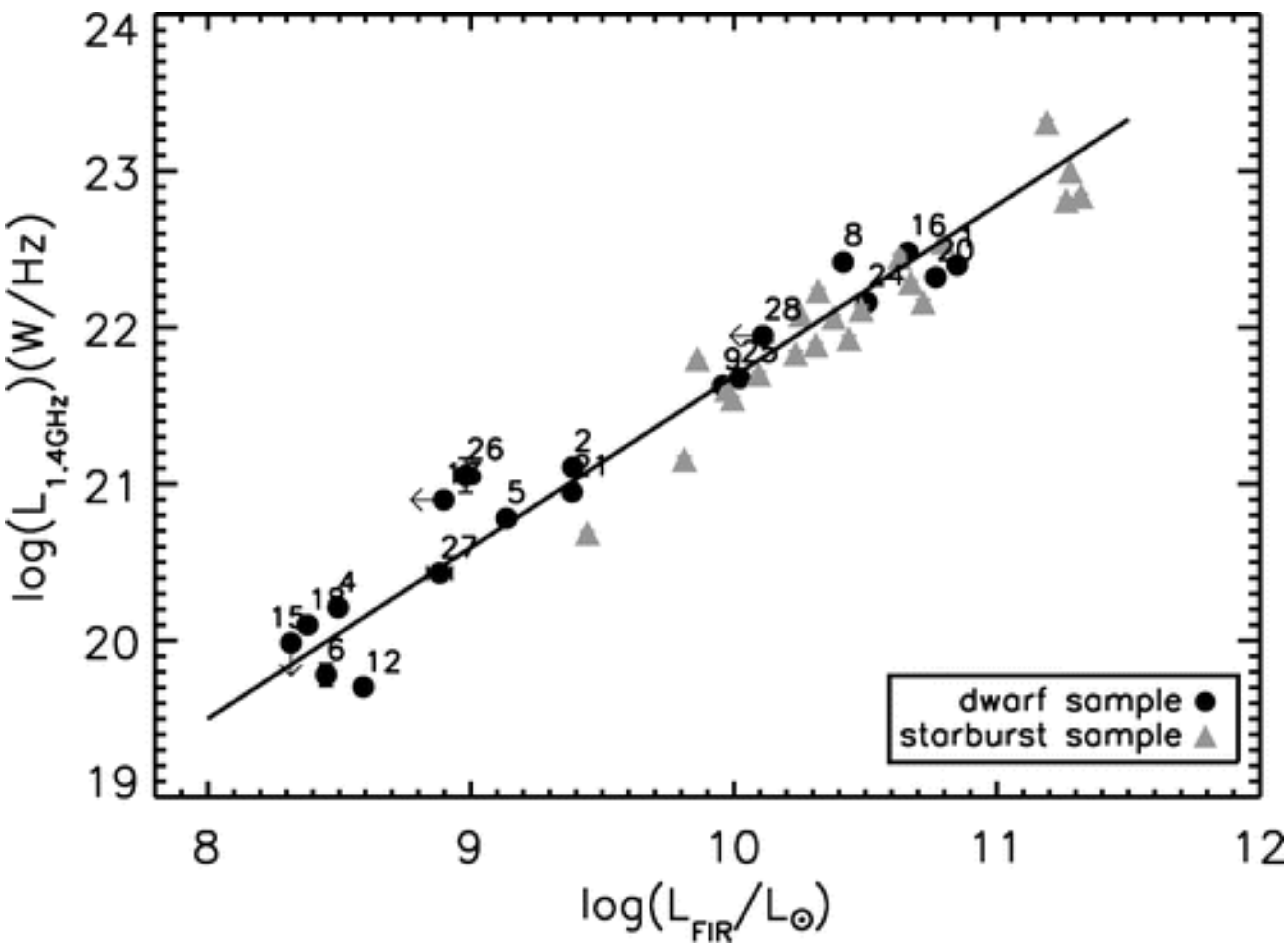
    = number of ionizing photons

    = number of massive stars
- Warm Dust
  - Photons warm surrounding dust ➔dust reradiates in sub-mm and far-IR (based on properties of dust: T and composition)
  - Unaffected by extinction (it *is* the extincting material!)

