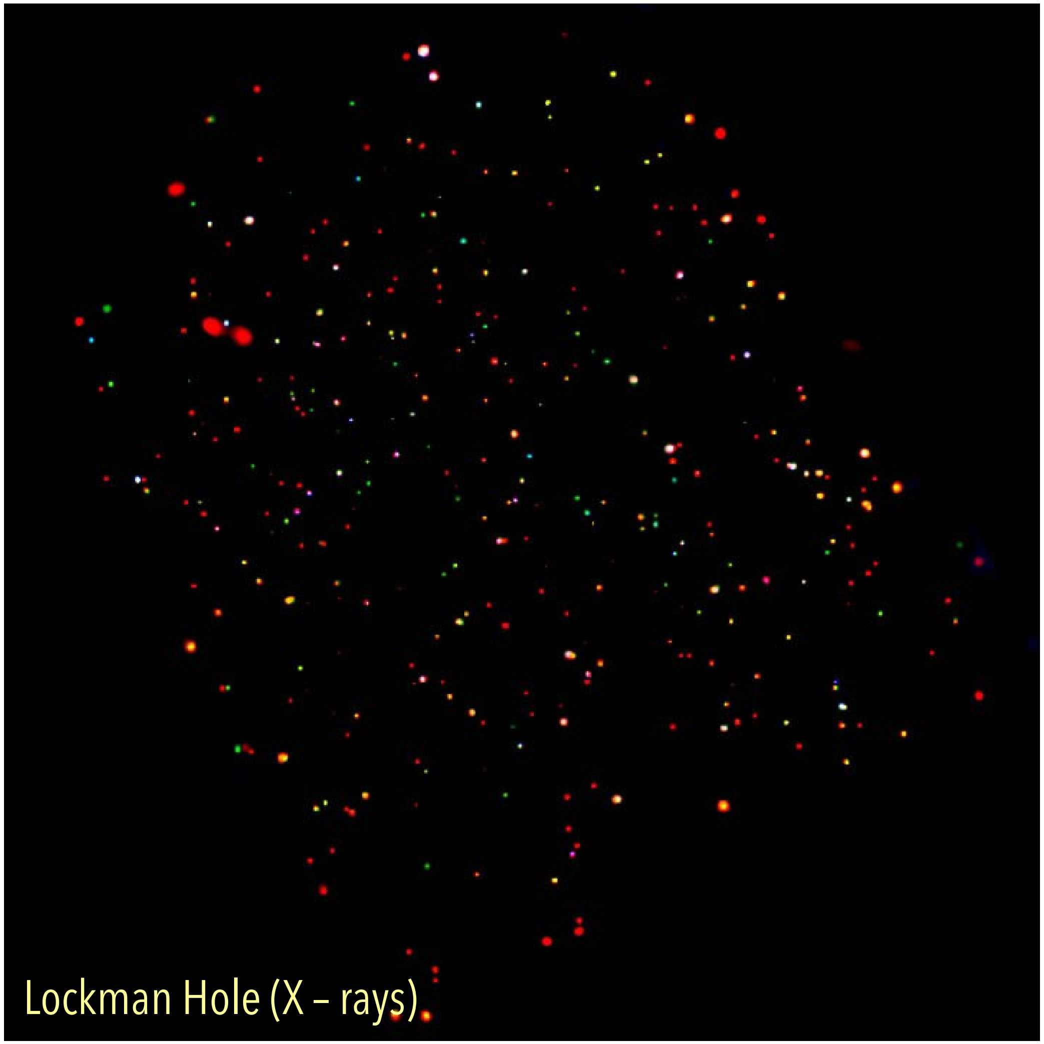
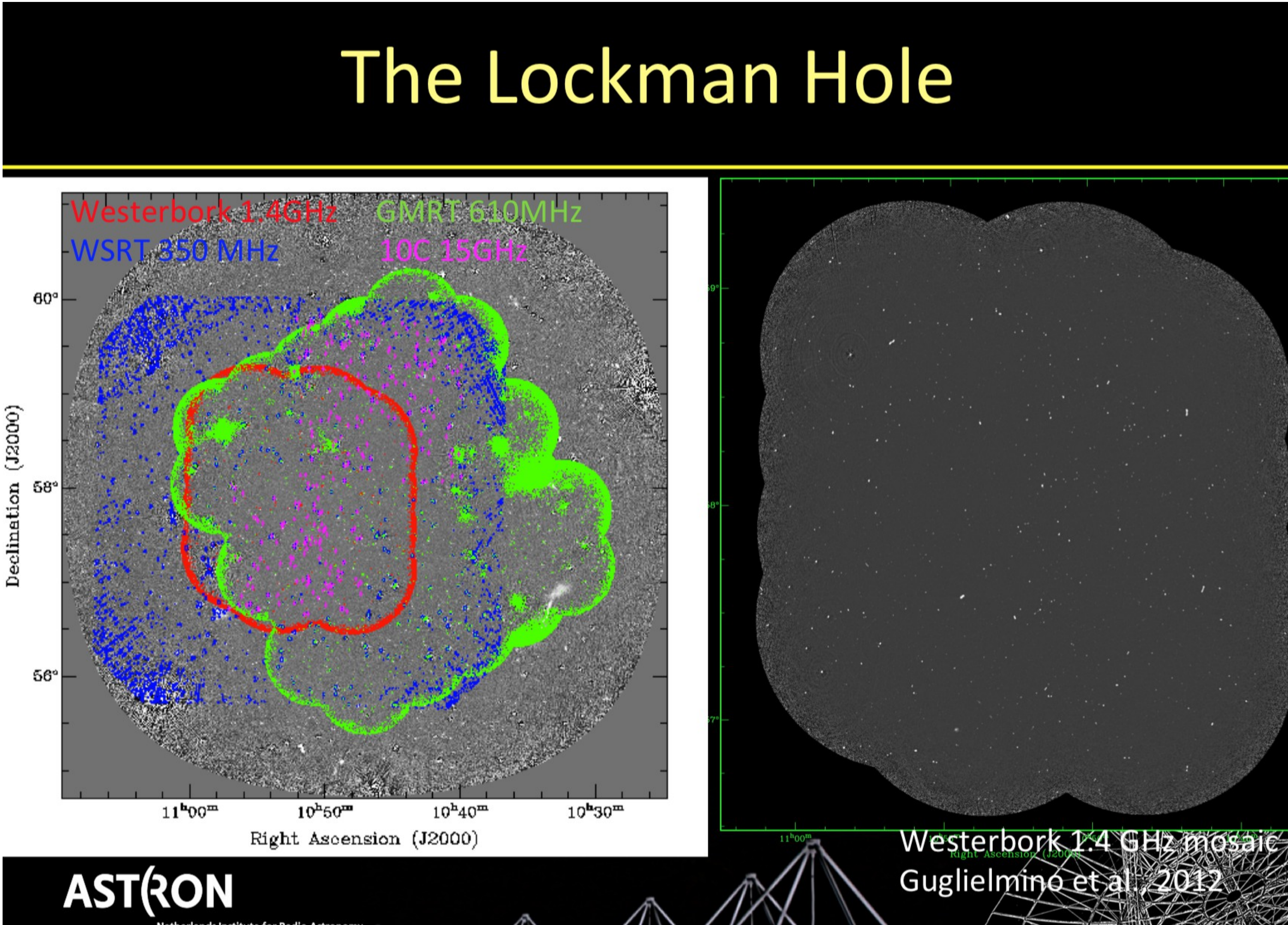
Radio Faint Population

Going deep in empty fields.

*Example: the Lockman Hole (direction with moderate **galactic** HI column density (6×10^{19} cm^{-2})*



Population studies at progressively lower and lower flux densities


The Lockman Hole
Westerbork 1.4GHz
GMRT 610MHz
WSRT 350 MHz
10C 15GHz
60°
58°
56°
Declination (J2000)
11h00m
10h50m
10h40m
10h30m
Right Ascension (J2000)
Westerbork 1.4 GHz mosaic
Guglielmino et al., 2012
ASTRON
Netherlands Institute for Radio Astronomy

Radio Faint Population: the "Lockman Hole"

HBA observations (110-180 MHz)

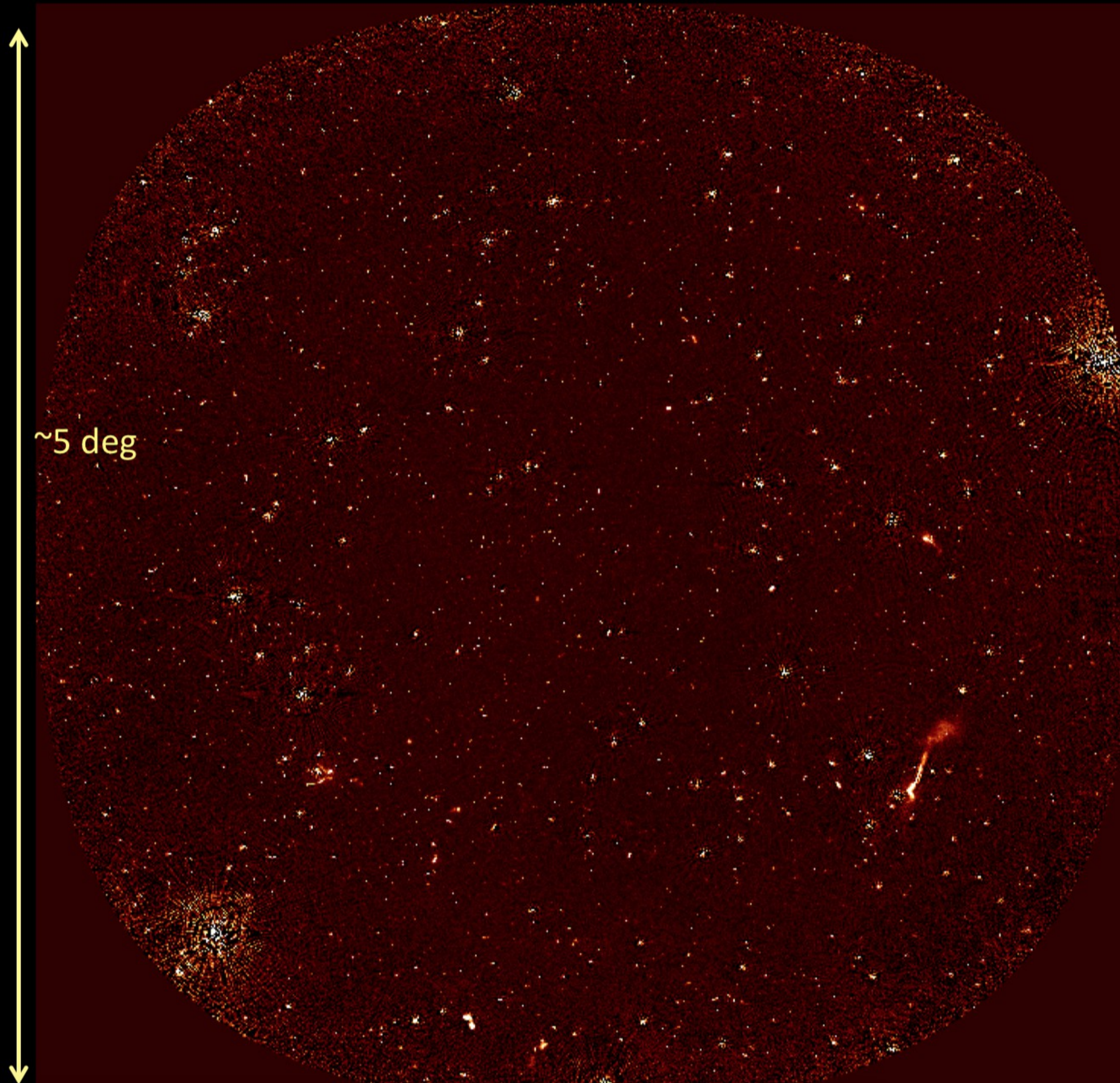
300 subbands (70 MHz bandwidth)

10 hrs int. time

14x18" resolution

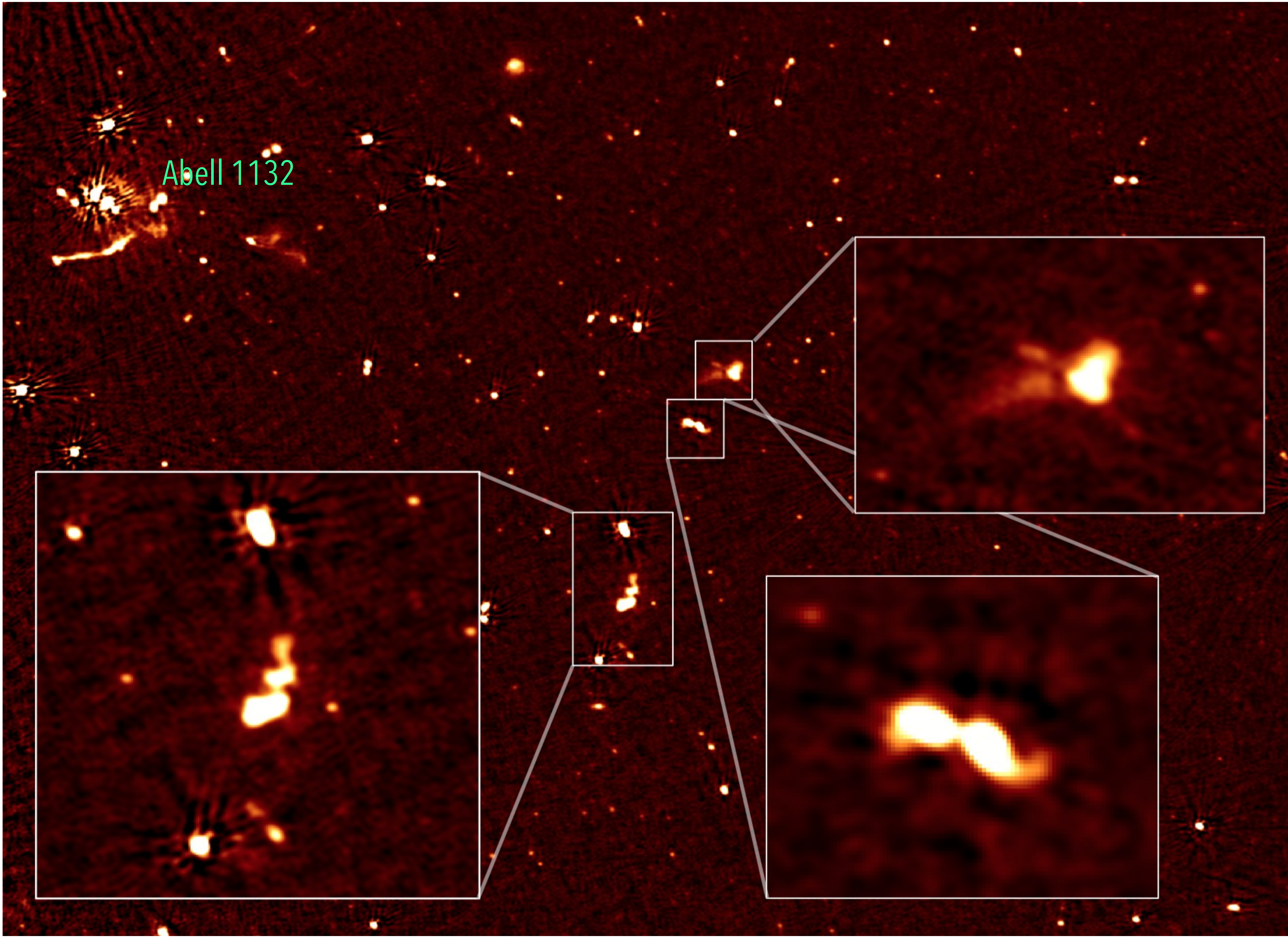
rms ~0.15 mJy

> 5000 sources detected



ASTRON
Netherlands Institute for Radio Astr

Radio Faint Population: the "Lockman Hole"



Radio (continuum) emission from

"NORMAL" GALAXIES (S, E, Lenticular)

STAR FORMING GALAXIES

ACTIVE GALAXIES

POPULATION STUDIES

Evolutionary model(s) for individual radio sources in AGNs

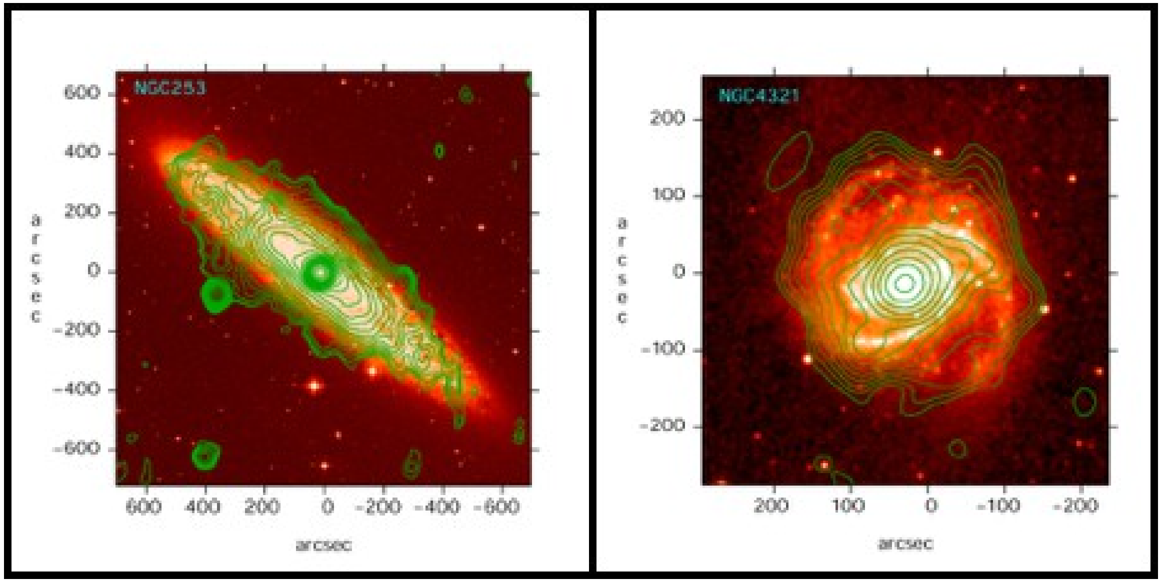
Radio (continuum) emission from "normal" galaxies

⟹ Condon, 1992, ARA&A, 30, 575-611

- *Ingredients: Bremsstrahlung, Synchrotron,… (some line emission?)*
  Diffuse emission: Disk (non-thermal & thermal), Halo (non thermal, low frequencies)
  Compact objects: SNR & RSN (non-thermal), HII regions (thermal) [Central source (!)]

- Ellipticals (& lenticulars)

- Spirals (& Irregulars)



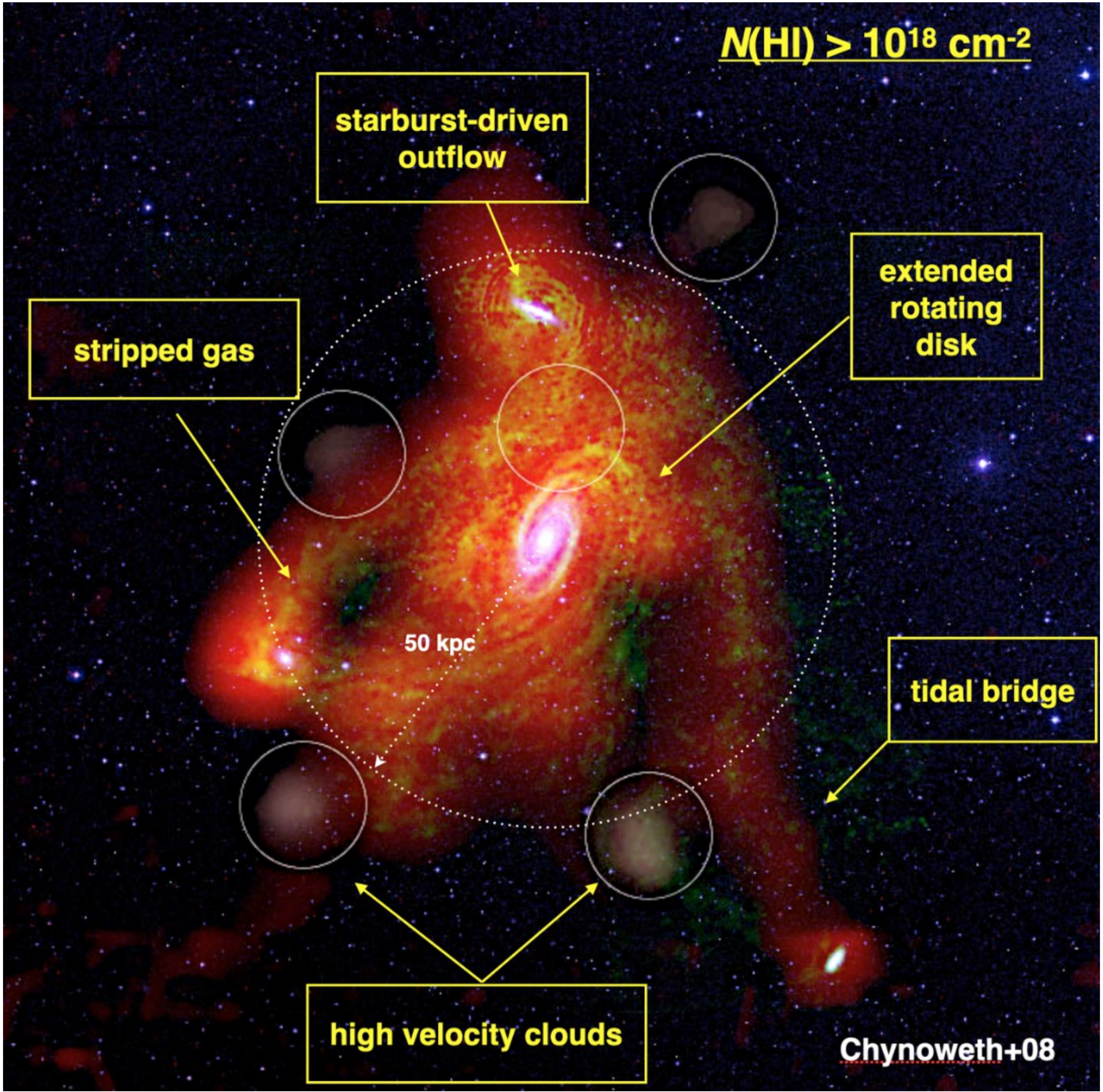
⟹ "Normal" interpreted as "without significant emission from an active nucleus"

Radio Continuum from Galaxies: a nearby example, the M81 – M82 group, > 34 galaxies

M82

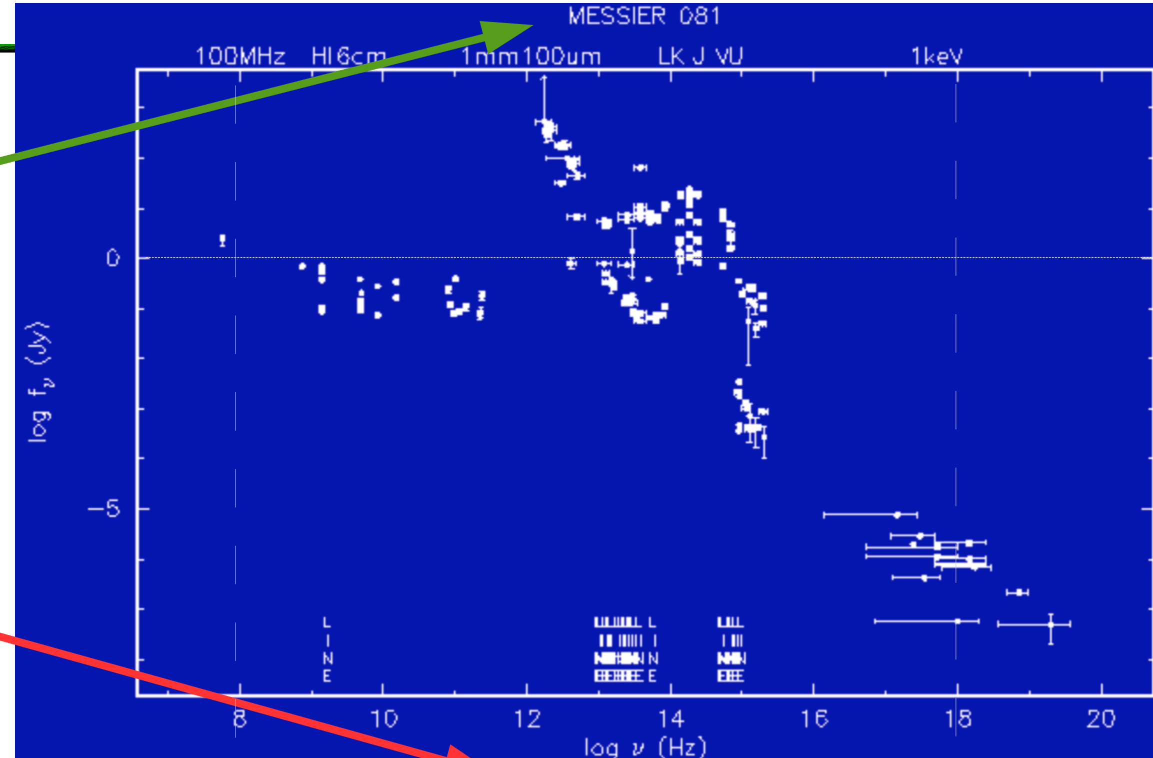
M81

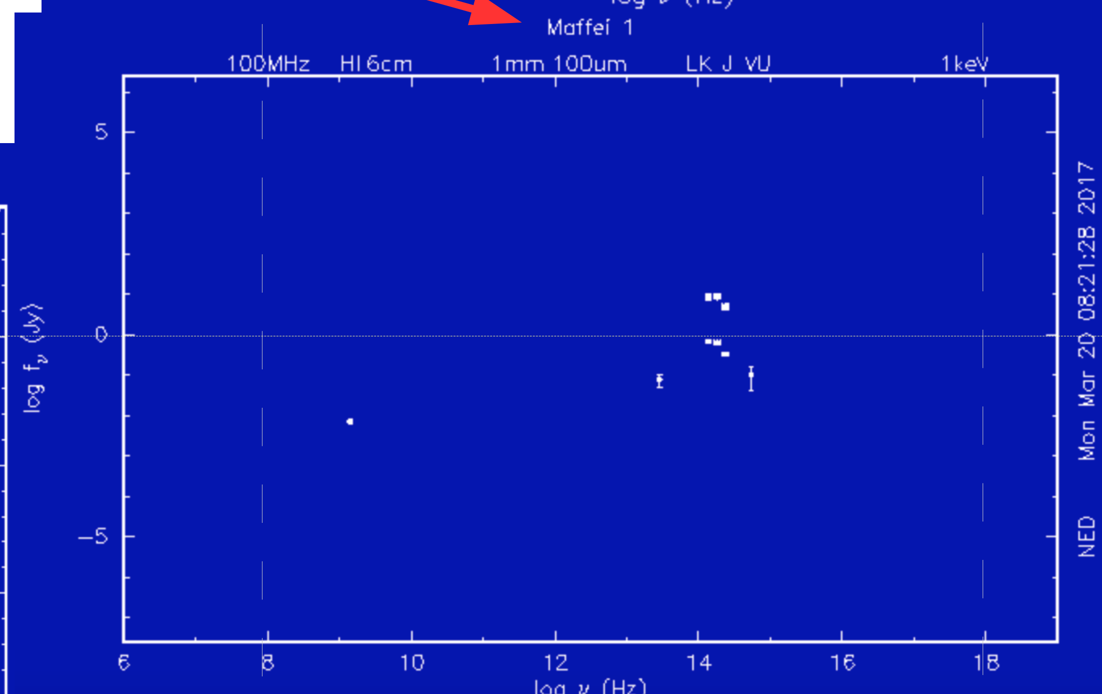
NGC2403

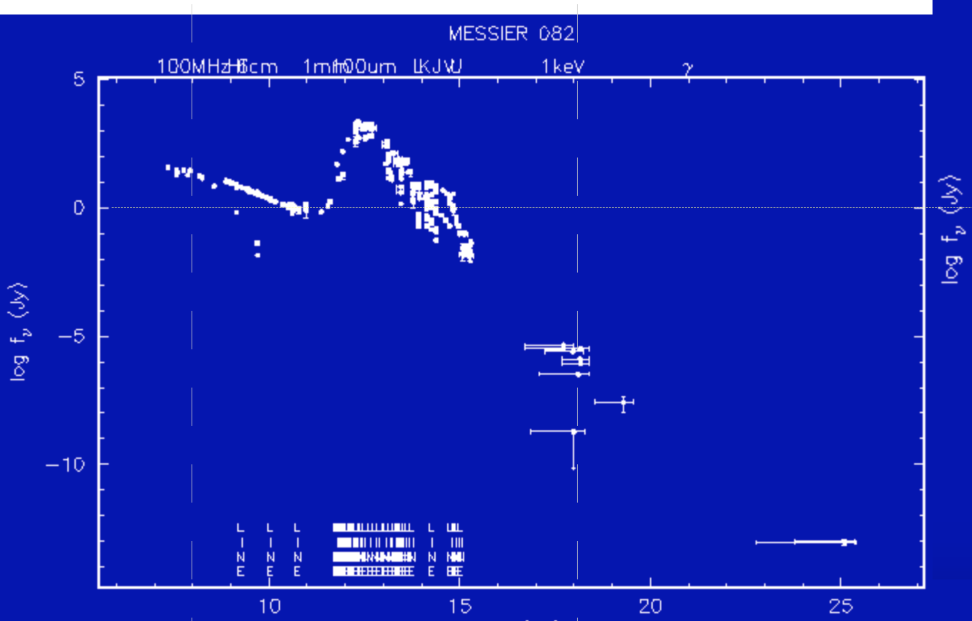


Nearby examples

- M81 (spiral, 3.63 ± 0.34 Mpc)
- M82 (starburst, 3.5–3.8 Mpc)
- Maffei 1 (elliptical, 2.85 ± 0.36 Mpc)





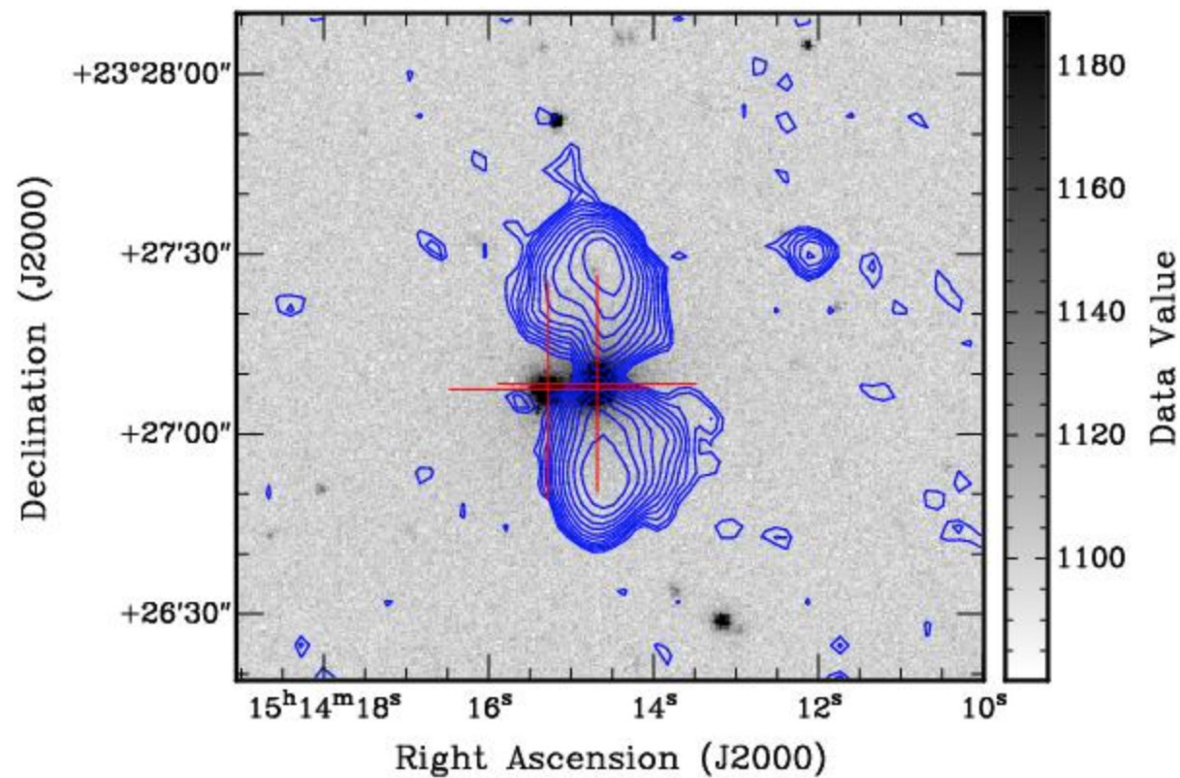


Ellipticals (& lenticulars)

- Wen Y.N. +, 2012 Cross match NVSS+FIRST & SDSS – DR6
- Sample of interacting (475) .vs. non–interacting (1828) galaxies (pairs): 6.7 % are detected (42/475 i.e. 8.8% .vs. 112/1828 i.e. 6.1%), while only 3.0% of isolated (59/2000) objects are detected

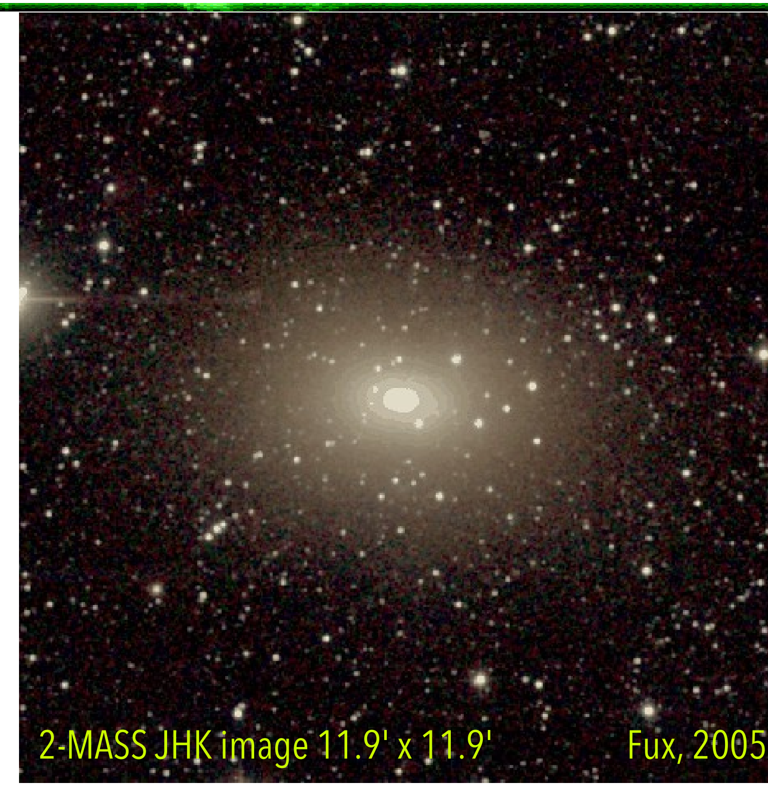
- Significant increase of fraction with luminosity (mass)

- **AGN emission**

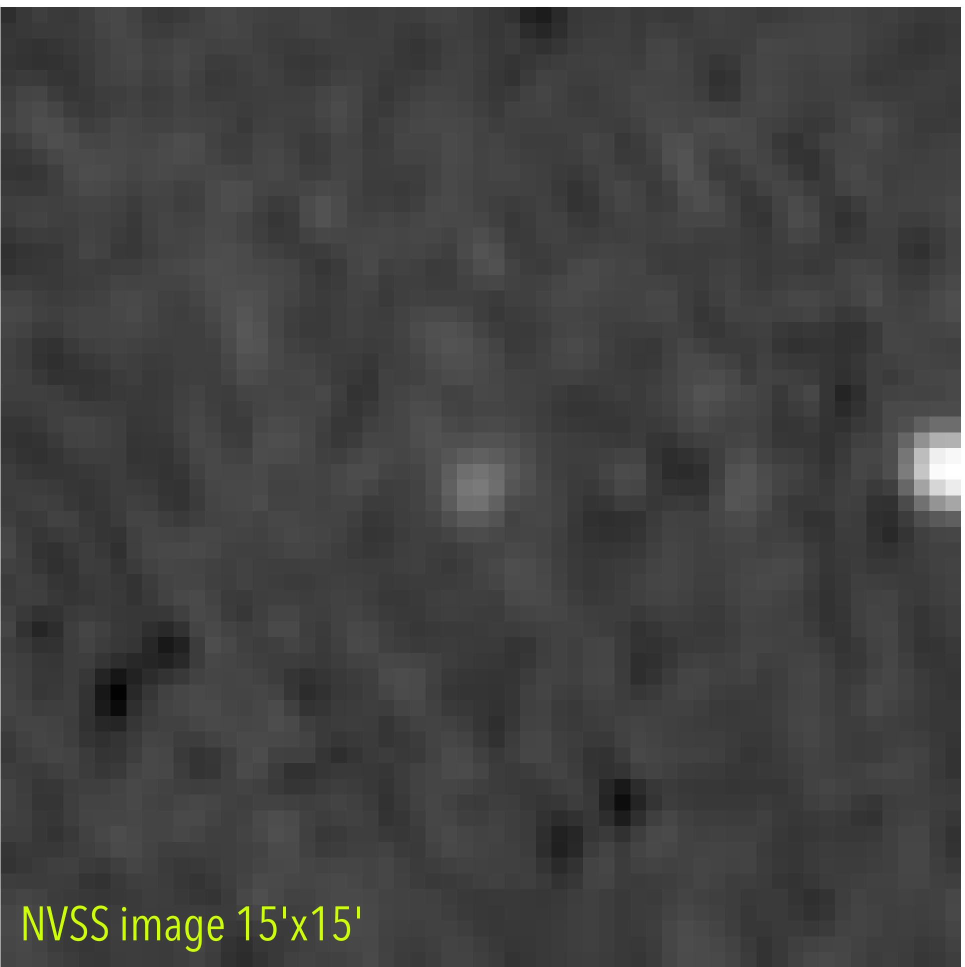


Ellipticals (& lenticulars)

- Maffei 1:
  closest ellipitcal galaxy (2.9 Mpc, behind the galactic plane)
- Radio image (bottom), NIR image (right)



images with same scale

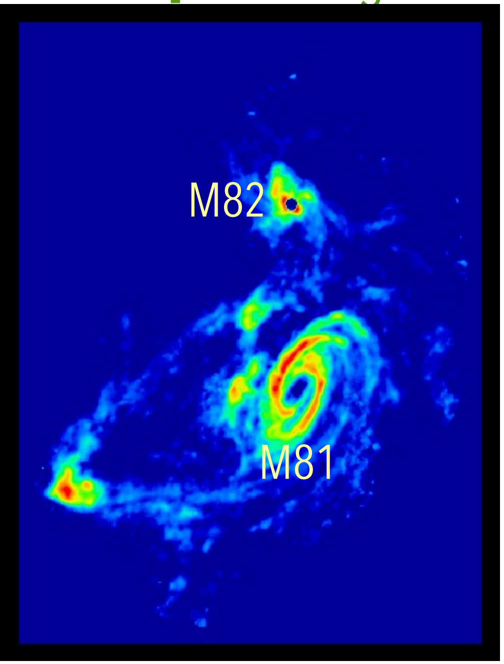


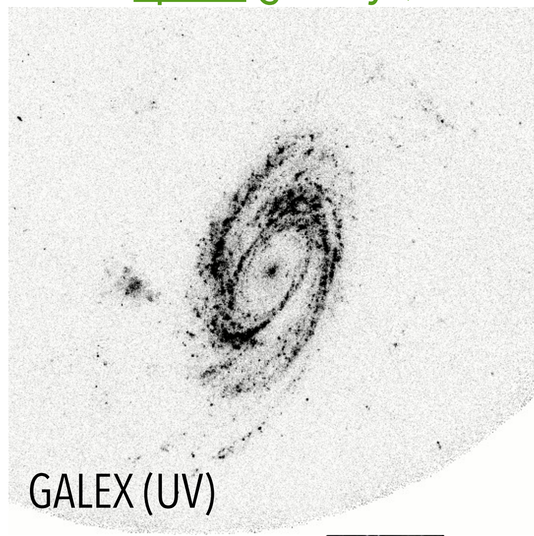
$$\text{at } 1.4\,\text{GHz}, \quad S(\nu) = 7.1\,\text{mJy}$$

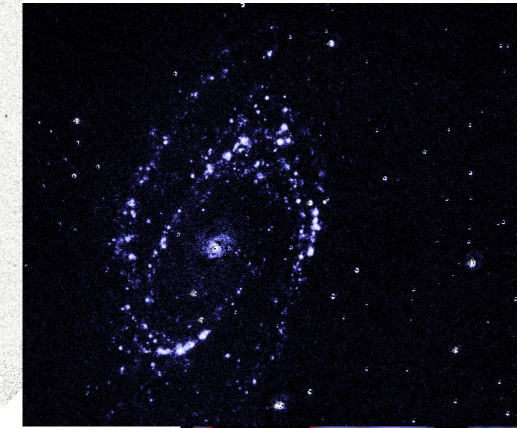
$$L_\nu = 4\pi D_L^2 S(\nu)$$

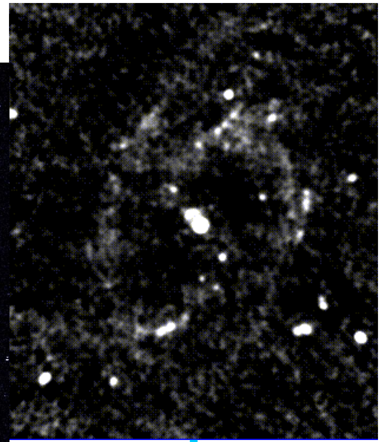
$$L_{1.4\text{GHz}} = 7.1 \cdot 10^{18}\,\text{W}\,\text{Hz}^{-1}$$

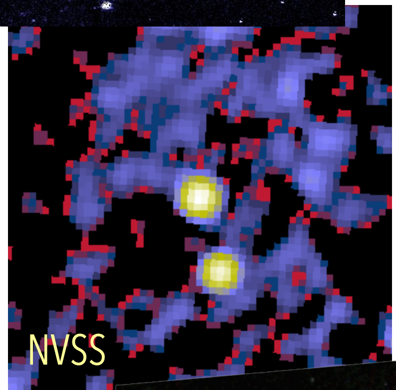
M81 [excluding Andromeda, closest spiral galaxy (@3.7 Mpc) (group with M82)]