Tracers of massive stars: radio continuum

- Continuous radiation from free electrons (free-free emission)
  - Depends on electron density ρ_e
  - ρ_e depends on numbers of ionizing photons and massive stars
    - Unaffected by extinction
- Radio synchrotron emission
  - Massive stars explode ➔ expanding shocks accelerate particles to relativistic velocities ➔ combine with magnetic field ➔ synchrotron emission
    - Indirect measure of number of Sne
- The Far-IR/Radio continuum correlation:
  - Massive stars warm dust ➔ Far-IR
  - SNe accelerate cosmic rays ➔ radio continuum
    - But this hasn't really been demonstrated and
    - Implies a fixed fraction of SNe energy is converted into cosmic rays

Far-Infrared – Radio-Continuum correlation



Wu et al. 2008, AJ 676, 970

Tracers of star formation

- Is any one better than the others?
  - Depends on redshift
  - UV hard to measure at low redshift
    - not visible from ground
  - Hα hard to measure at high redshift
    - moves into NIR where sky is bright
  - Sub-mm sensitivity and radio continuum sensitivity isn't what it needs to be for high-redshift measurements

- Primary limitations are two-fold:
  - Only measures the number of massive stars (those massive enough to emit lots of ionizing photons)
  - No single tracer can be used well over broad range in redshift

Estimating Star-formation rates

- Assume:
  - All ionizing photons, $Q(H^0)$, produced by stars
  - Each ionizing photon ionizes an atom
  - The rate of ionization is balanced by the rate of recombination (Osterbrock):
- Then:

$$Q(\mathrm{H}^0) = \int_0^{r_s} N_p N_e \alpha_B(T)\, dV$$

  - N_e = number of electrons
  - N_p = number of protons
  - α_B is recombination coefficient (Case B) *
  - r_s = Stromgren sphere
- If $N_e = N_p$ and we take the Ha luminosity to be:

$$L(\mathrm{H}\alpha) = h\nu_{\mathrm{H}\alpha} \cdot \int_0^{r_s} N_p N_e \alpha_{\mathrm{H}\alpha}(T)\, dV$$

- Then the number of Lyman continuum photons is:

$$N_{\mathrm{Lyc}} = L_{\mathrm{H}\alpha} \times 7 \times 10^{11}$$

* Gas is optically thick to ionizing (Lyman continuum) photons

Star-formation rates continued

- Recall Stellar IMF
  - $N_o \int dM\, M\, \xi(M)$ = total mass of burst/episode, $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
- Young, massive stars (on MS) producing nearly all ionizing radiation
- On MS there is a mass-T relationship
- Integrate IMF weighted by ionizing luminosity per star of mass M to get N_{Lyc}
- Extrapolate integral over full mass of IMF to get total mass
- Current best estimates: K98
  - SFR ($M_\odot$ year^{-1}) = 7.9×10^{-42} L(Hα) (ergs s^{-1}) = 1.08×10^{-53} Q(H^0) (s^{-1})
    - Case B for T_e = 10,000 K
  - SFR ($M_\odot$ year^{-1}) = $(1.4\pm0.4)\times10^{-41}$ L[OII]$_{\lambda3727}$) (ergs s^{-1})
    - empirical
  - In all cases, must correct for extinction

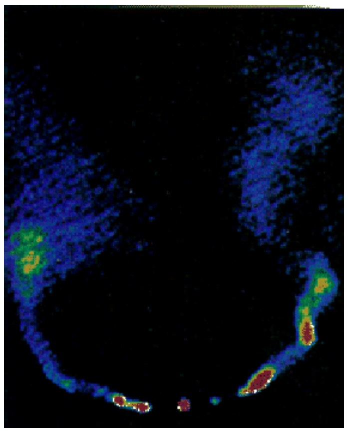
Can extend to Paschen series where extinction is smaller; see Calzetti et al. (2005)

- Why not measure N_{Lyc} directly?
- What about UV continuum at wavelengths longer than the Lyman limit?
- What about the FIR (what heats the dust)? Radio continuum?