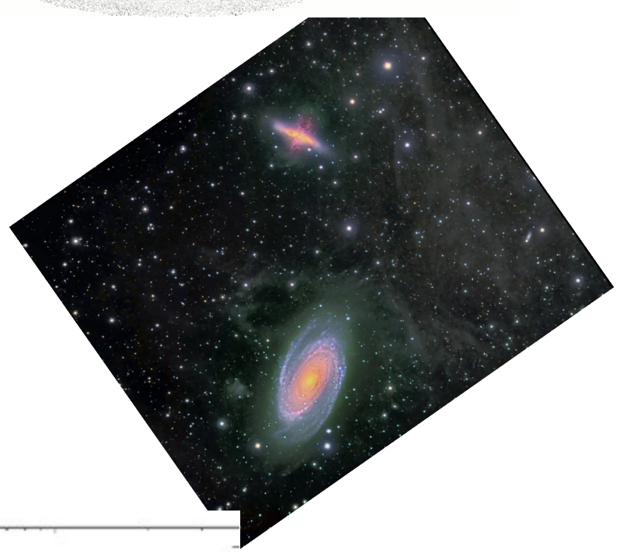


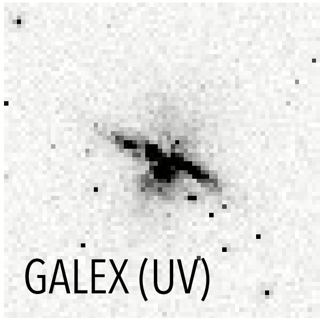


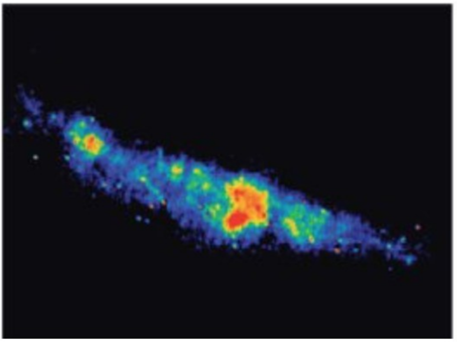


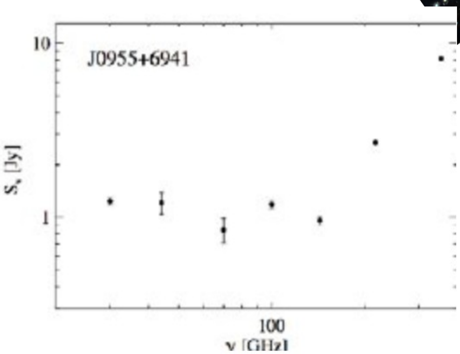


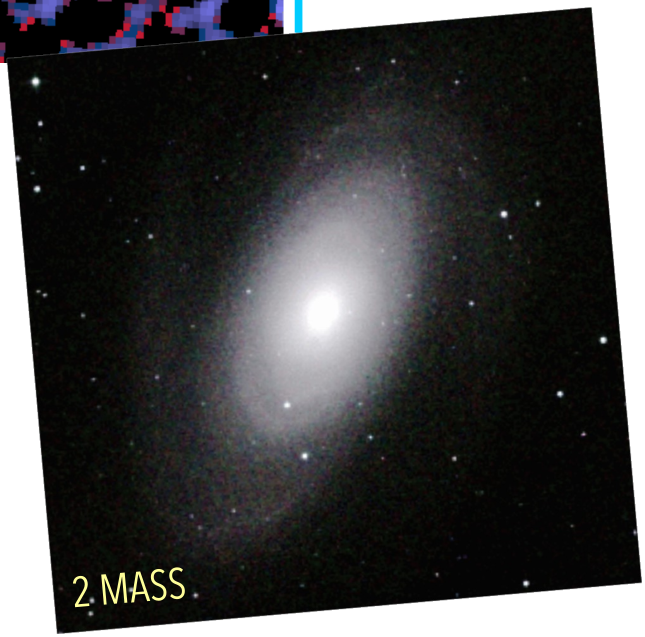




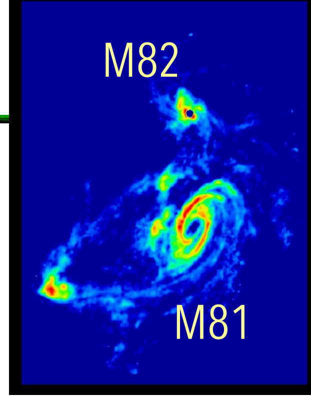


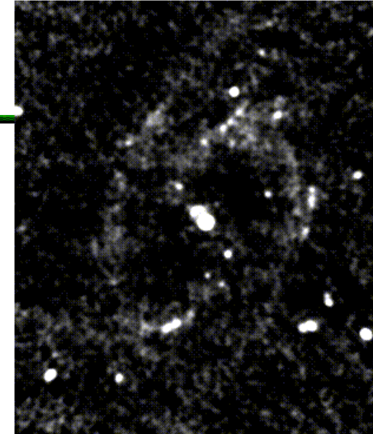




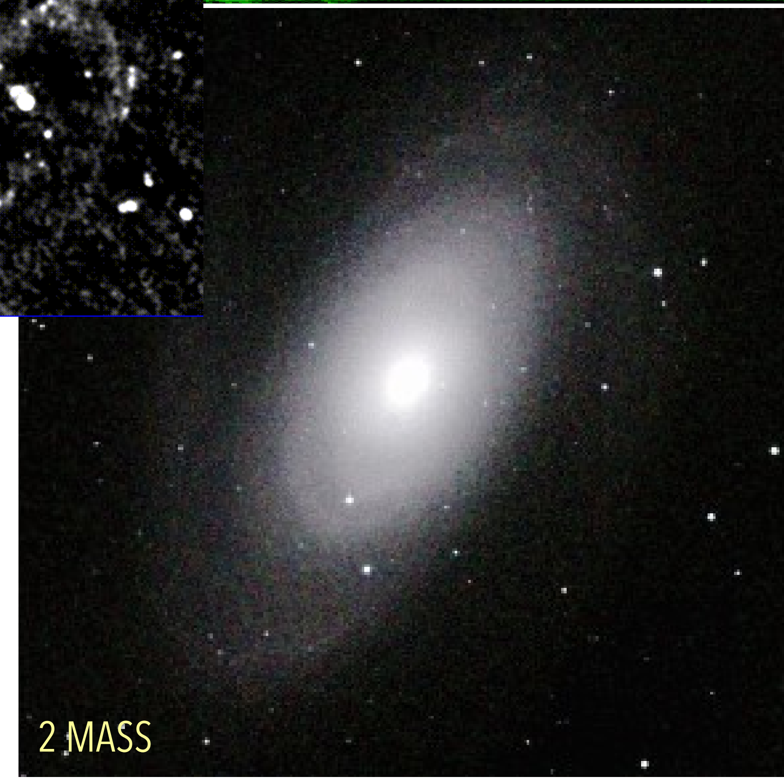


Spirals (& irregulars)

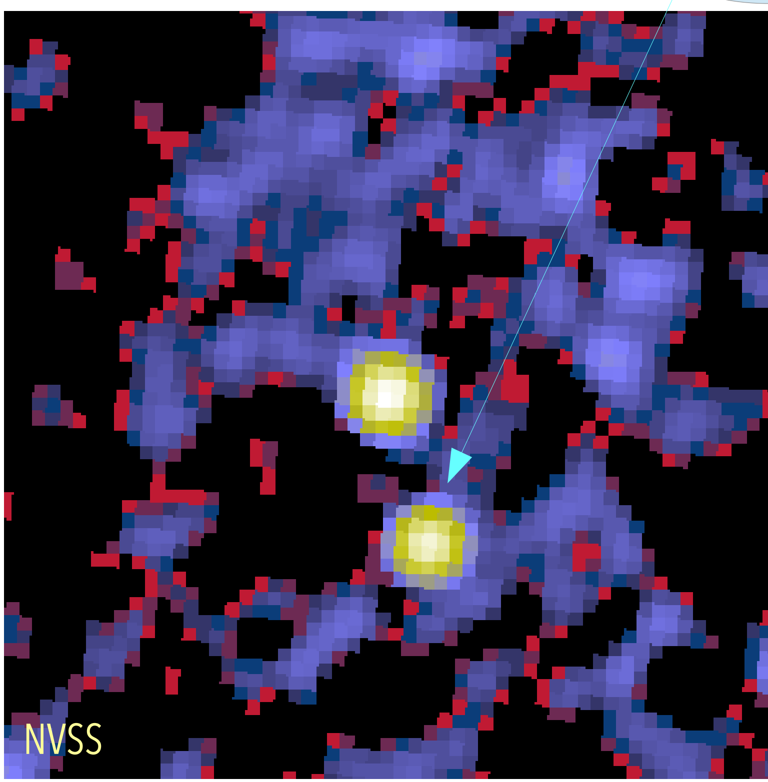




- M81
  closest spiral galaxy (3.7 Mpc) (group with M81)
- Radio image (bottom), NIR image (right)



Background QSO



images with same scale

$$L_\nu = 4\pi D_L^2 S(\nu)$$

at 1.4 GHz, it is difficult to separate nucleus/extended

$$S(\nu)_{nucleus} \approx S(\nu)_{ext} \approx 80\,\mathrm{mJy}$$

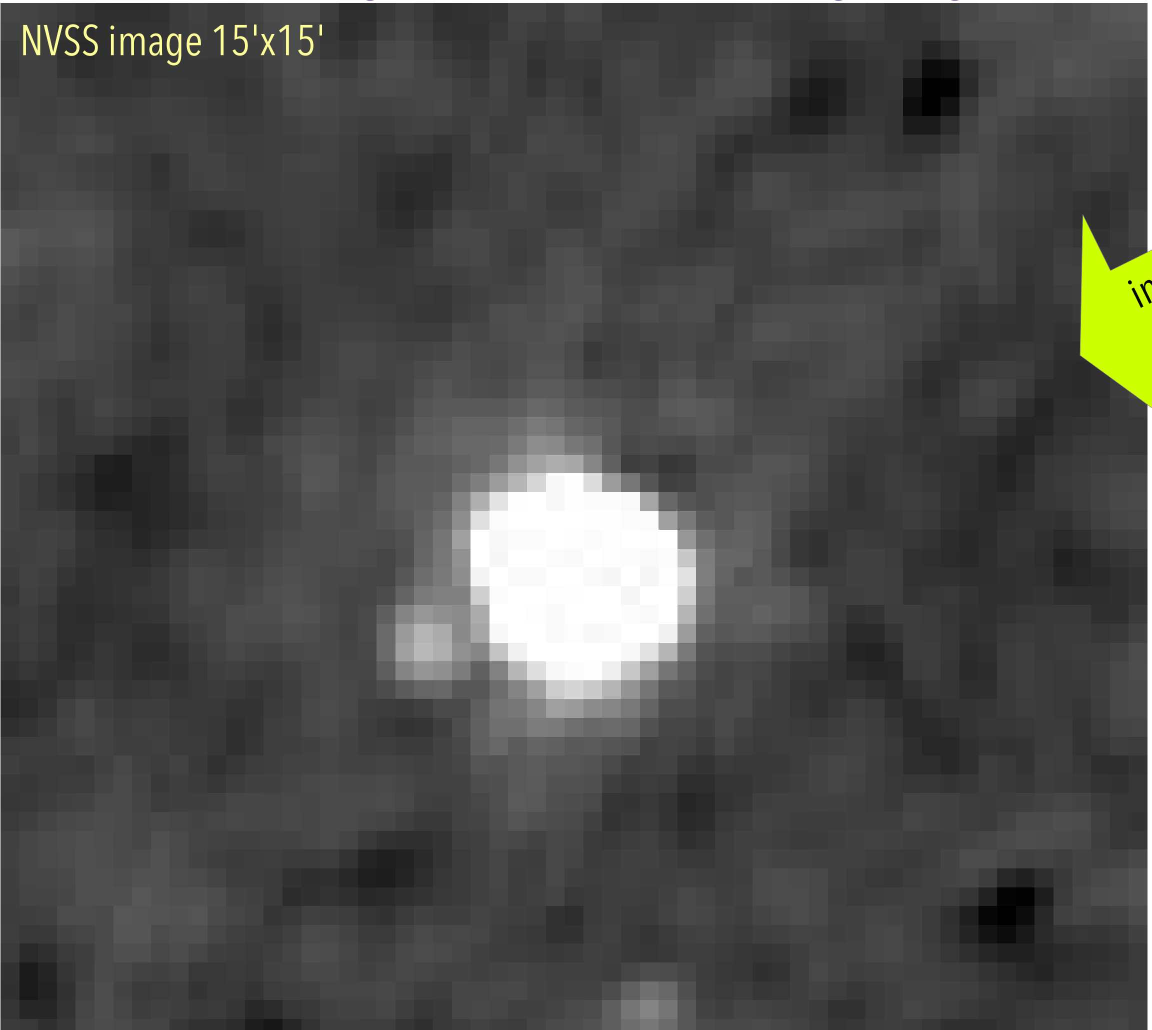
$$L_{1.4GHz} \approx 1.0 \cdot 10^{21}\,\mathrm{W\,Hz^{-1}}$$

For both AGN + extended emission

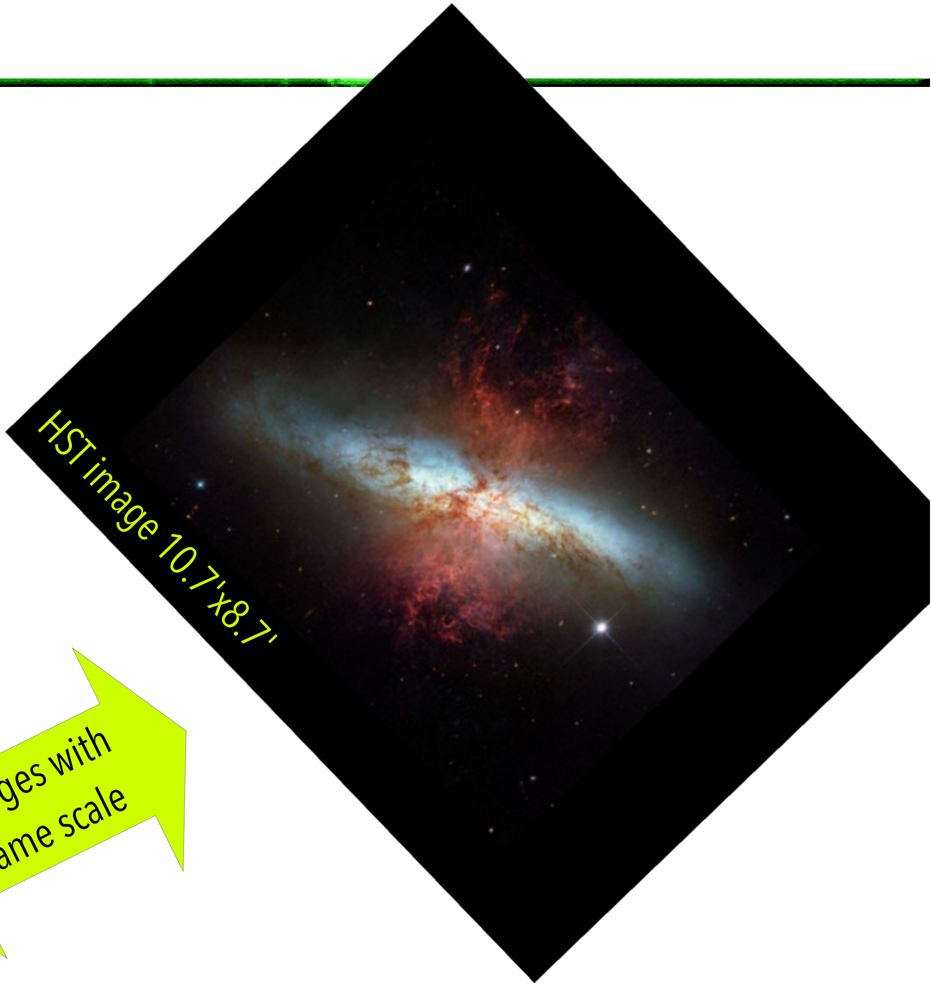
Also HI line emission detected → amount of gas

Spirals (& irregulars)

- M82
  closest starburst galaxy (3.7 Mpc) (group with M81)
- Radio image (bottom), NIR image (right)



images with same scale



$$L_\nu = 4\pi D_L^2 S(\nu)$$

at 1.4 GHz, $S(\nu) \approx 8\,\mathrm{Jy}$

$$L_{1.4GHz} \approx 1.0 \cdot 10^{23}\,\mathrm{W\,Hz^{-1}}$$

Summary:

- ***Ellipticals & Lenticular*** *galaxies: very low radio power, generally undetected, except the closest objects, associated to small scale emission (SMBH?)*

- ***Spiral*** *galaxies: 2-3 orders of magnitude stronger than E & L, most of the emission from cosmic rays, extended emission, on a volume larger than that defined by the stars*

- ***Starburst*** *galaxies: enhanced star formation generates extra cosmic rays (supernovae, pulsars, pulsar wind nebulae) and the radio emission can be considered a proxy of the SFR. Radio emission and star forming regions are co-spatial. Often star formation occurs on large volumes and the morphology of the galaxy is not that clear. The radio power can be as strong as FR-I radio galaxies*

Radio Continuum from Galaxies: nearby SBG are tools to investigate IMF and stellar evolution

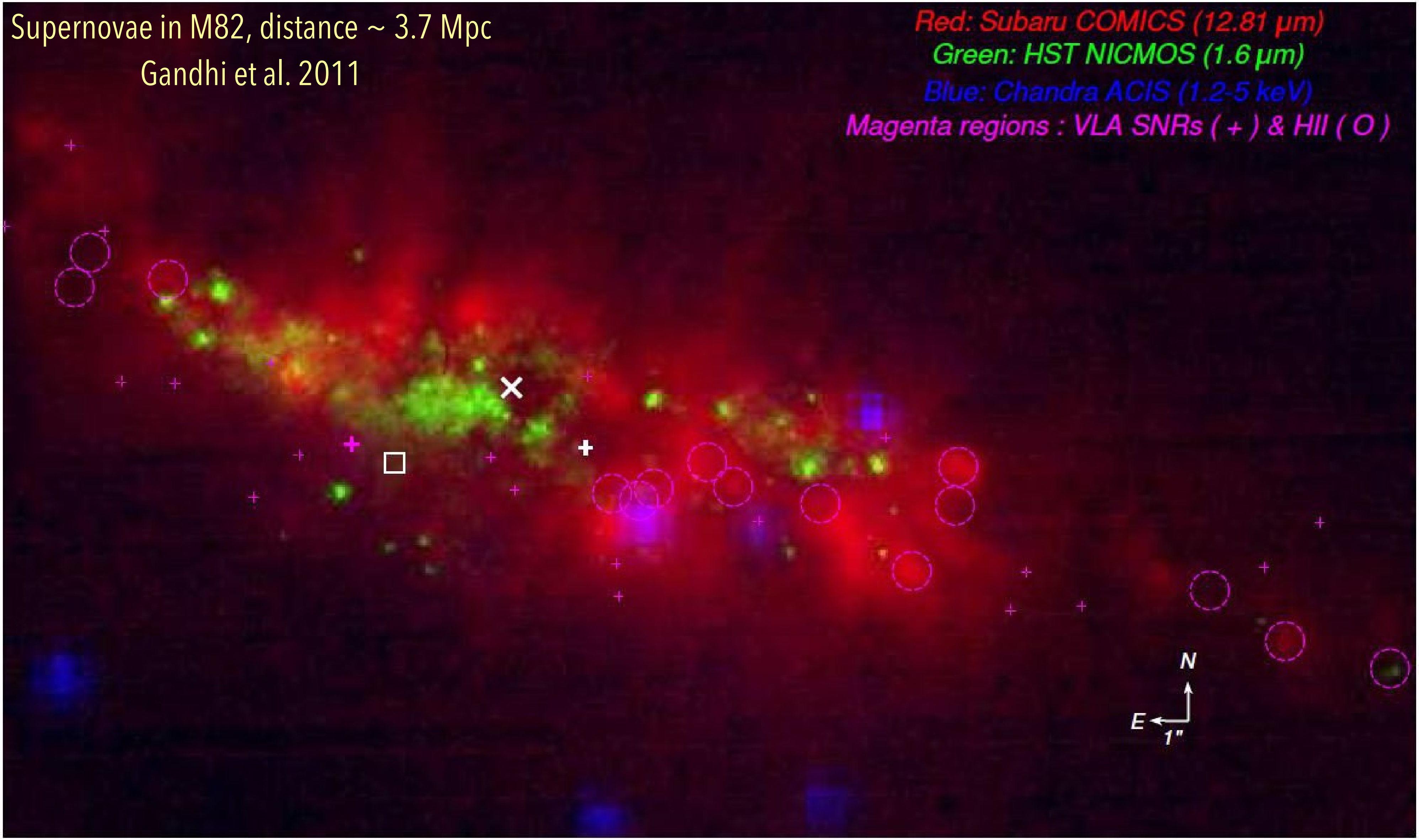
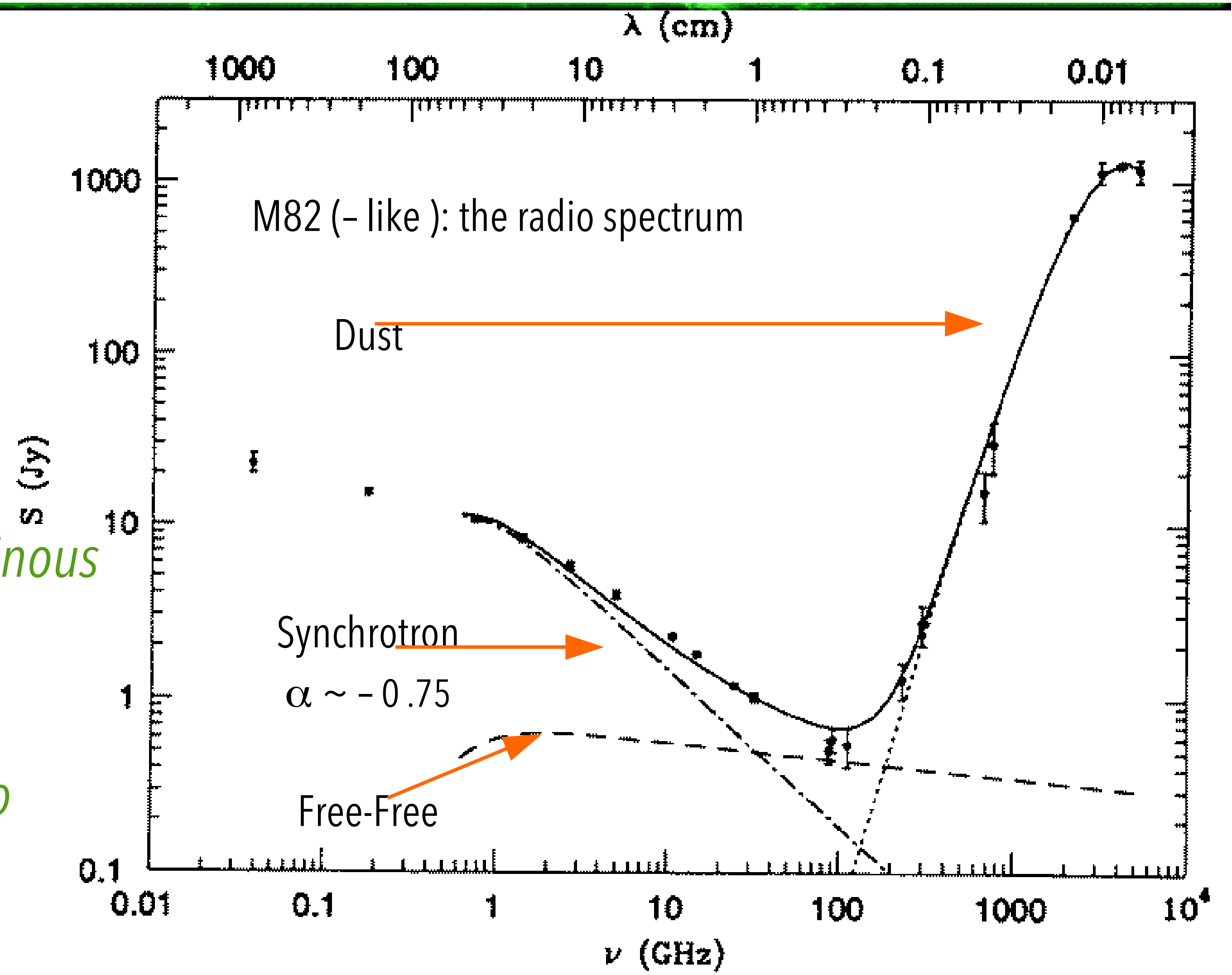


Fig. 6. RGB overlay of the three panels from Fig. 5, with radio regions plotted as dashed circles (HII regions) and SNRs (plus signs). The white X sign is the kinematic center (Weliachew et al., 1984). There are two heavy plus signs: about 4″ to the East of the center, and 1″ South is the AGN candidate in magenta (see § 8), and about 2″ to the West and 1″ South is SN 2008iz in white (Brunthaler et al., 2009). The white box marks the position of the unusual radio transient reported by Muxlow et al. (2010).