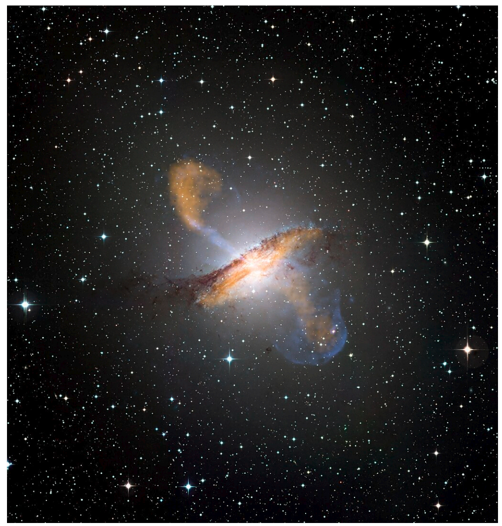
- See: Kennicutt et al.: 1983 1984, 1989, 1998, 2003, 2009; Lee et al. 2009

Feedback: Motivation

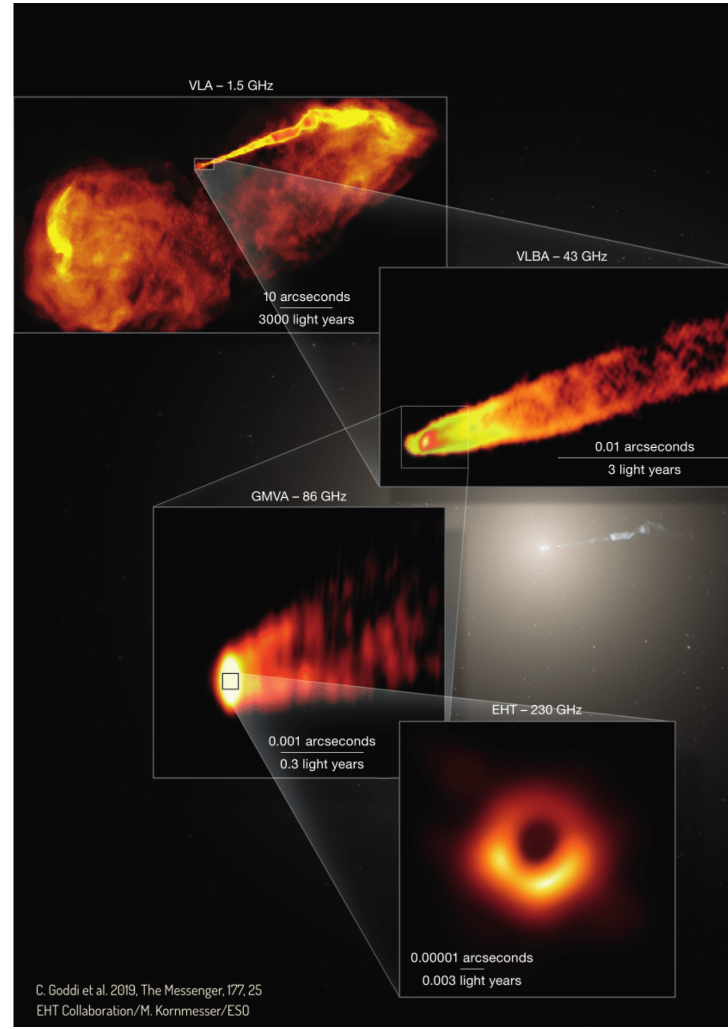
- We know AGN and SNe inject a lot of energy into the ISM