Radio Continuum from Galaxies: nearby SBG are tools to investigate IMF and stellar evolution

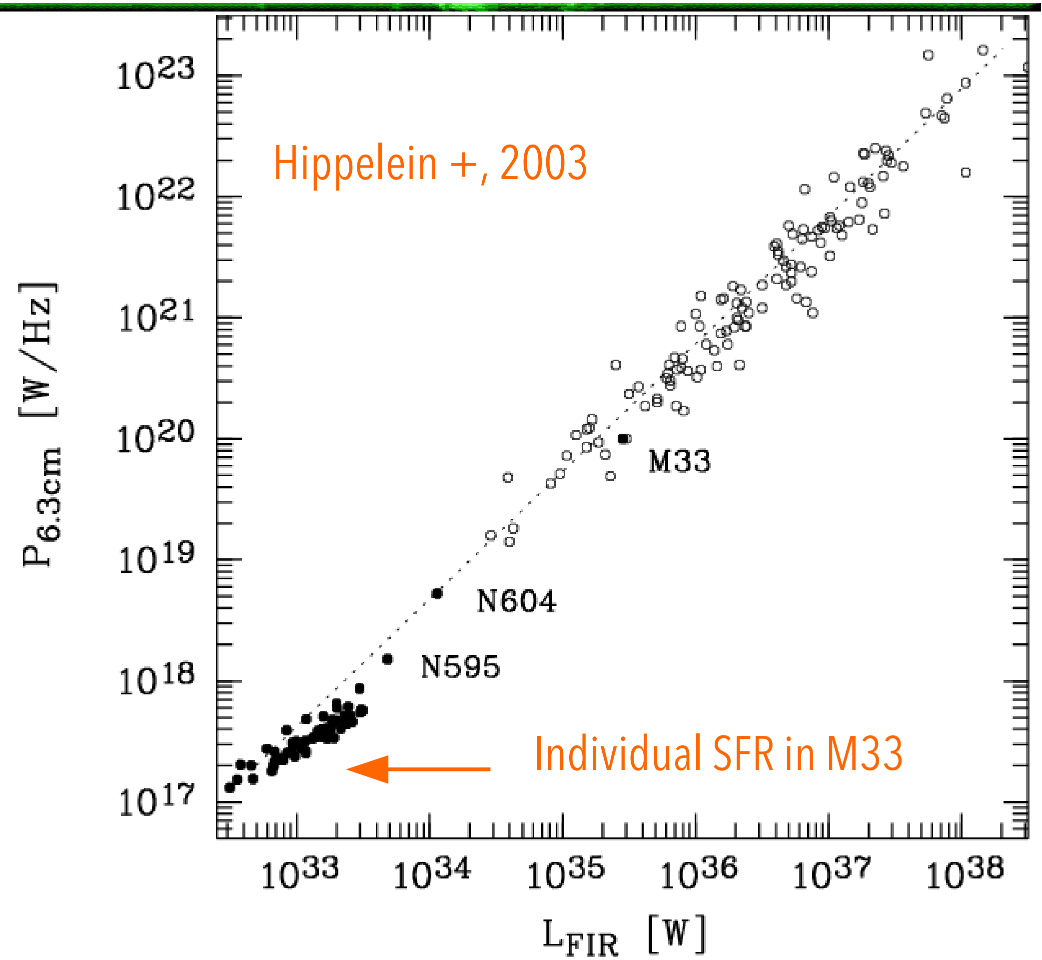
- *Radio (& μ-wave) spectrum in spiral and starburst galaxies*



- *Starburst: similar shape to normal spirals, but more luminous*
- *Free-free emission becomes optically thick at ~ 1 GHz, also to synchrotron emission (FFA)*
- *Thermal free-free emission dominant at 30-200 GHz, before being swamped by dust emission (T ~ 50 K)*

Radio Continuum from Galaxies: nearby SBG are tools to investigate IMF and stellar evolution

- *The Radio continuum – FIR connection for spiral galaxies*
- (Massive) Star formation linked to generation of relativistic particles (SN explosions pulsars, PWN)
- Discovered by van der Kruit (1971,73), thought to be synchrotron. Harwit & Pacini (1975): IR from dust + free-free in HII regions.
- Condon + (1982) use it to find "monsters" in normal galaxies
- $M \geq 8\,M_\odot$ stars live $< 3\ 10^7$ yr, generate type II, Ib SNR lasting for 10^{5-6} yr, while cosmic rays can live 10^8yr.

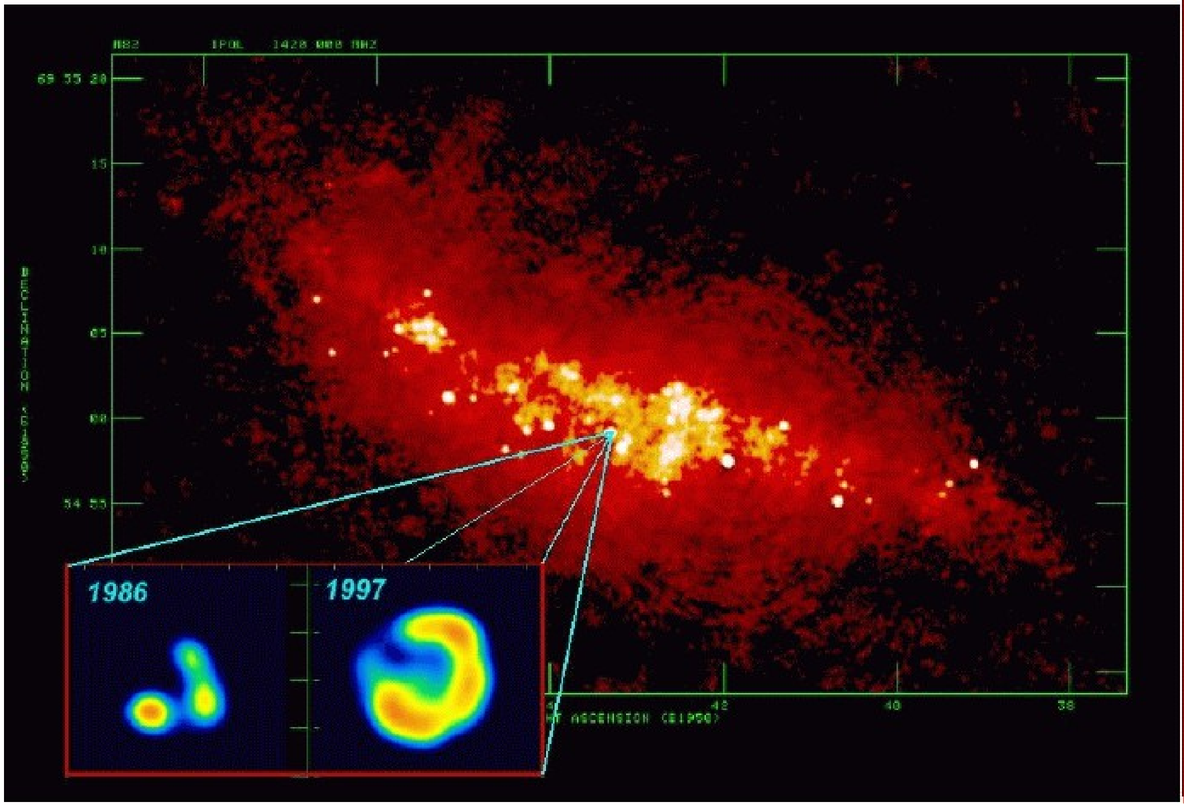


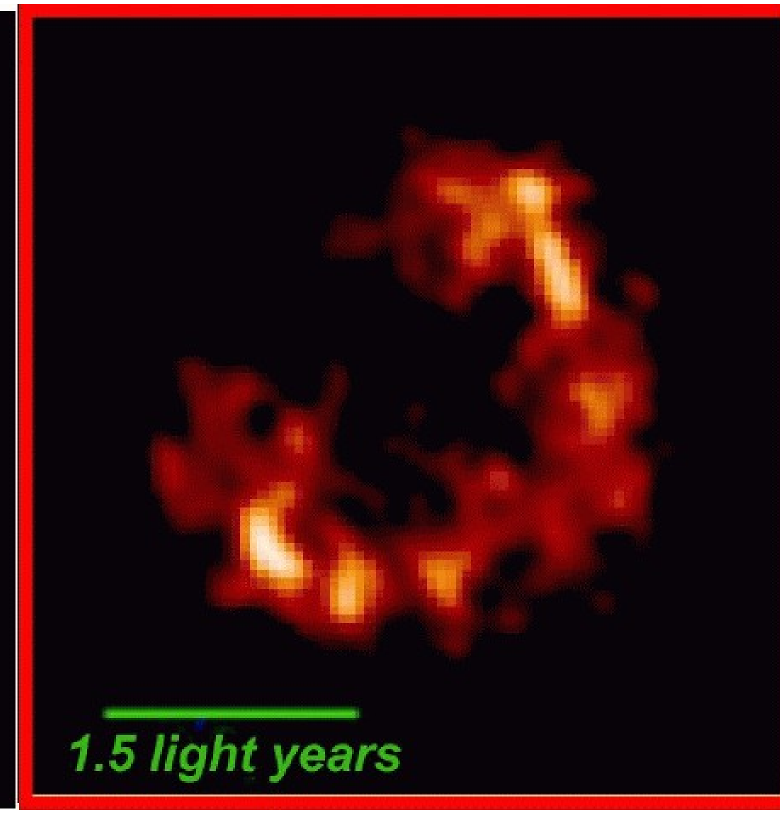
From IRAS
$$\left(\frac{FIR}{W\,m^{-2}}\right) = 1.26\cdot10^{-14}\left(\frac{2.58\cdot S_{60\mu m}+S_{100\mu m}}{Jy}\right)$$

$$q = \log\left(\frac{FIR}{3.75\cdot10^{-12}\,W\,m^{-2}}\right) - \log\left(\frac{S_\nu}{W\,m^{-2}\,Hz^{-1}}\right)$$

Radio Continuum from Galaxies: nearby SBG are tools to investigate IMF and stellar evolution

Radio astrophysics in nearby galaxies



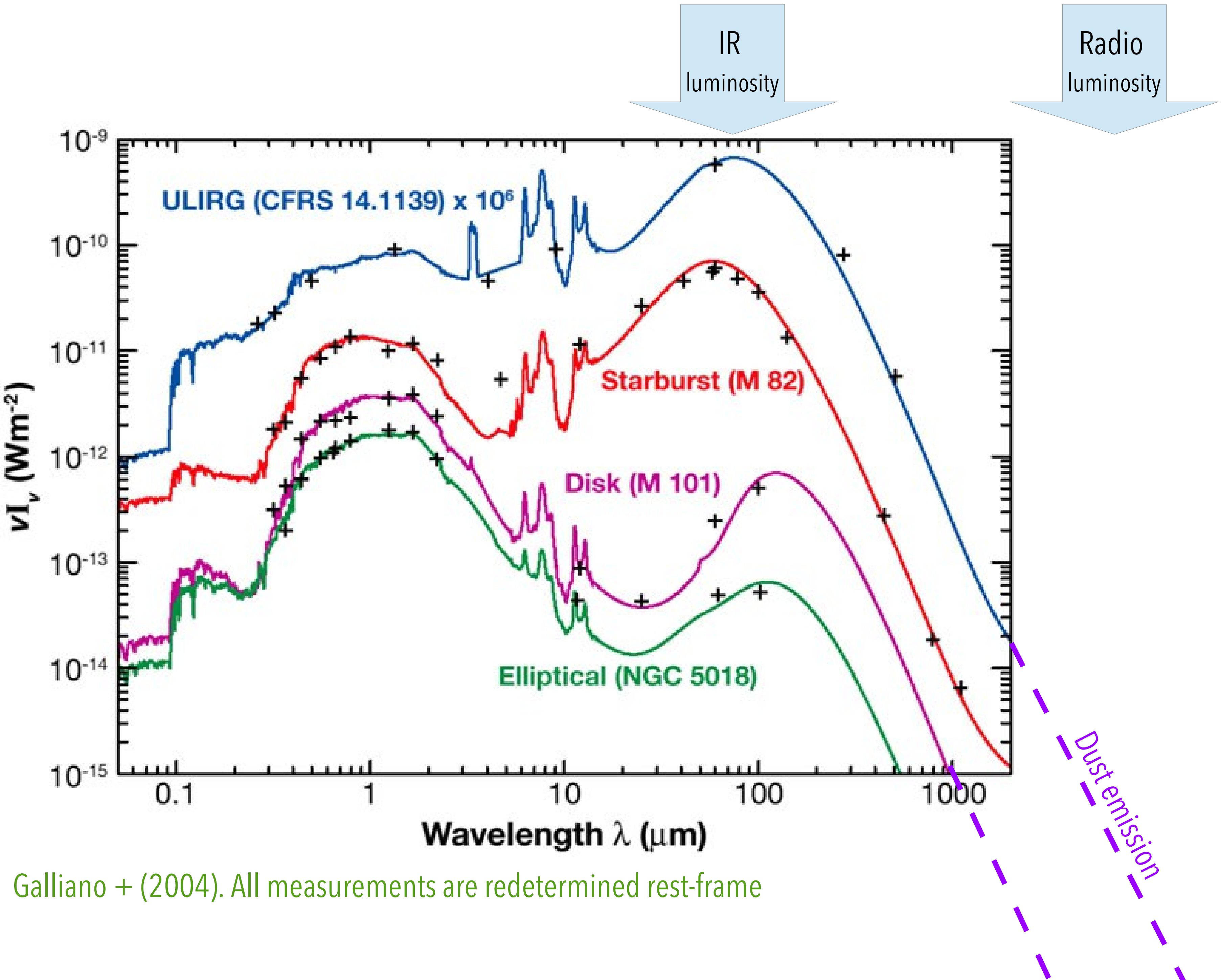


Emission from Synchrotron, HII, supernovae

i.e. Non-thermal (generally dominant) and thermal emission

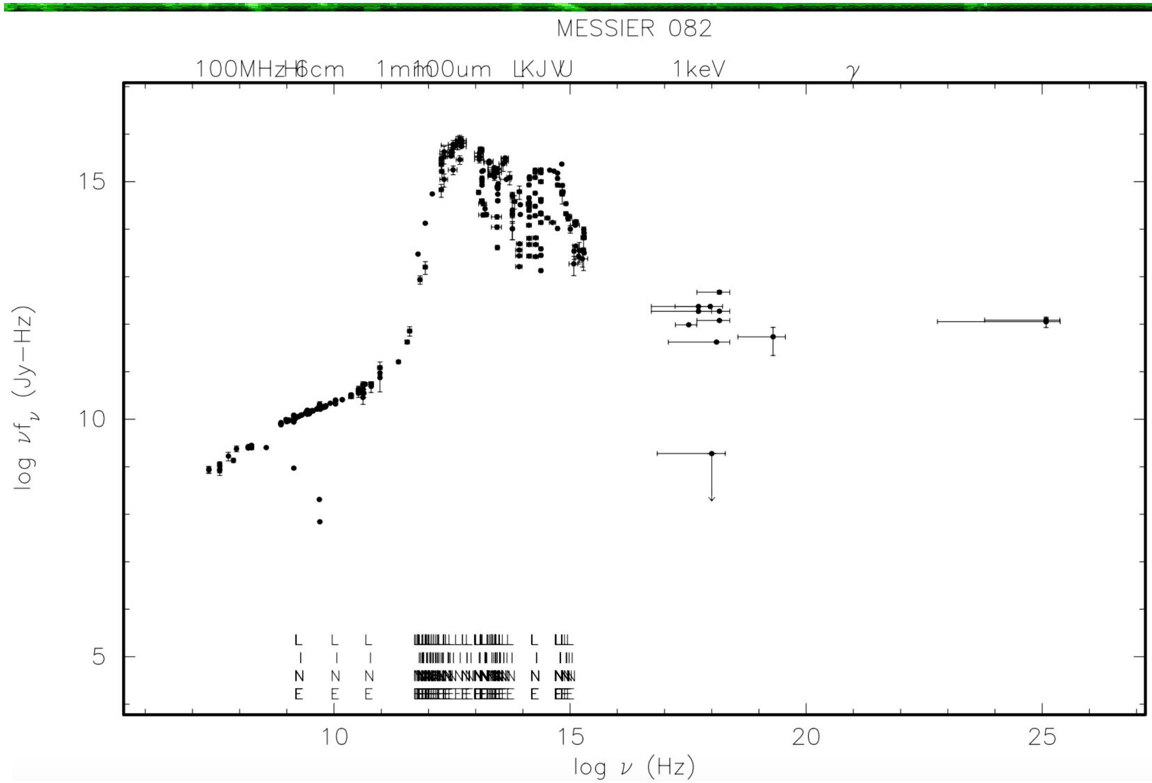
- RSN: Expansion speed, age, rate
- Synchrotron continuum: CR production & magnetic field intensity & topology
- HII: SFR, IMF, CNM & WMN

Radio / FIR [/ CO] correlation[s] – The reason why…



Galliano + (2004). All measurements are redetermined rest-frame

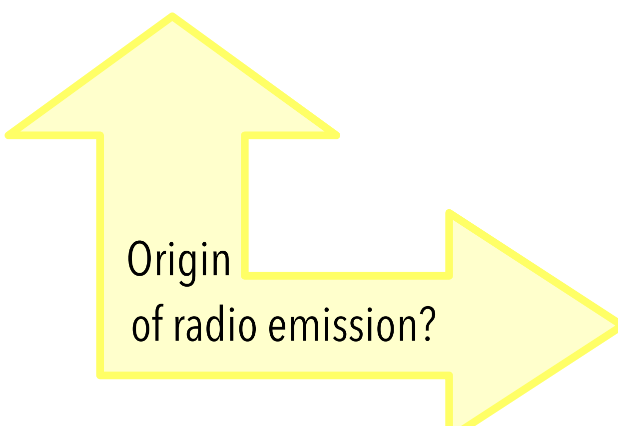
Radio / FIR [/ CO] correlation[s]

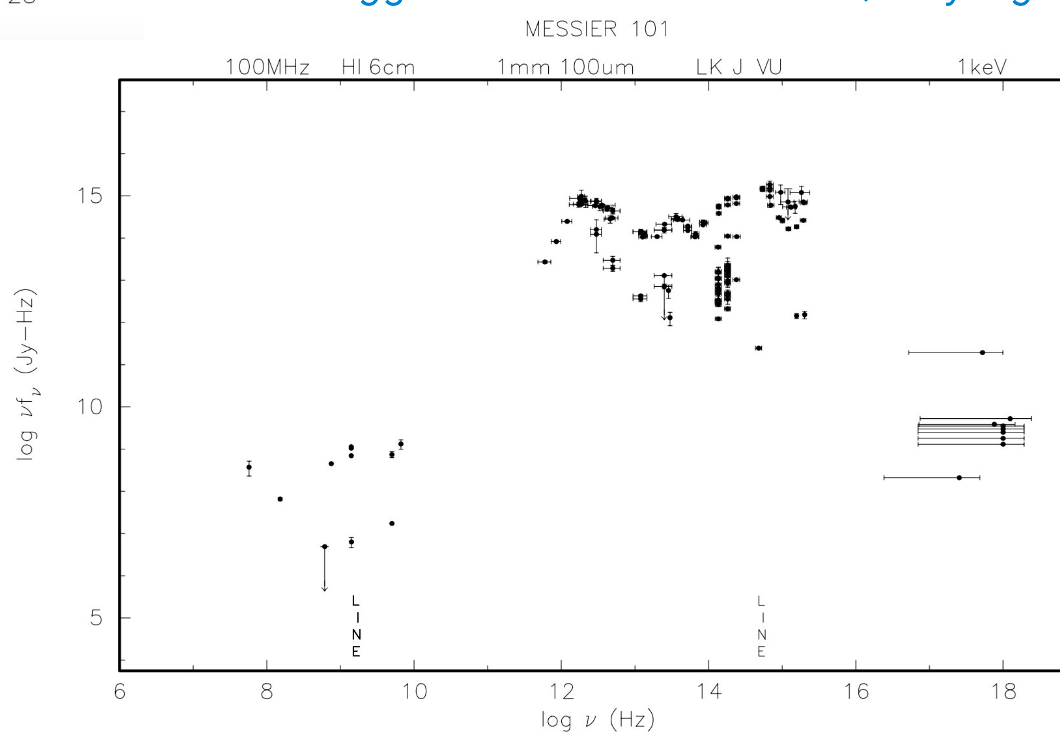


M82: $M_{gas} \sim 6 \times 10^9 M_\odot$ $SFR \sim 15 M_\odot /yr$

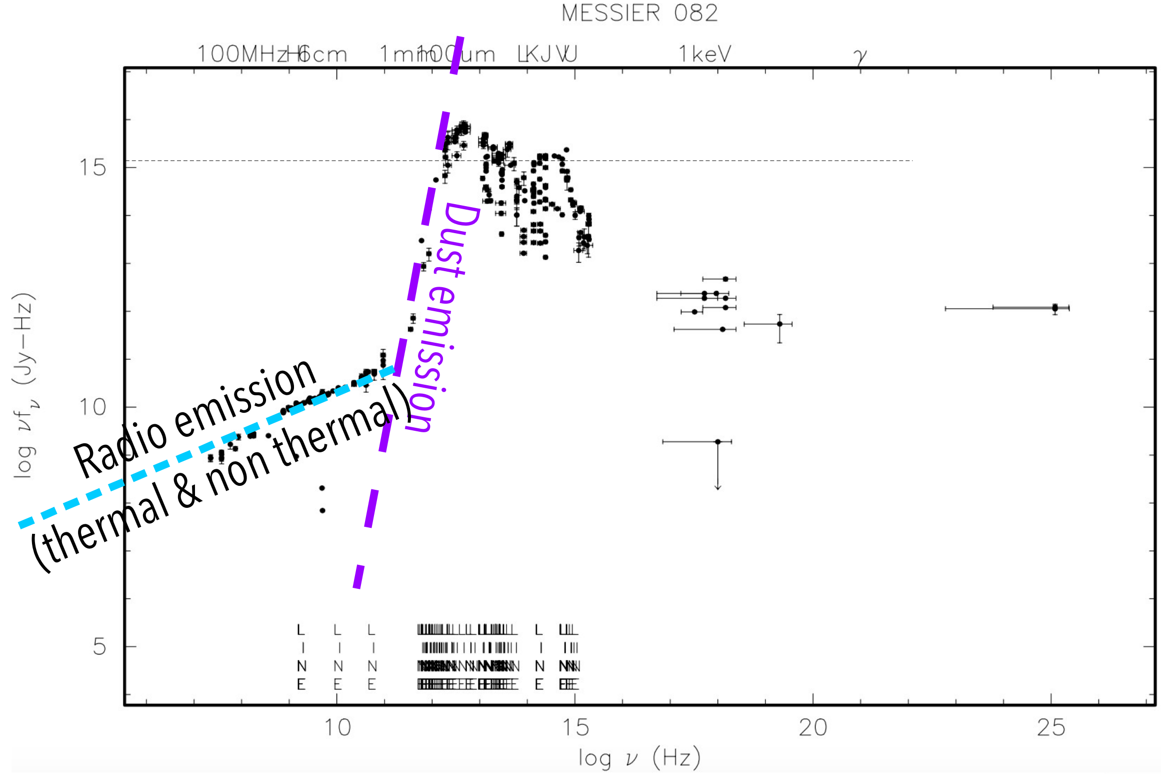
All gas will be gone in $\sim 4 \times 10^8$ yr

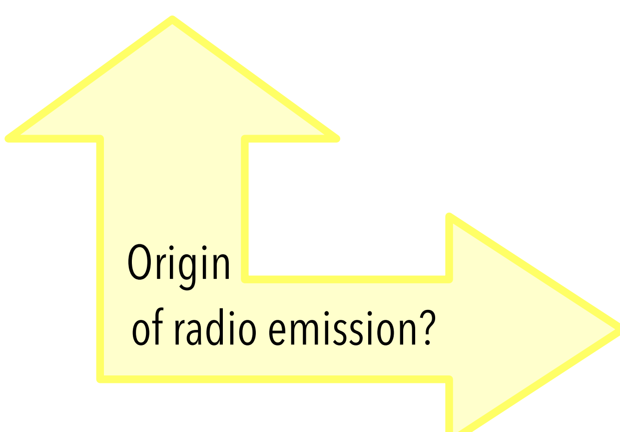
External trigger to enhance SFR: M81 (10^8 yr ago)

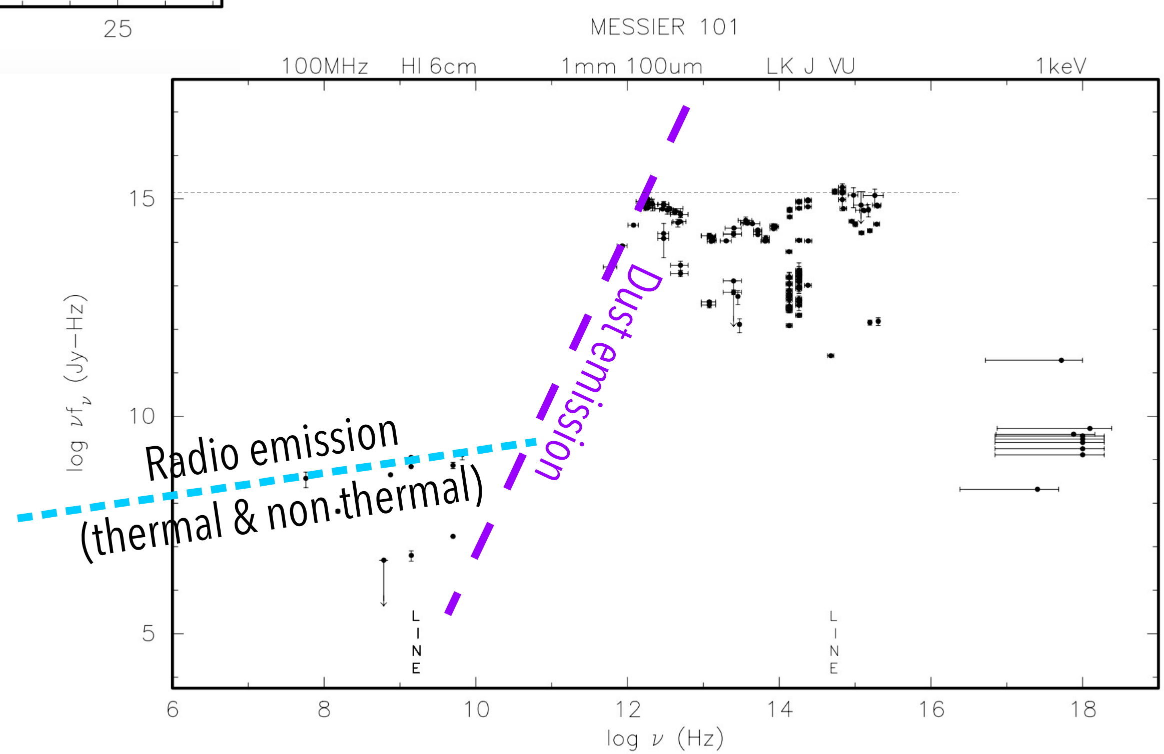




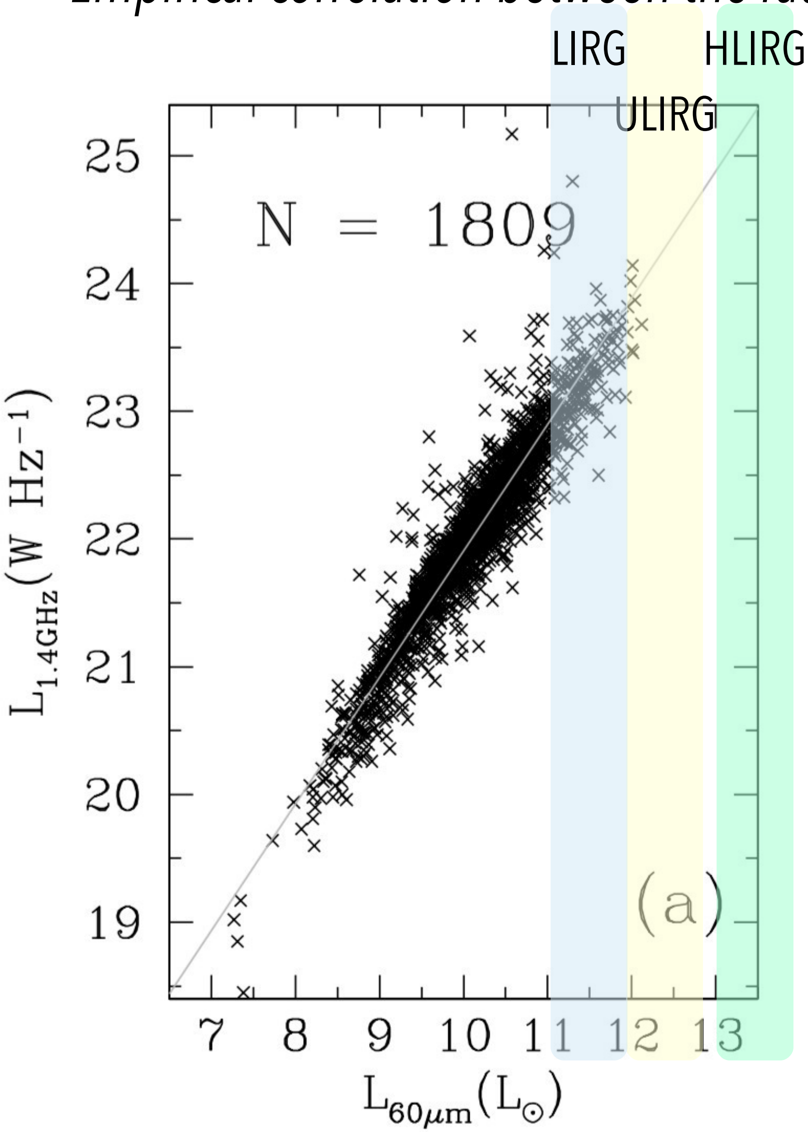
Radio / FIR [/ CO] correlation[s]







Empirical correlation between the radio continuum and far infrared emission



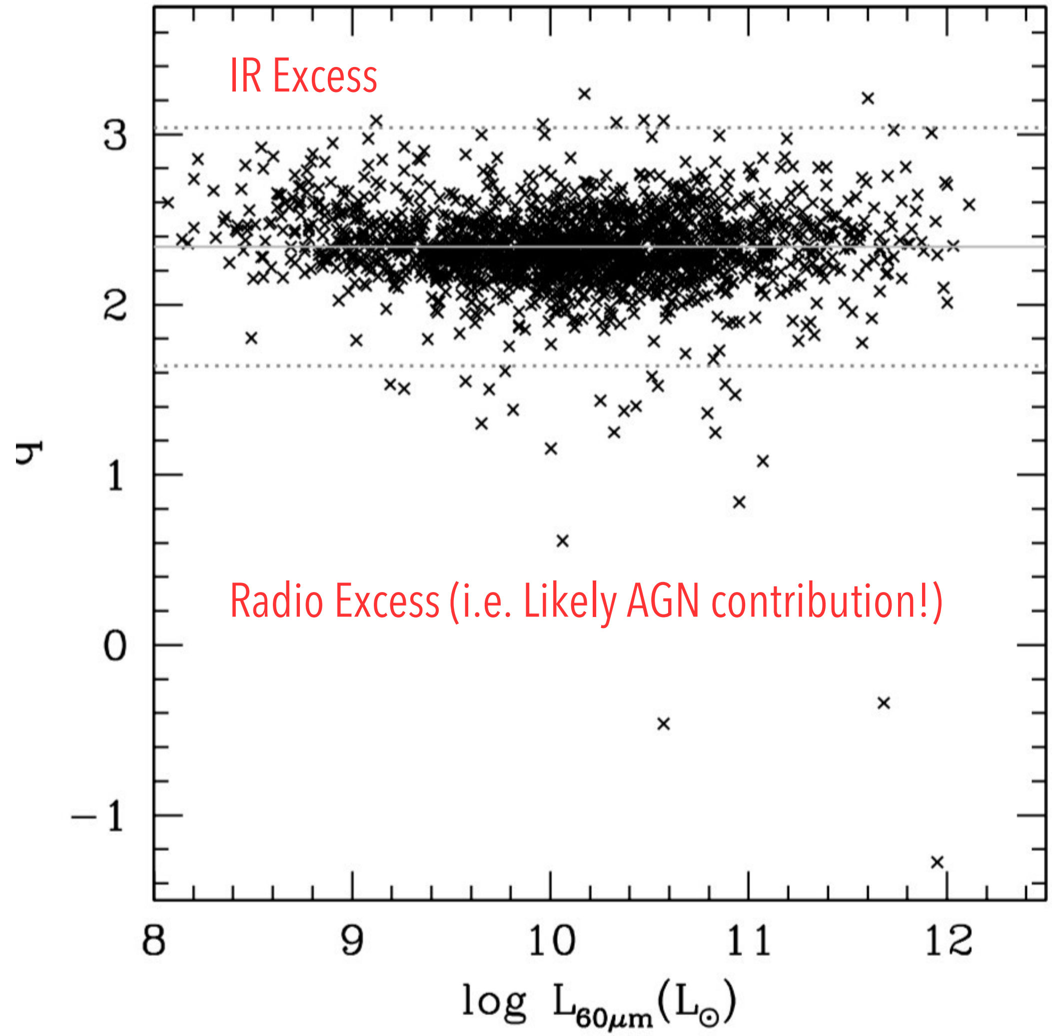
$$\log(L_{1.4GHz}) = (0.99 \pm 0.01)\log\left(\frac{L_{60\mu m}}{L_\odot}\right) + (12.07 \pm 0.08)$$

Yun, Reddy & Condon (2001)

Local sample of 1809 FIR galaxies ($S_{60\mu m}$ >2 Jy), out to z~0.15, from IRAS and NVSS

Empirical correlation between the radio continuum and far infrared emission

(from Lisenfeld et al. 2015 (Spanish SKA White Book))



$$q = \log\left(\frac{FIR}{3.75\cdot 10^{12}\, W\, m^{-2}}\right) - \log\left(\frac{S_{1.4GHz}}{W\, m^{-2}\, Hz^{-1}}\right)$$

Radio / FIR [/ CO] correlation[s]

Various versions of the FIR / Radio Empirical correlation

e.g: Yun + (2001) $L_{FIR} \approx 2.4 \times 10^5 L_{radio}$

$$\frac{L_{1.4GHz}}{W\,Hz^{-1}} = 1.18 \times 10^{12} \frac{L_{FIR}}{L_{\odot}} = 2.95 \cdot 10^{-15} \frac{L_{FIR}}{W}$$

Rationale:

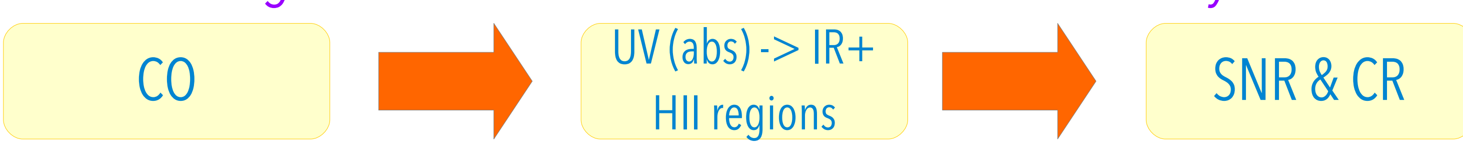
Star formation is the key: Stars form in dusty clouds (IR!): most massive stars ($M > 5\,M_{\odot}$) can heat the dust (UV-optical absorption, 2/3 of the star radiation is reprocessed by dust)

When massive stars form, HII regions ($M > 5\,M_{\odot}$) radiate part of the plasma energy

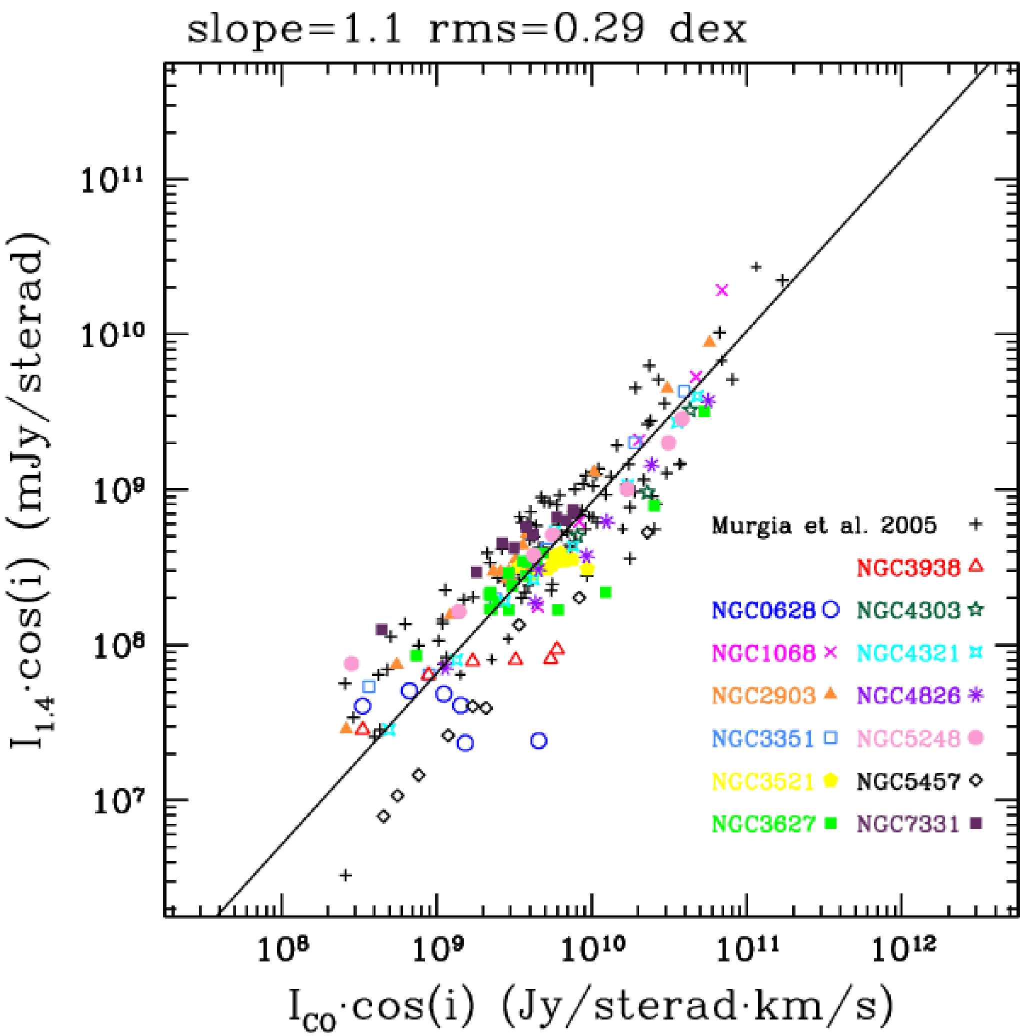
Recently formed massive stars ($M > 8\,M_{\odot}$) end with a supernova explosion injecting relativistic plasma (CR & magnetic field) into the ISM

Idea based on:

- *Short lifetime of massive stars*
- *Short duration of SNR (& CR injection)*
- *Lots of cold gas ⇨ Lots of star formation ⇨ Lots of CR & synchrotron emission*

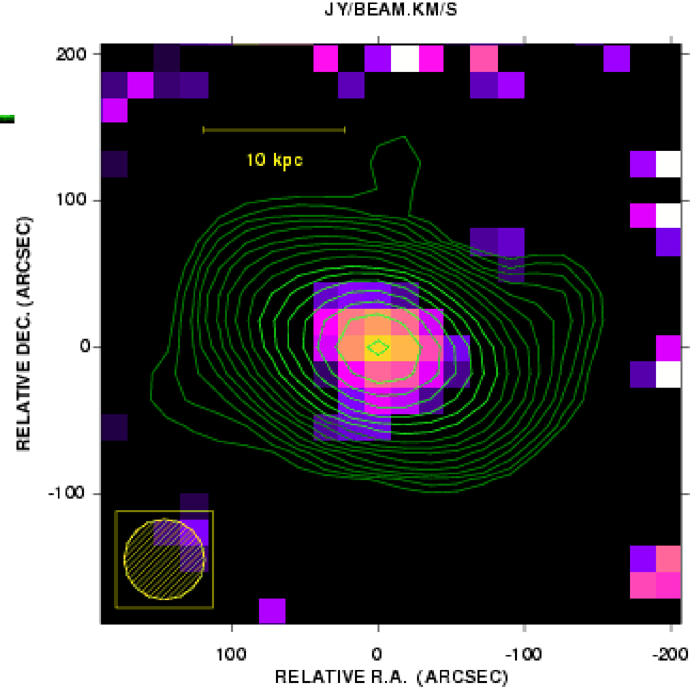


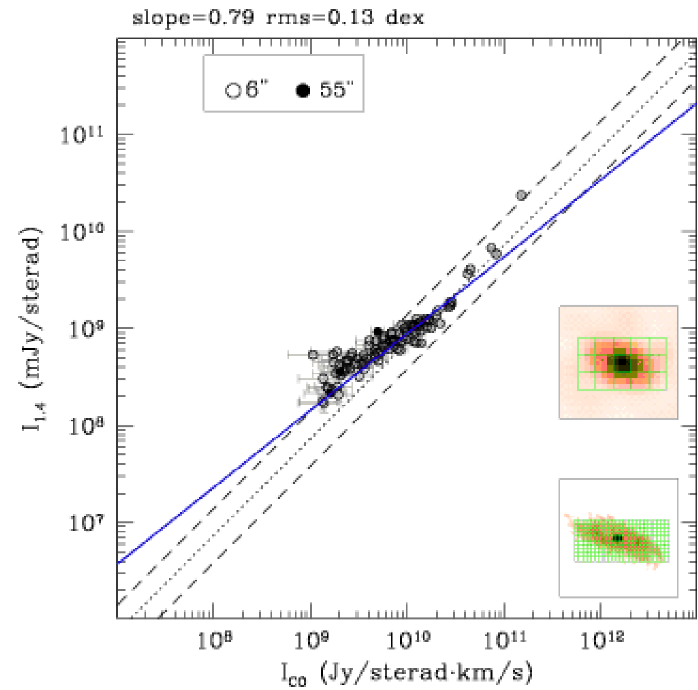
Empirical correlation between the radio continuum and CO: local values within a number of galaxies: possible explanation:
idrostatic pressure rules all the players (dust, (relativistic) plasma, cold gas, ...)



Paladino et al. 2006

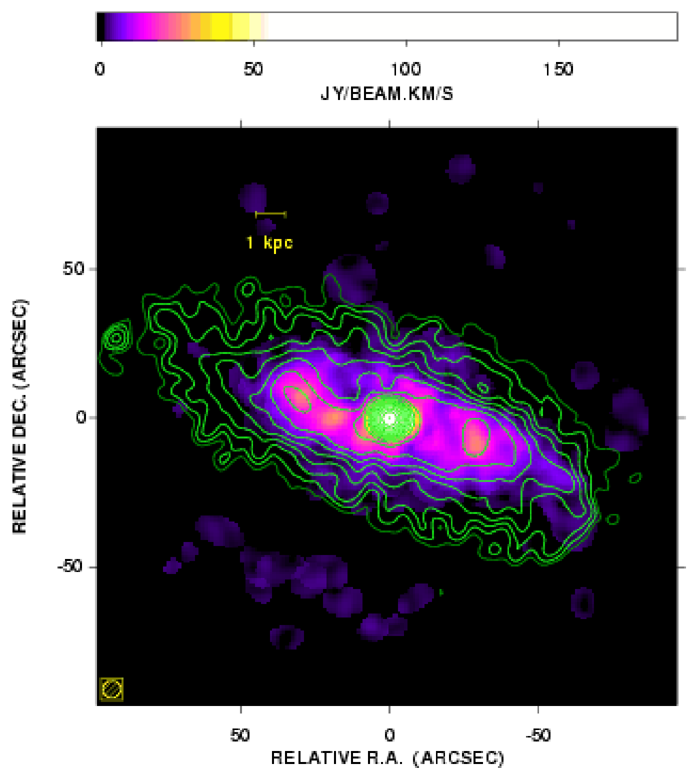
Radio / FIR [/ CO] correlation[s]

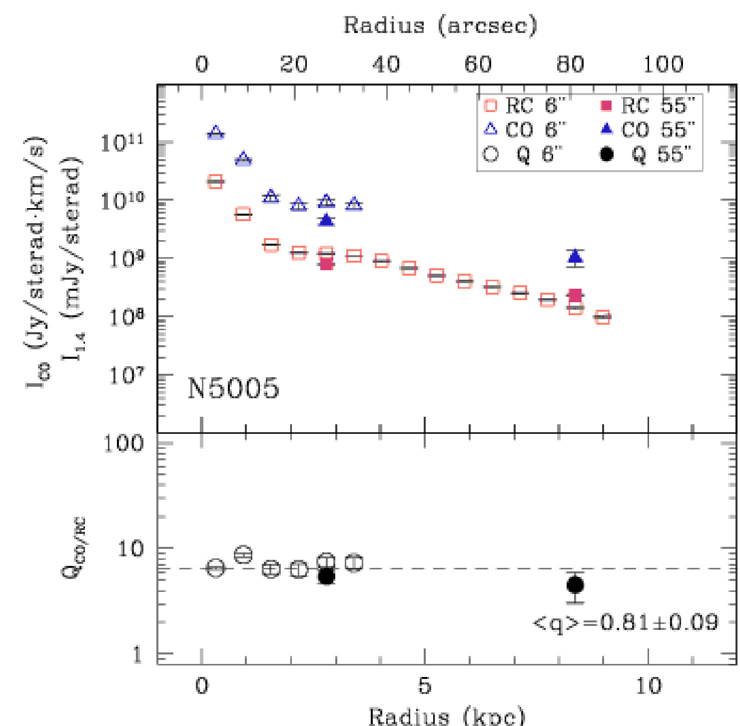




Murgia +, 2005

LOCAL ratio between CO and radio (1.4 GHz) intensities within galaxies





All this is related to star formation, estimated via a number of other tracers:

$$SFR_{H_\alpha} = \frac{L(H_\alpha)}{1.5\cdot 10^{34}\, W}\; M_\odot\, yr^{-1}$$

$$SFR_U = \frac{L_U}{1.5\cdot 10^{22}\, W\, Hz^{-1}}\; M_\odot\, yr^{-1}$$

$$SFR_{FIR} = \frac{L_{60\mu m}}{5.1\cdot 10^{23}\, W\, Hz^{-1}}\; M_\odot\, yr^{-1}$$

$$SFR_{1.4\mathrm{GHz}} = \frac{L_{1.4\mathrm{GHz}}}{4.0\cdot 10^{21}\, W\, Hz^{-1}}\; M_\odot\, yr^{-1}$$

Warning: only stars with mass in excess of 5 $M_\odot$ are considered by these relations

Consequence: Universal IMF?