NGC 1265: Begelman& Rees1996
VLA, radio continuum



Cen A: orange: 850um, blue xray



M87 in Virgo cluster; Goddi+2019

- Massive radio jets extend to ~Mpc scales.
- Found in *massive* (cD) *galaxies* in clusters.
  - (Asides: bent tails tell us about CGM (hot gas in clusters; hooked tails tell us about SMBH precessing)

Feedback: Motivation

- We know SNe and AGN inject a lot of energy into the ISM (see next slide for SNe)

NASA: HST

NASA: HST + Spitzer (infrared, colored red), Chandra (X-ray, colored blue)

Feedback: Impact of Massive Stars

- Stellar winds + SNe dump $10^{53.5}$ ergs into ISM
- Creates hot bubble surrounded by swept up ISM and circumstellar matter
  - gas heated by inward moving shock
- X-ray emission should be aligned with HI holes
- growth of chimneys
  - means of getting hot gas into the halo

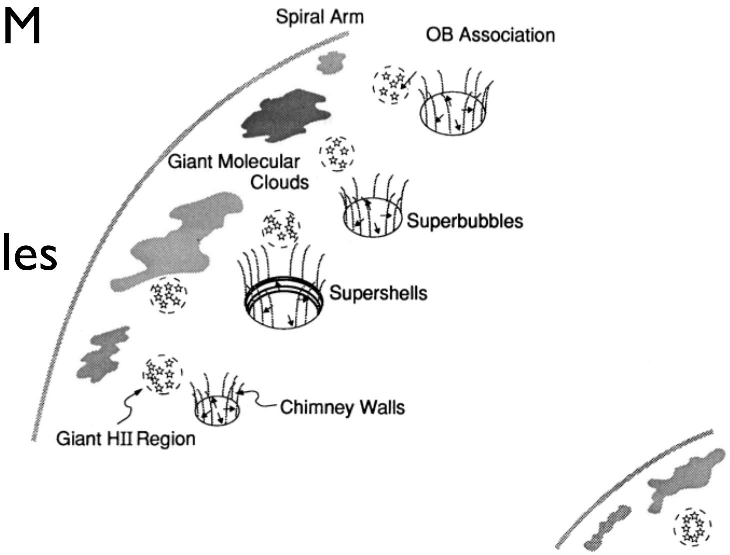
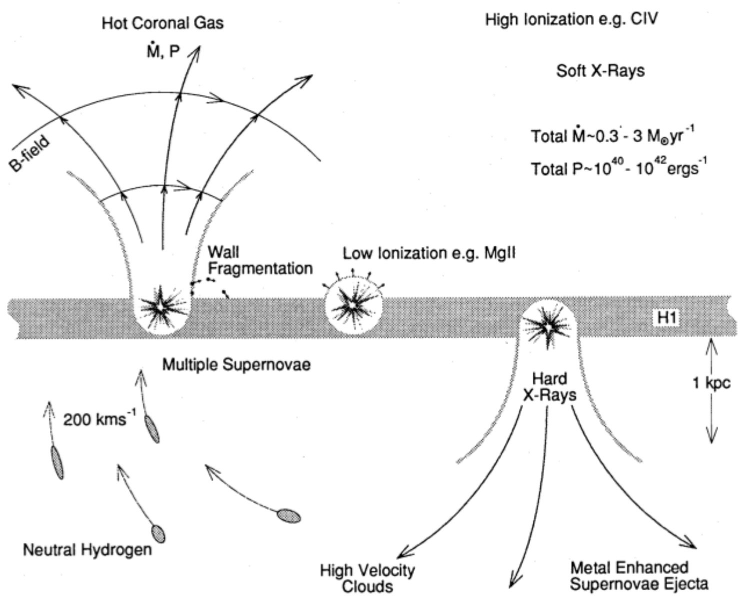
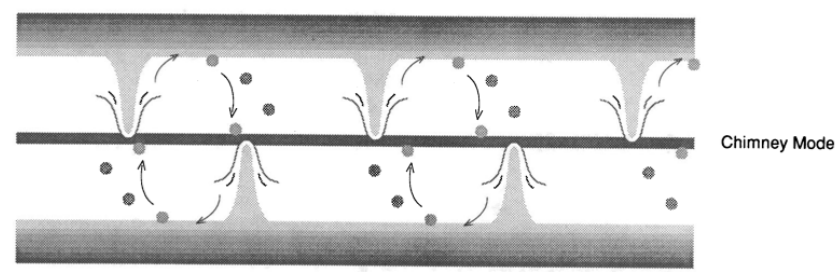