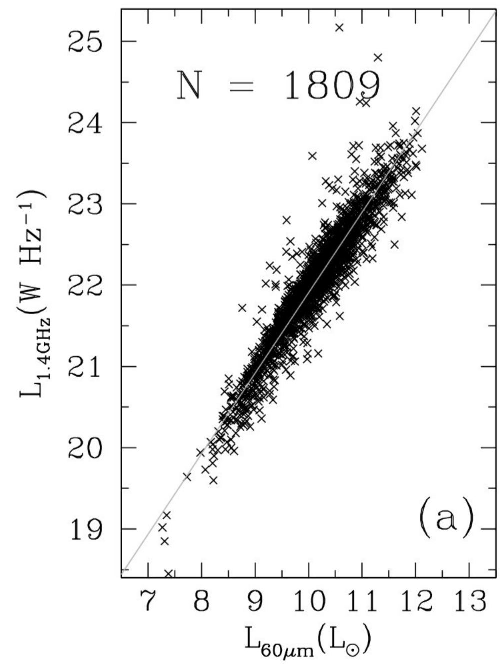
Gas-rich interacting galaxies provide a lot of cool gas available for star formation

Definition of Starburst Galaxy: unavailable… however, there is consensus on
Gas consumption time (much) shorter than Hubble time $M_{gas}/SFR < t_{Hubble}$

Example: ***M82:*** $M_{gas} \sim 6 \times 10^9\, M_\odot$ $SFR \sim 15\, M_\odot/yr$
All gas will be gone in $\sim 4 \times 10^8$ *yr*
External trigger to enhance SFR: M81 (10^8 *yr ago)*

Large efficiency in gas to star mass conversion:
~5% in normal galaxies, up to 50% in SBG

Reach $L_{radio} \sim 10^{25}\, W\, Hz^{-1}$*, becoming progressively weaker and weaker at high redshift (when most of the stars formed!)*



Yun, Reddy & Condon (2001)

In general weaker radio emission than (powerful, i,e, FR II type) AGNs
(and can cover different, i.e. smaller, redshift distance)

- The AGN phenomenon is a transient phase of the galaxy evolution
- The star formation (rate) is not constant over the cosmic age

Luminous, UltraLuminous & HyperLuminous IR Galaxies (LIRGs, ULIRGs & HLIRGs), defined by their high IR luminosities: $10^{11}L_{\odot} \le L_{IR} < 10^{12}L_{\odot} \le L_{IR} < 10^{13}L_{\odot} \le L_{IR}$ ranges

IR luminosity: optical + UV from intense SF & AGN, absorbed by dust and re-emitted in the IR

ULIRGs $\Longrightarrow$ transition phase from mergers to dusty quasars (Sanders +, 1988; Veilleux +, 2002):
gas-rich spiral galaxies merge, molecular gas clouds channeled towards the merger nucleus trigger nuclear starbursts and AGN activity via the accretion of the available fuel on to the central super massive black hole (SMBH).

According to this scenario, the starburst phase evolves into a dust-enshrouded AGN phase, and once (most of) the gas and dust are consumed the system evolves into a bright QSO phase.

Hydrodynamical simulations of mergers show that merger processes leads gas inflows towards the center triggering starbursts and AGN activity (e.g Springel +, 2005)

SF, ULIRGs

- Role of ULIRGs in galaxy evolution is not limited to the local ($z < 0.3$) Universe
  At high redshift ($z > 1$) they are more numerous and have a substantial contribution to the total IR luminosity density (Le Floc'h +, 2005; Caputi +, 2007) compared to local ULIRGs (Soifer & Neugebauer 1991; Kim & Sanders 1998). There is a significant population of ULIRGs beyond z □1 (e.g Goto +, 2011a)
- Observations: ULIRGs at $1.5 < z < 3.0$ are mostly (□ 47%) mergers or interacting galaxies; also non-interacting disks, spheroids and irregular galaxies (Kartaltepe +, 2012).
  Beyond $z > 2$ morphological properties of sub-mm galaxies (SMGs) consistent with mergers and interacting sytems (e.g. Tacconi +, 2008).
- PAH emission indicates ongoing star formation, observations support that high z ULIRGs are starburst dominated. A similar conclusion is also achieved by the X-ray studies of high z ULIRGs (e.g Johnson +, 2013).
- Size of SF regions in high z ULIRGs larger than local ULIRGs with similar L_{IR} (Rujopakarn+. 2011). In these galaxies star formation do not occur in merger nuclei but, it is distributed galaxy wide. The similarities of star forming regions of high z ULIRGs and local quiescent star forming galaxies point out a different origin than merger-induced star formation (Rujopakarn +, 2011). Although the evolution of ULIRGs is not fully understood yet, observations provide evidence for changing properties with redshift.

Link between ULIRGs and QSOs

- ULIRGs evolve into red/elliptical-type remnants by the 'negative feed- back' mechanisms (e.g. in the form of powerful winds and outflows) that inhibit star formation and AGN activity (e.g. Hopkins +, 2006, 2008a,b, 2009).

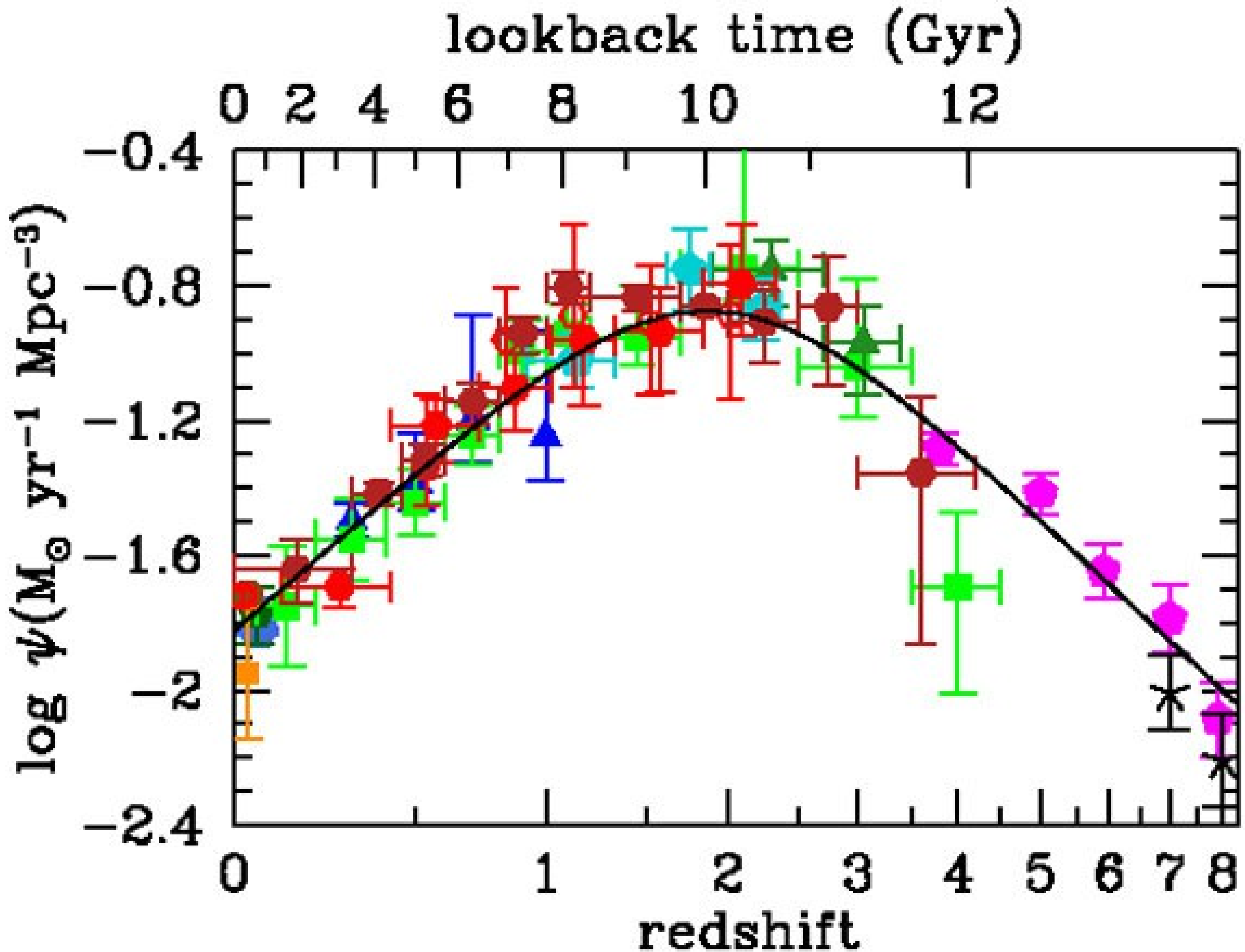
Link between ULIRGs and QSOs:

- LIRGs: disk galaxies (if $\log(LIR/L_{\odot}) < 11.5$) or interacting systems (if $11.5 \leq \log(LIR/L_{\odot}) < 12.0$)

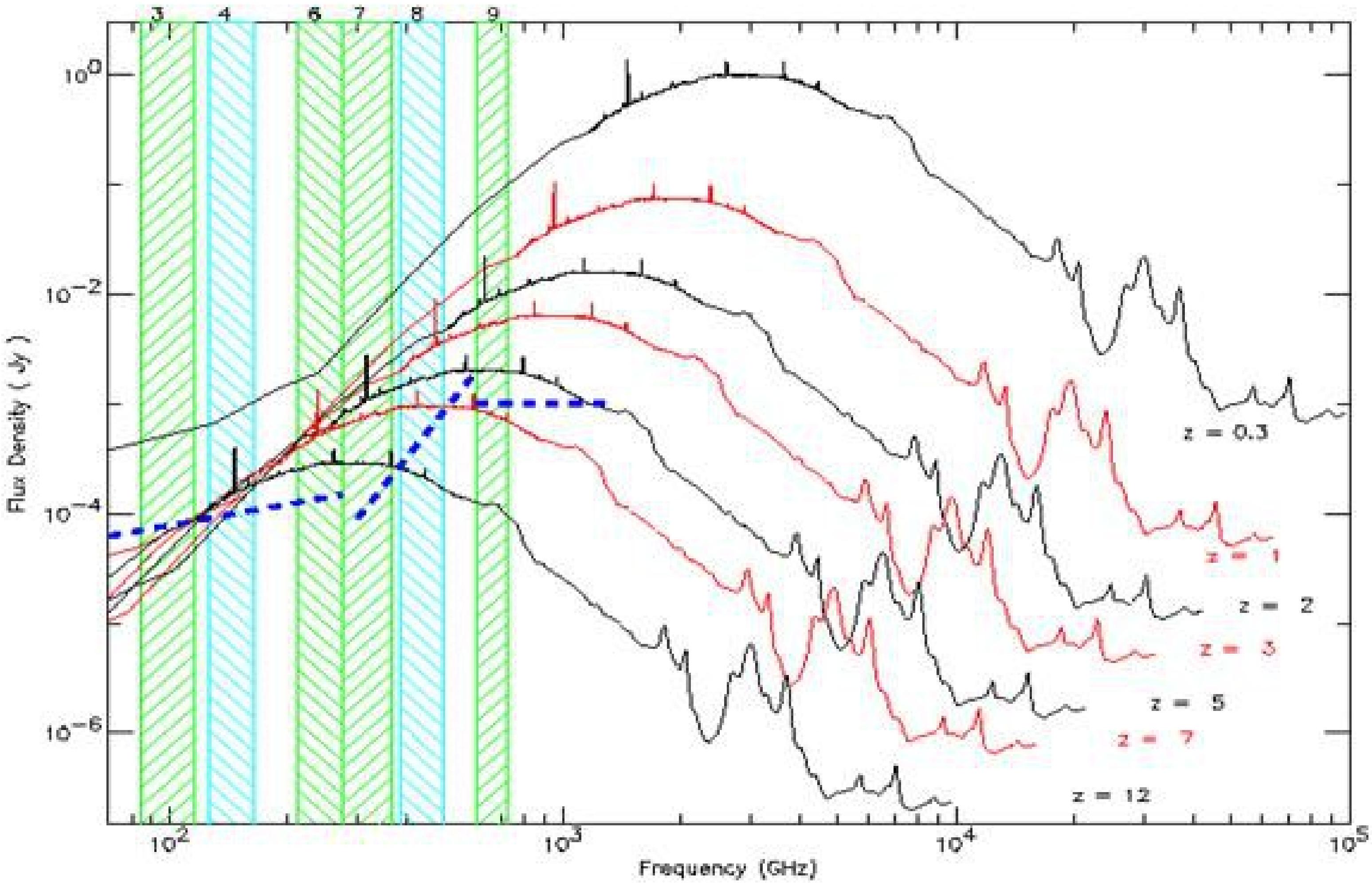
- Morphological properties of ULIRGs: interacting galaxies in pre/ongoing/late merger stages (Farrah +, 2001; Kim +, 2002; Veilleux +, 2002, 2006) . ULIRGs: advanced mergers (Veilleux +,2002; Ishida 2004). Dynamical masses obtained from near-infrared (NIR) spectroscopy show that they are major mergers of nearly equal mass galaxies (Veilleux +, 2002; Dasyra +, 2006a,b).
- CO observations proved that ULIRGs contain the required cold molecular gas for central starbursts
- > 70% of 164 local ($z \leq 0.35$) ULIRGs harbor an AGN (Nardini et al. 2010).
  Co-existence of a starburst and an AGN show that both contribute to the total IR luminosity.

- *The AGN phenomenon is a transient phase of the galaxy evolution*
- *The star formation (rate) is not constant over the cosmic age*

Star forming galaxies may become the dominant population when going at low power/flux densities for a given cosmic era

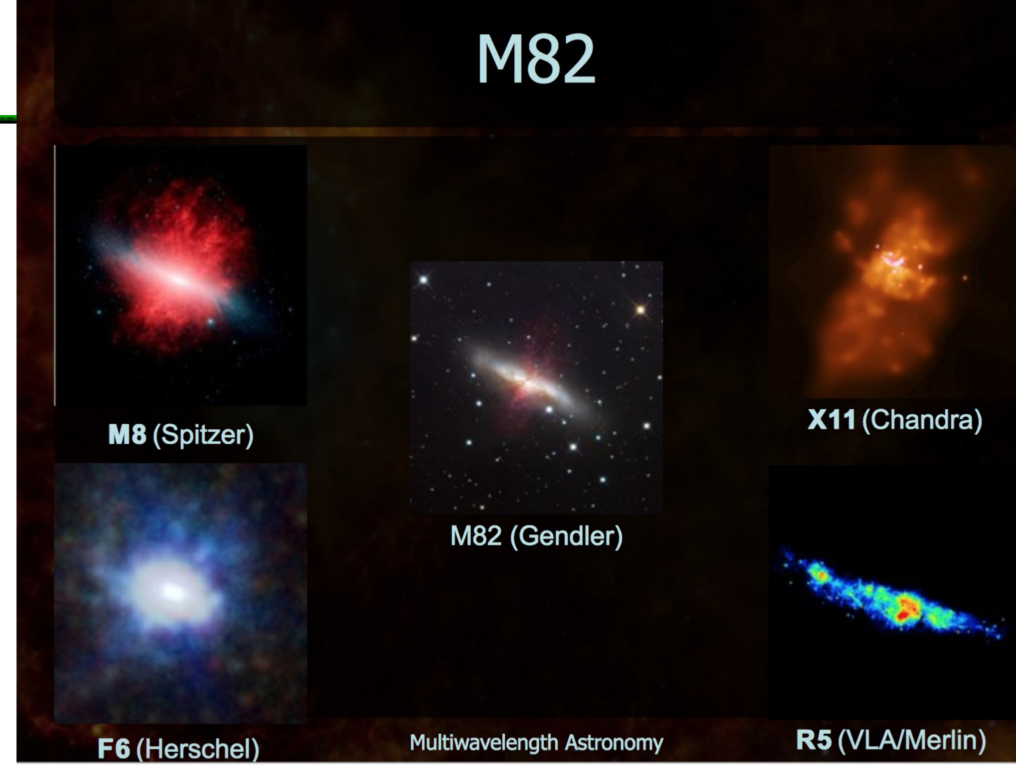


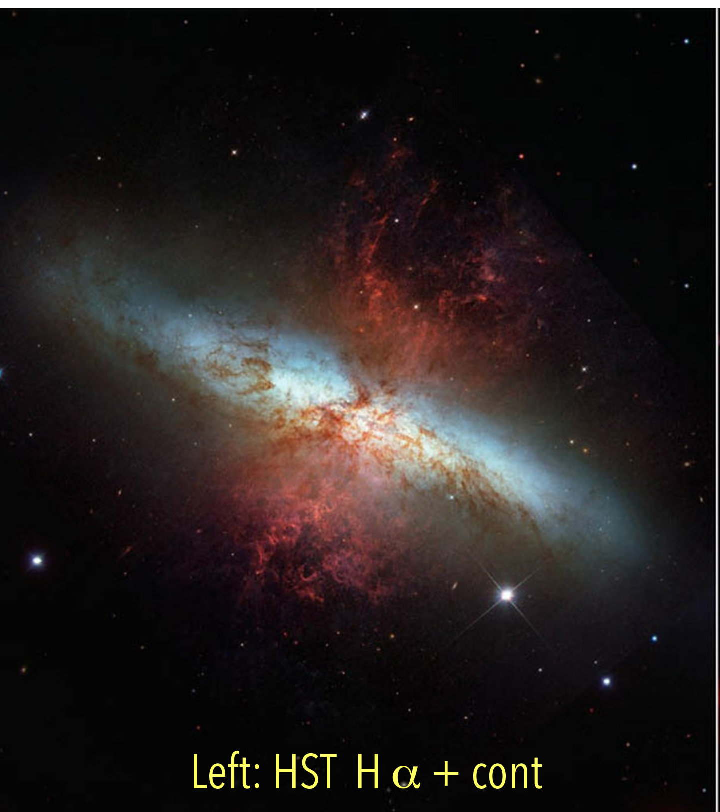
The impact of ALMA on high z studies of SB galaxies

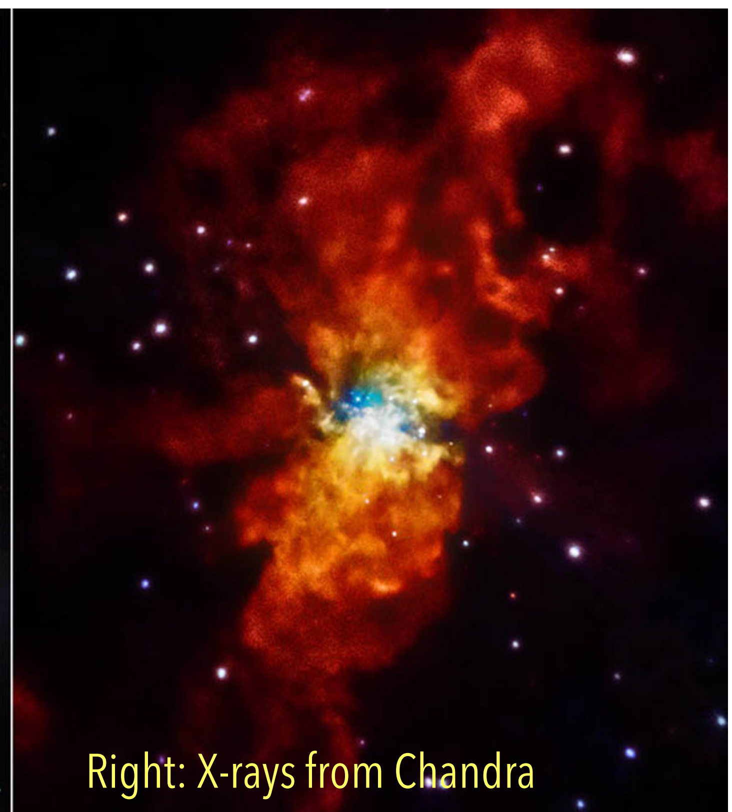


The measured spectrum of M82 as might be observed at different redshifts. Because of the K-correction effect, as the radiation grows fainter with distance, the peak of the radiation curves moves toward the red. In receiver bands 4, 6, and 7 of ALMA, we find that we continue to detect the galaxy with nearly equal sensitivity even as it recedes in distance

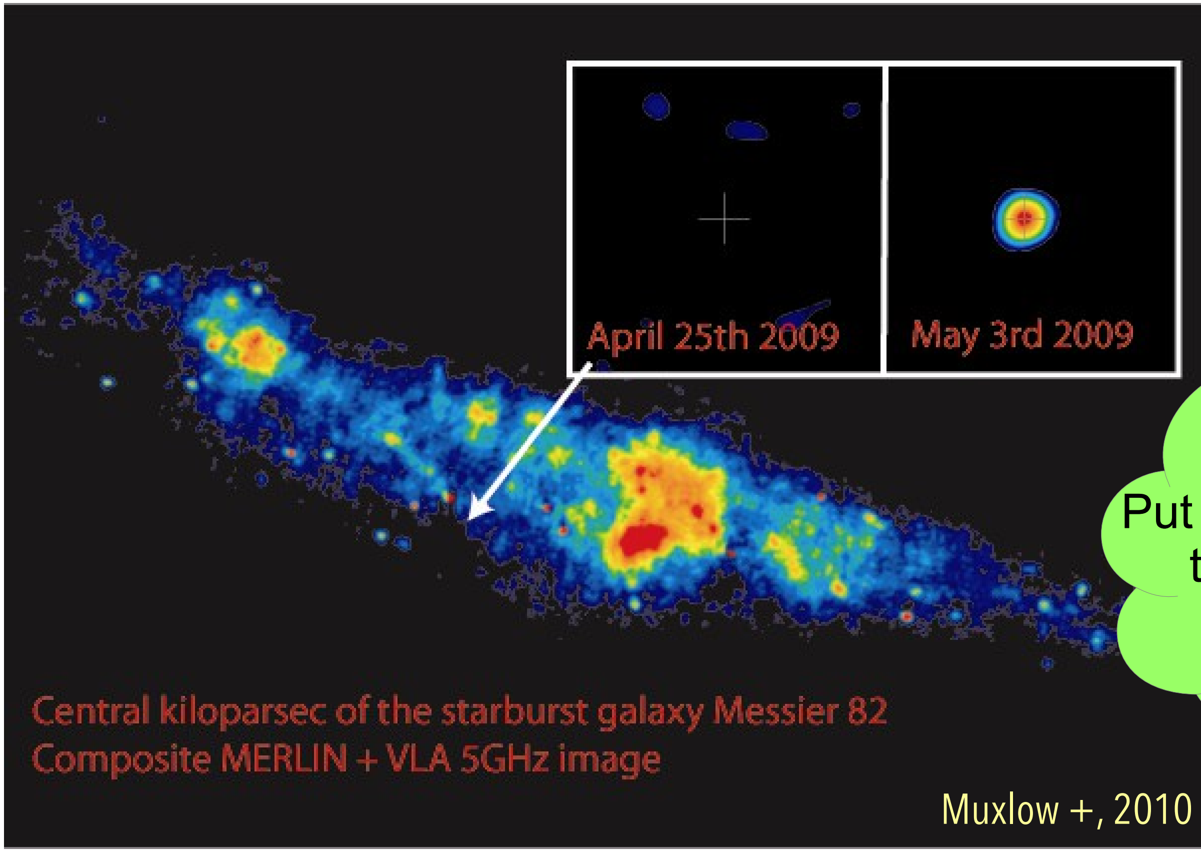
Starburst Galaxy in various bands







Radio astrophysics in nearby galaxies: Supernovae in external galaxies:



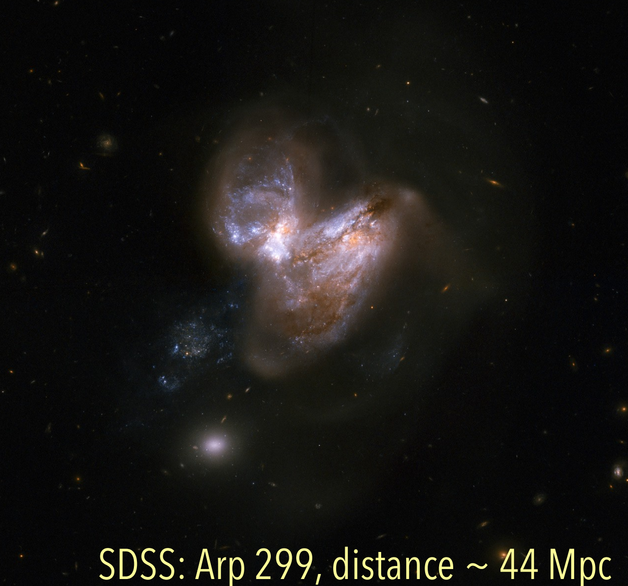
Put together items from other topics discussed earlier

Emission from Synchrotron, HII, supernovae

i.e. Non-thermal (generally dominant) and thermal emission

- RSN: Expansion speed, age, rate
- Synchrotron continuum: CR production & magnetic field intensity & topology
- HII: SFR, IMF, CNM & WMN

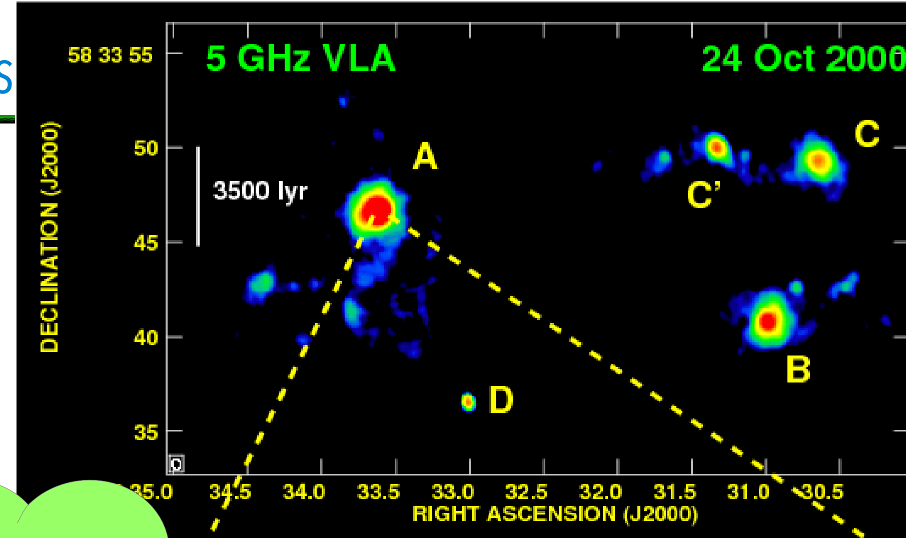
SN(R) in external galaxies



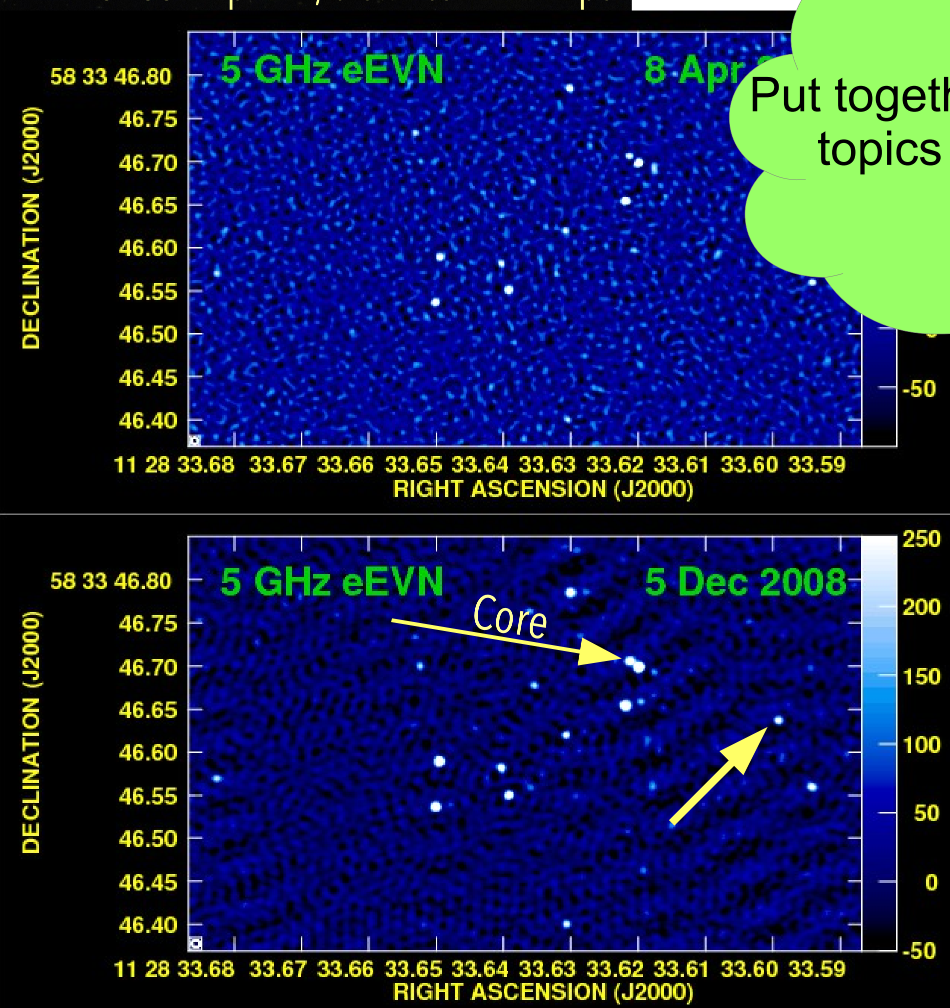
Arp 299a

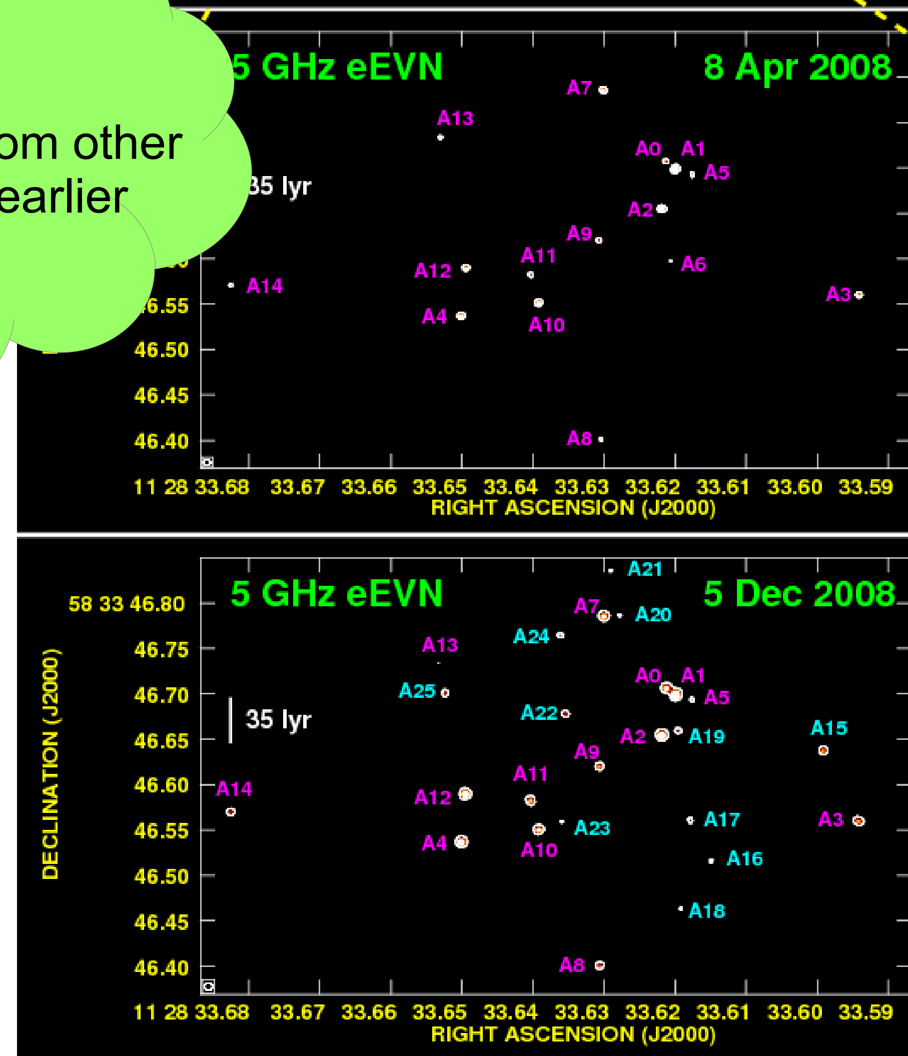
Bondi +, 2012 (VLBI obs)

[optical is obscured!!]



Put together items from other topics discussed earlier





Supernovae in external galaxies: the radio paradigm (we see them all!)

- SN rates:

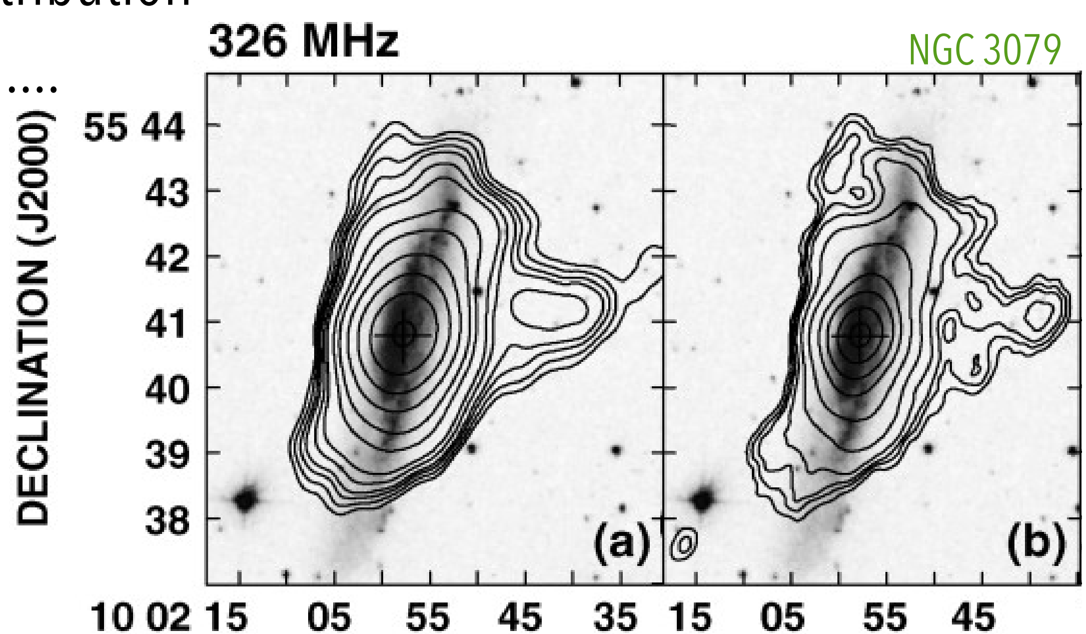
  Number .vs. duration

  Number .vs. SFR ⟹ IMF

Put together items from other topics discussed earlier

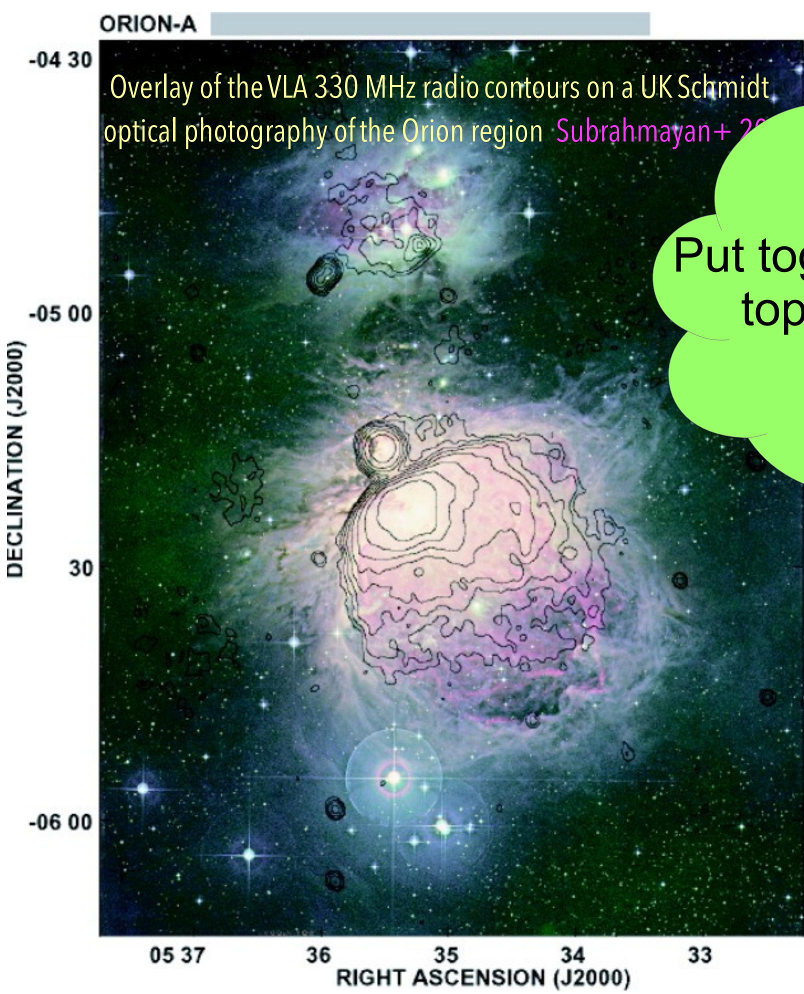
Implications:

- Energy release in the ISM (heating, radiation, hydrodynamical effects, ...)
- CR production: energetics, lifetime, distribution
- Gas enrichment (metallicity, gradients, ...
- Extra–planar gas + CR leakage (HI + synchrotron!)

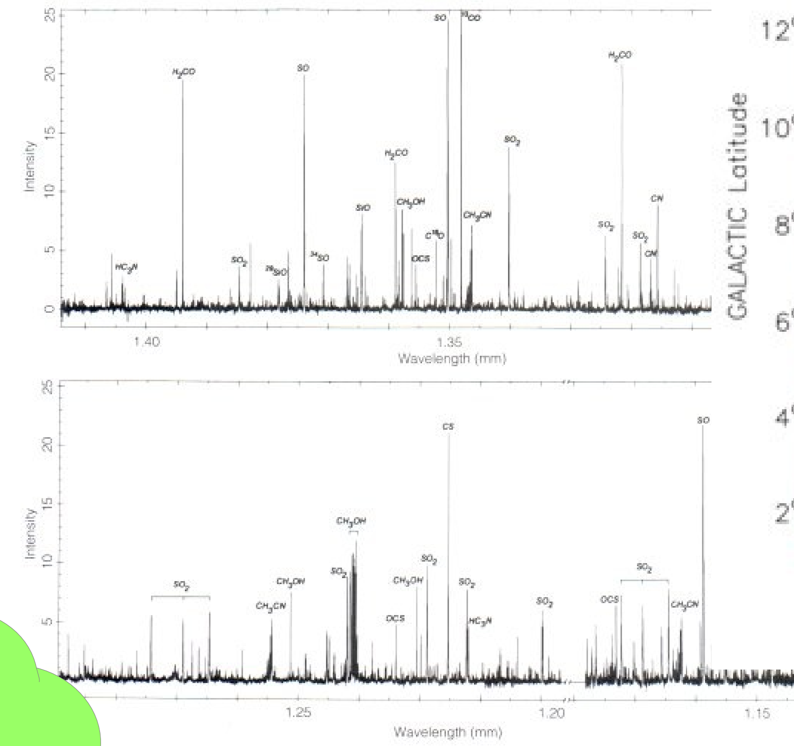


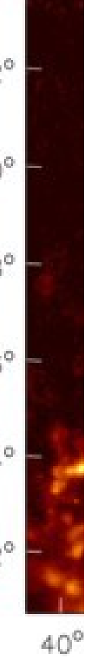
HII regions: …. in our Galaxy

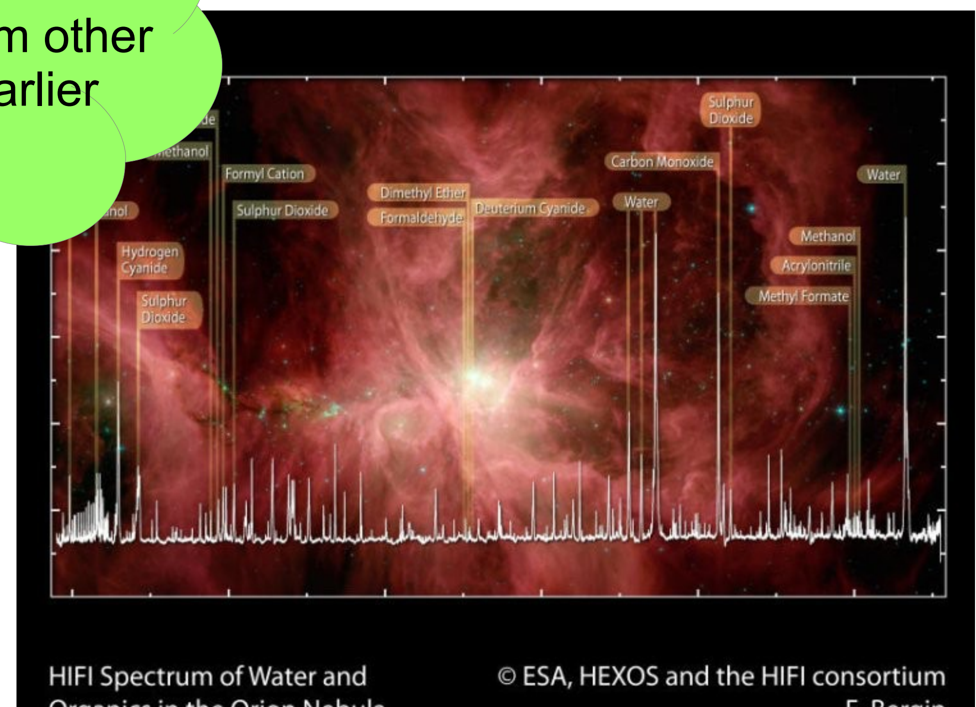
- In Star Forming Regions
- LOS intercepts both WIM, WNM and CNM
- FF continuum (radio) + emission lines (CNM) & recombination lines & dust emission (μ – wave & IR)



Put together items from other topics discussed earlier







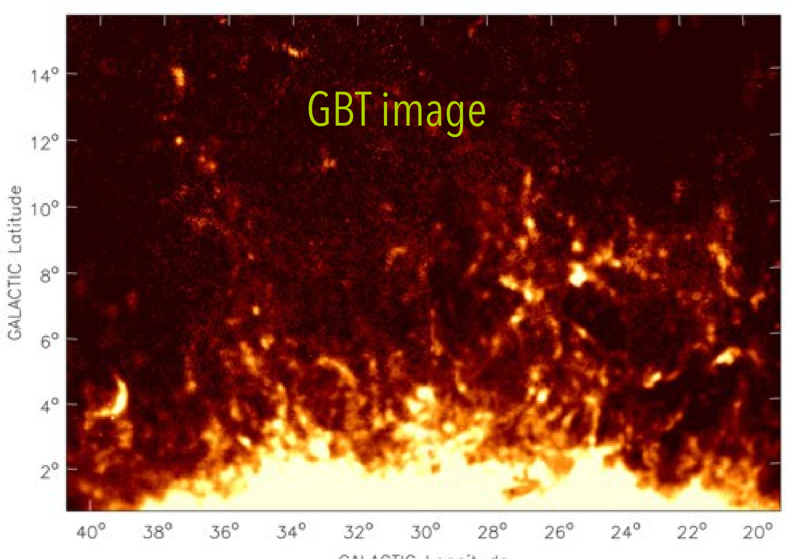
157 – 212 & e 240 – 625 μm @ HIFI on board of HERSCHEL

HII regions:in our Galaxy

- In Star Forming Regions
- LOS intercepts both WIM, WNM and CNM
- FF continuum (radio) + emission lines (CNM) & recombination lines & dust emission (μ – wave & IR)

The free-free absorption coefficient of an H II region is well approximated by

$$\left(\frac{\kappa}{pc^{-1}}\right) \approx 3.3\cdot 10^{-7}\left(\frac{n_e}{cm^{-3}}\right)^2\left(\frac{T_e}{10^4\,K}\right)^{-1.35}\left(\frac{\nu}{GHz}\right)^{-2.1}$$



http://images.nrao.edu/Galactic_Sources/Galactic_Halo/575
Purple: HI, Green: HII, Black: HI+HII

HII regions:in external galaxies

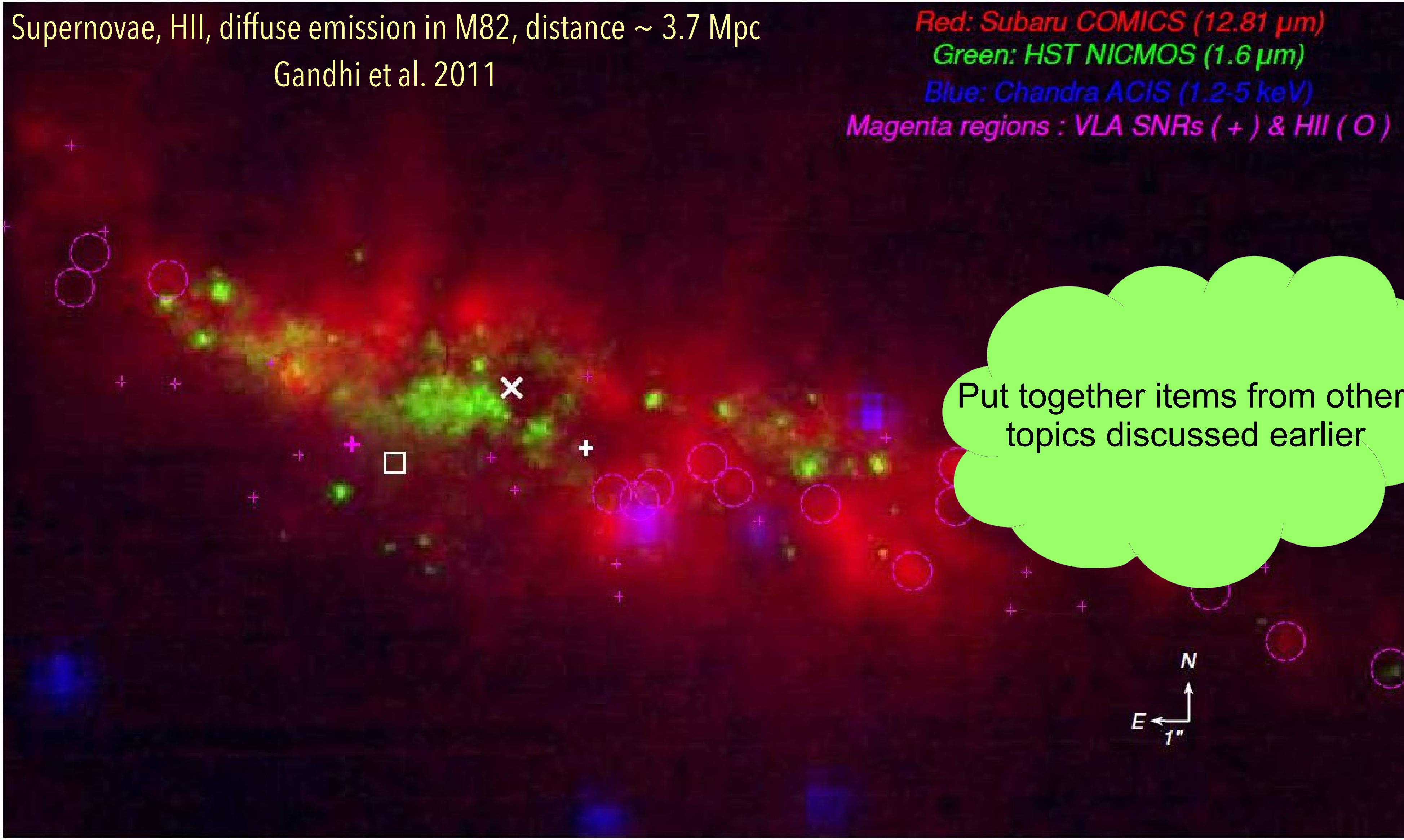


Fig. 6. RGB overlay of the three panels from Fig. 5, with radio regions plotted as dashed circles (HII regions) and SNRs (plus signs). The white x sign is the kinematic center (Weliachew et al., 1984). There are two heavy plus signs: about 4″ to the East of the center, and 1″ South is the AGN candidate in magenta (see § 8), and about 2″ to the West and 1″ South is SN 2008iz in white (Brunthaler et al., 2009). The white box marks the position of the unusual radio transient reported by Muxlow et al. (2010).