Fig. 4a





Norman & Ikeuchi 1989

Feedback: Bubbles

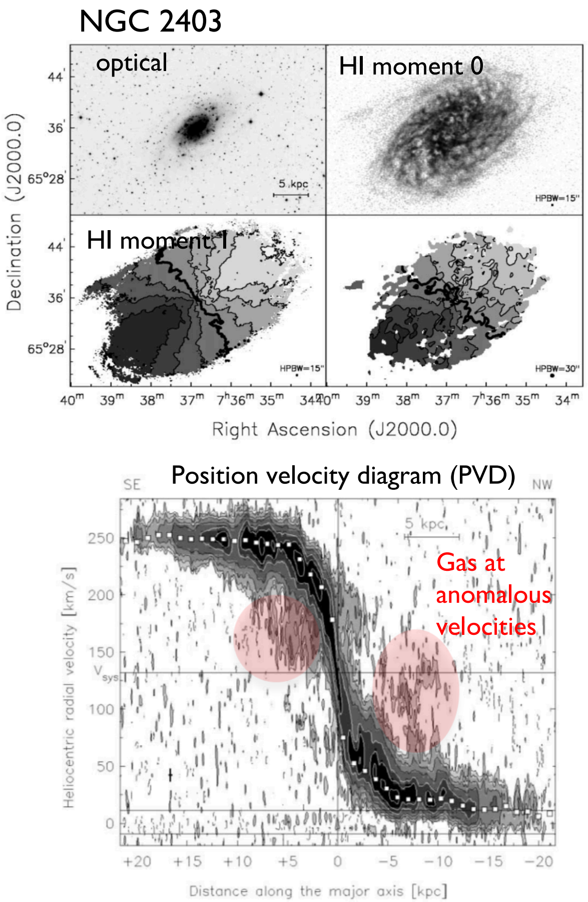
- Stellar winds/SNe drive expanding bubbles into ISM
  - $R_s \sim 100\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}$ pc (McCray & Kafatos 1987)
  - $V_s = L_W^{1/5} n_0^{-1/5} t_7^{-2/5} \sim 6\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}$ km s^{-1}
  - Reverse shock heats bubble to 10^6-10^7 K → X-ray emitting
  - Shell includes swept up ISM, dense neutral gas, possibly accelerated particles

R_s – shell size
N_* - number of stars formed with $M>7M_\odot$
T_7 – time-scale in 10^7 yr
E_{51} - SN energy / 10^{51} ergs
n_0 – intial electron density cm^{-3}
V_s – shell speed
L_W – mechanical luminosity of winds

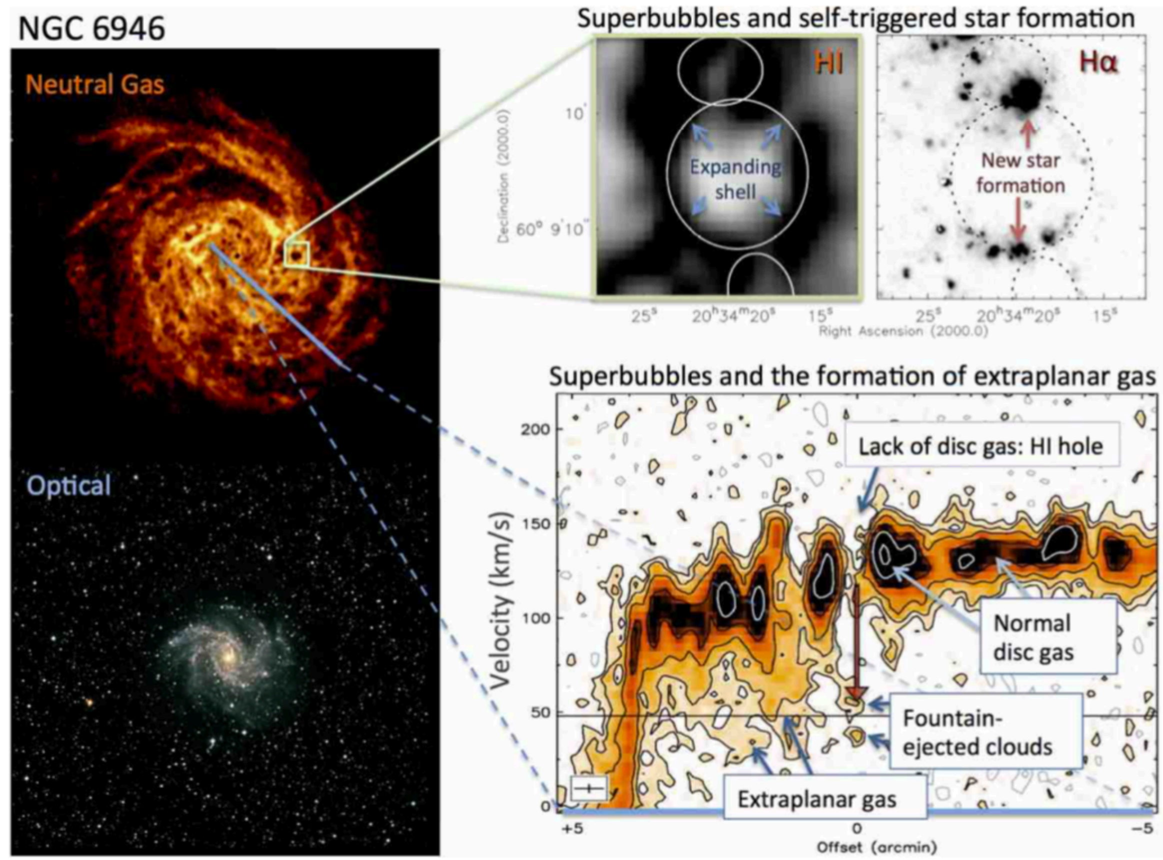
- Ultimate fate
  - Shell/bubble expands until $P_{bubble} = P_{ISM+IGM}$
  - Breaks out of disk if

    $P_{bubble} > P_{ambient}$, $V_{shell} > V_{escape}$
  - Shell accelerates in density gradient

Feedback: Bubbles in HI data

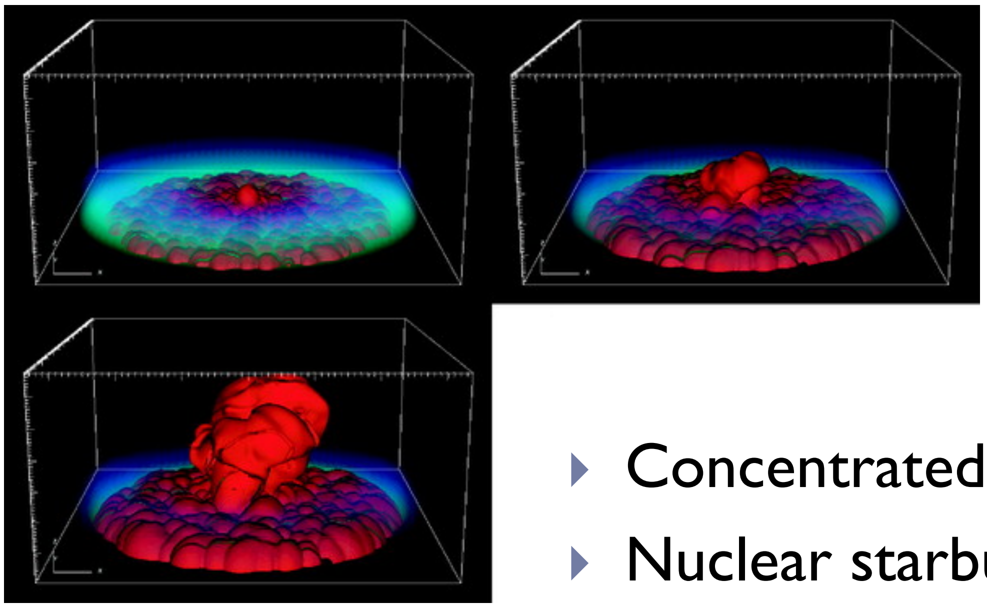


Fraternali+01



Fraternali+17

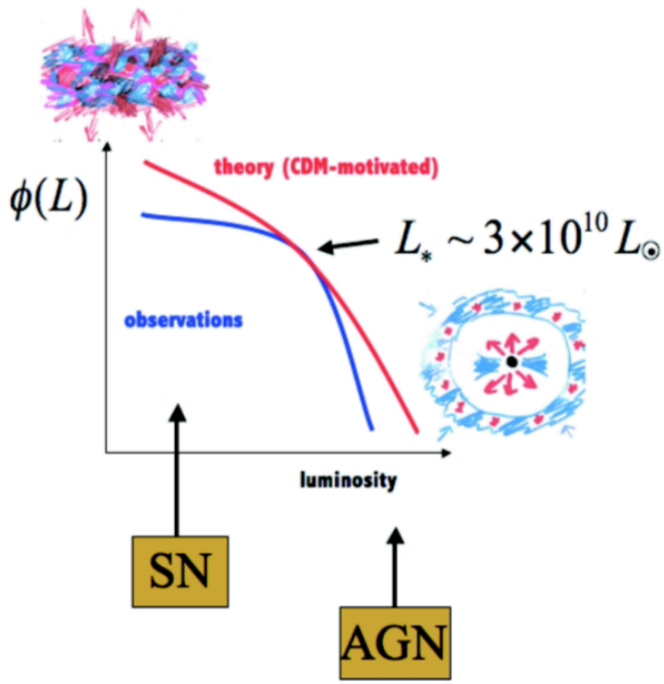
Extreme "Feedback"

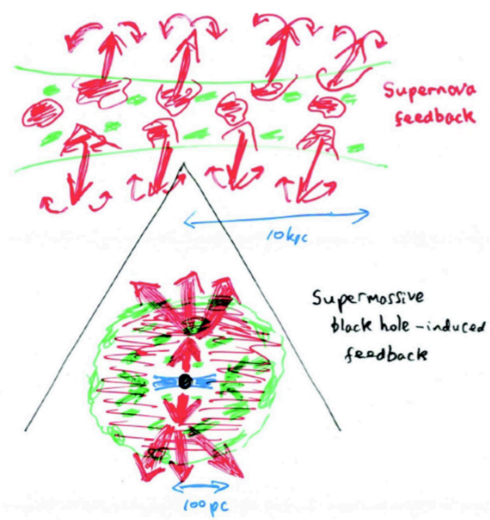


- Concentrated SNe
- Nuclear starburst → complete blowout of the ISM
  - What will M82 look like in 10^7-10^9 years?
  - Bursting dwarfs? (Dekel & Silk 1986)

Feedback: Motivation (continued)

- There is a discrepancy between the predicted dark-matter halo mass function and the observed luminosity (or stellar mass) function.





Silk cartoons

Feedback: other references

- In dwarf galaxies:
  - Dekel & Silk (1986)
- Broad context:
  - Silk & Norman (2009)
- Stellar feedback and galactic scale winds in simulations:
  - Hopkins, Quartaert, Murray (2012)
- Galaxy formation with feedback (review articles):
  - Somerville & Dave (2015)
  - Naab & Ostriker (2017)