Summary:

- Spirals (irregulars) have diffuse emission related to SFR (e.g. Radio – FIR correlation) both from thermal & non-thermal processes. The former have the predominant contribution between 30 and 200 GHz (bremsstrahlung), while the latter are most relevant below 30 GHz (synchrotron)

- Ellipticals (lenticulars) do not possess significant diffuse emission Some ellipticals are AGNs (both High and Low luminosity), likely unrelated To mergers, but correlated with the total mass of the host

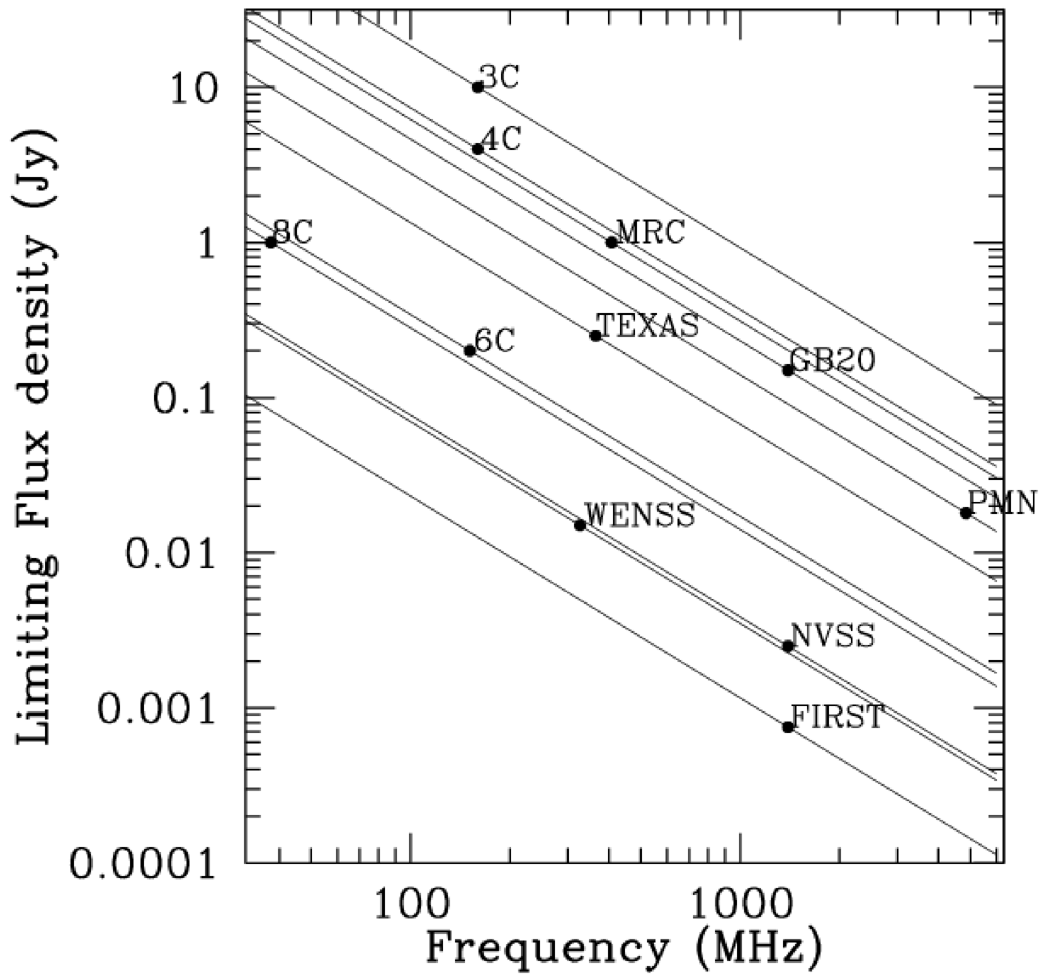
- A weak "core" is often found in all (both spiral & elliptical) galaxies.

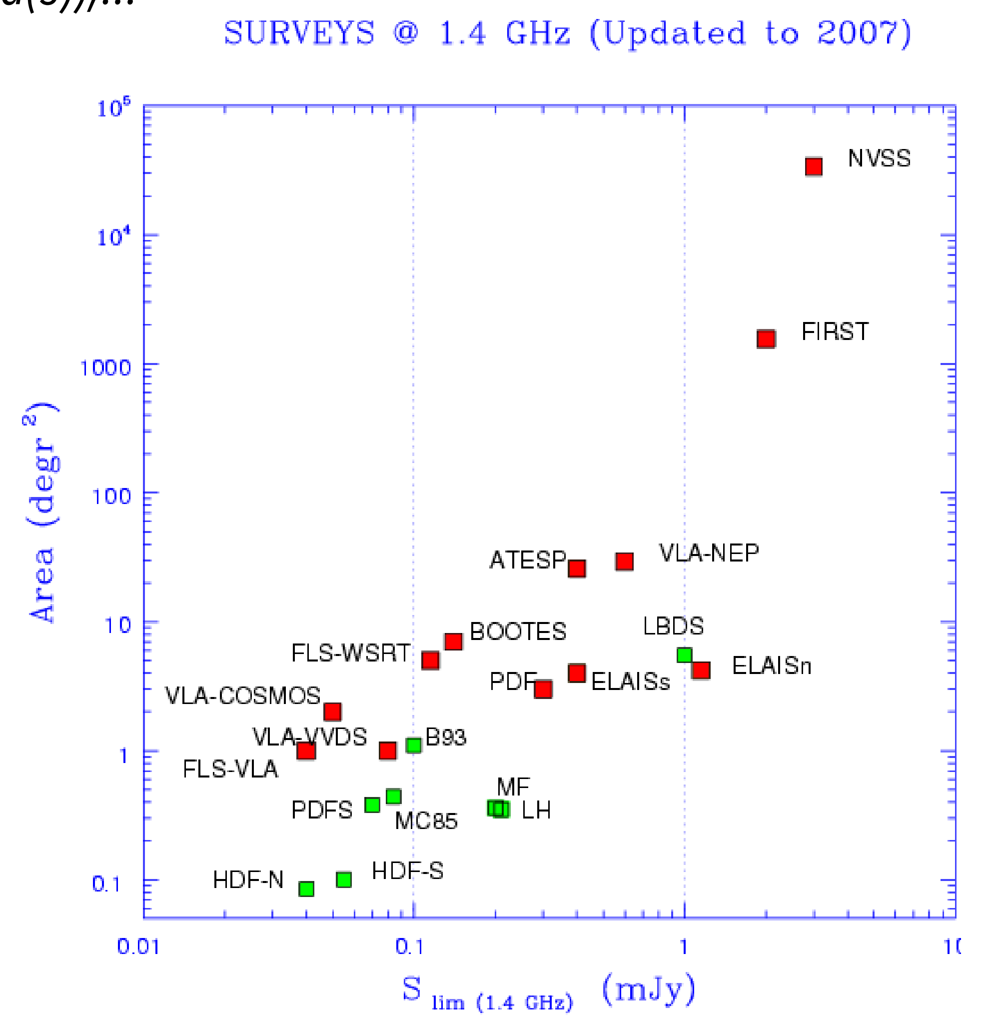
(question: Does any galaxy contain a LLAGN?)

Surveys are a very effective tool to study populations

There are several approaches to plan and carry out a survey:

Area, flux density limit, resolution, frequency (band(s)),...





Green single fields, red mosaics

Choices to be made:

- Target objects: Frequency, resolution, sensitivity
- Telescope: FoV, resolution, sensitivity (bandwidth, time), surveyed area

$\Rightarrow$ observing time

Wide area surveys: shallow, "low resolution"

Example: **NVSS**

VLA @ 1.4 GHz, whole sky north of DEC = – 40°, D configuration $\Rightarrow$ 45" resolution, r.m.s. noise ~0.45 mJy/beam

Example 2: **LoTSS**

LOFAR @ 144 MHz, ongoing, the northern sky, resolution ~5", r.m.s. noise ~0.1 mJy/beam

Deep fields: small area, high resolution (take into account "confusion" noise)

Example: **VLA - COSMOS**

VLA @ 1.4 GHz +, resolution ~1" (A configuration), noise a few μJy/beam (confusion limited)

In general, MOSAICS are necessary!

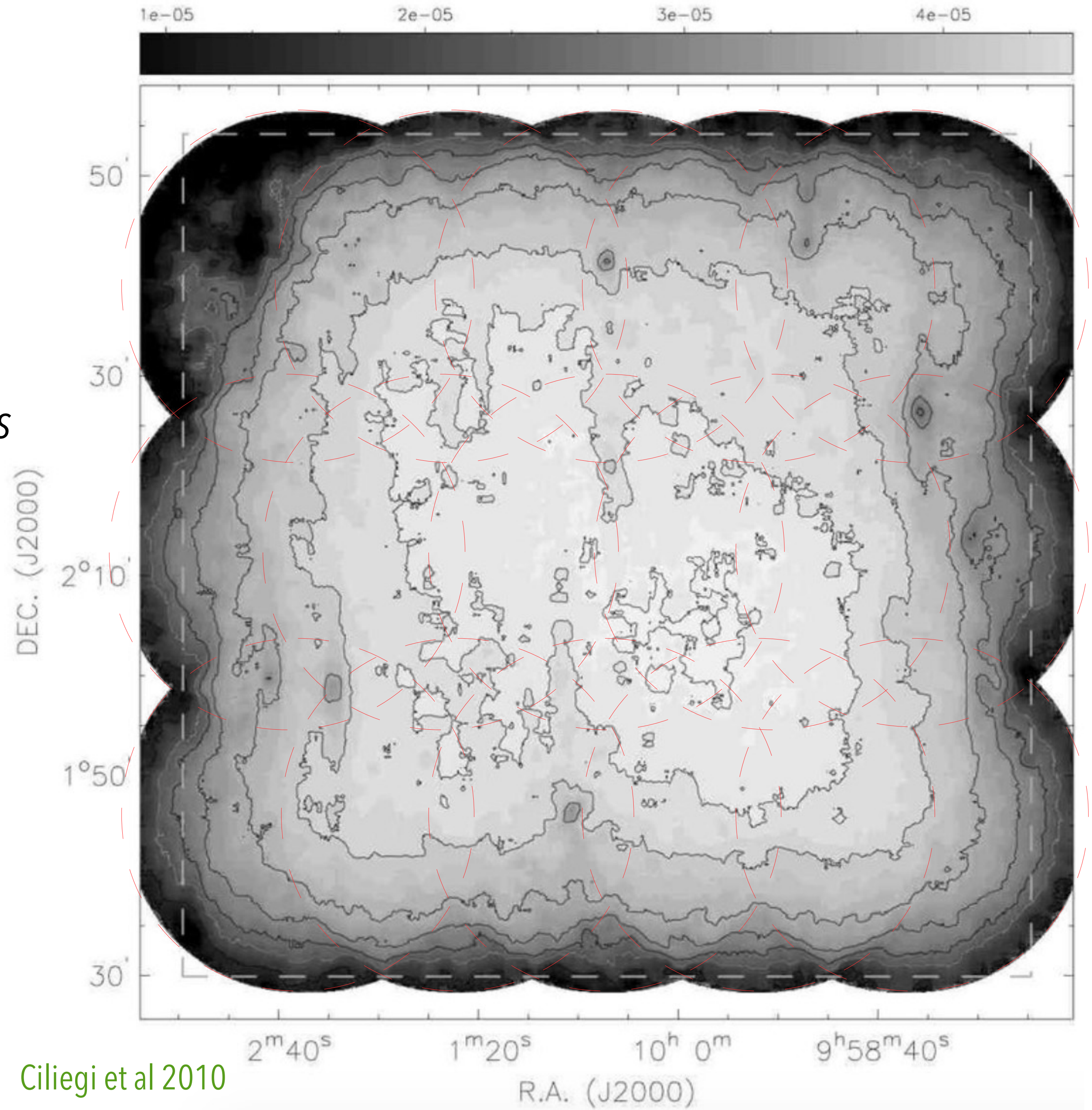
(the FoV of and interferometer is small!)

Blind searches over a large sky area: mosaic of several overlapping pointings provides a uniform sensitivity:

Each pointing is represented by a red dashed circle

The sensitivity in each pointing decreases from the centre outwards

The overlapping regions grant a uniform sensitivity over the whole area (image of the noise over the whole area covered in the survey)



Ciliegi et al 2010

The VLA – COSMOS field:

VLA: 250 hr in A config
25 hr in C config
Resolution ~ 1.5″

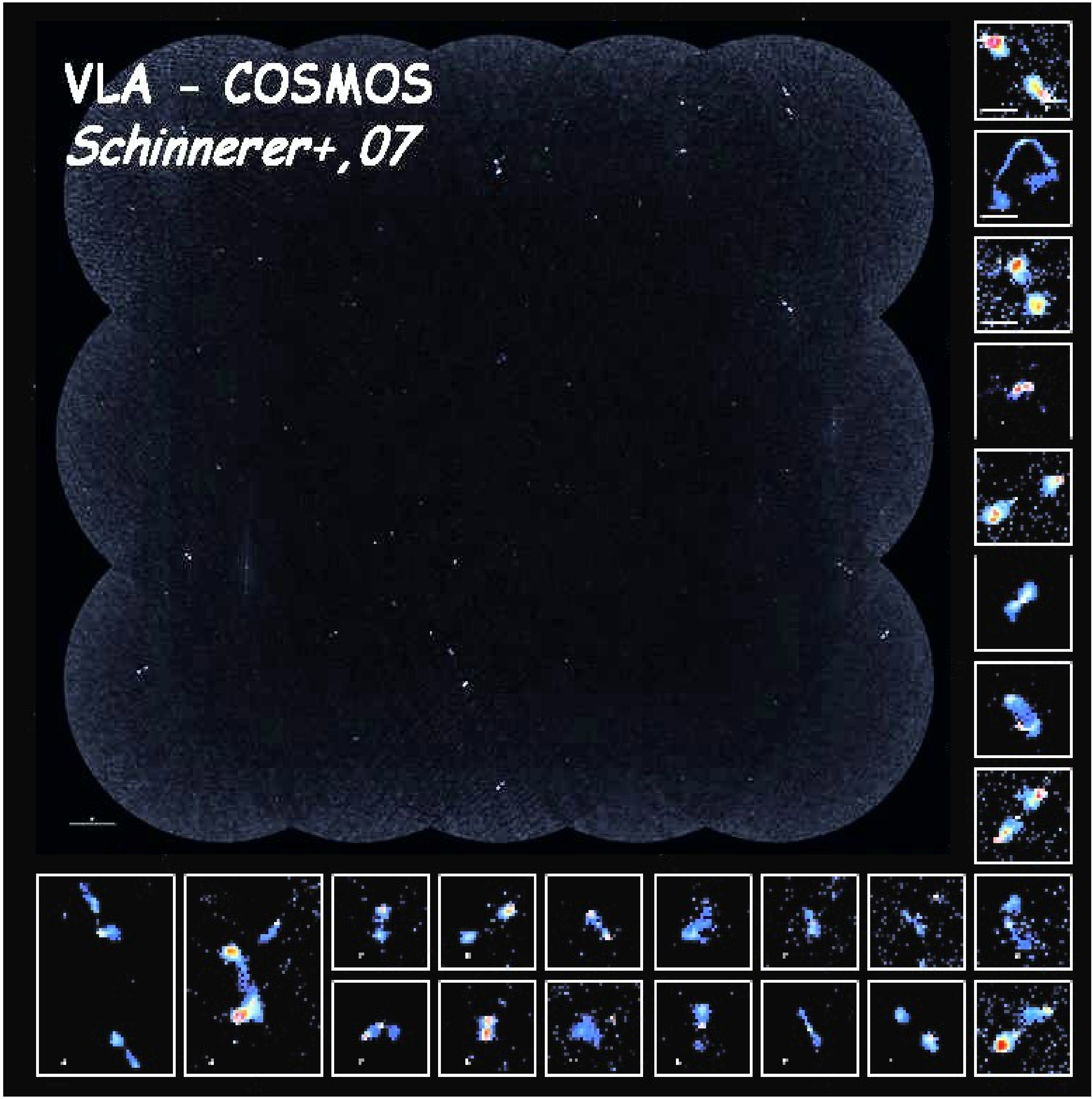
75 MHz in spectral line mode
centered at 1.4 GHz

10.5 μJy rms in the 1°x1° field

15 μJy rms in the 1.4°x1.4° field

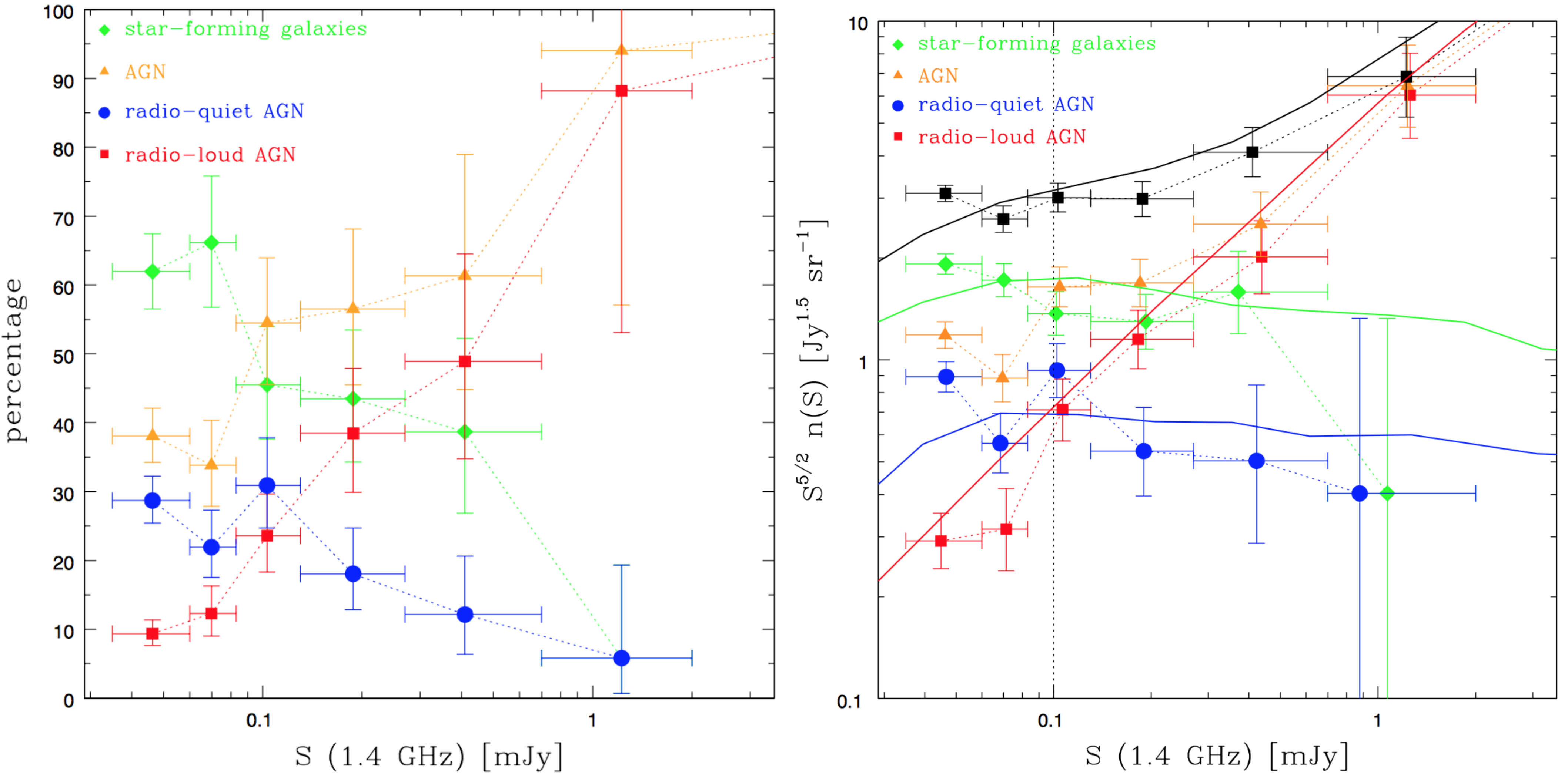
2,417 sources (down to 5 sigma)
(3,643 sources down to 4.5 sigma)

http://www2.mpia-hd.mpg.de/COSMOS/



Radio Faint Population: population studies .vs. flux density limit

One of the products of a deep field: substantial change in r-s population around 0.1 – 1 mJy!

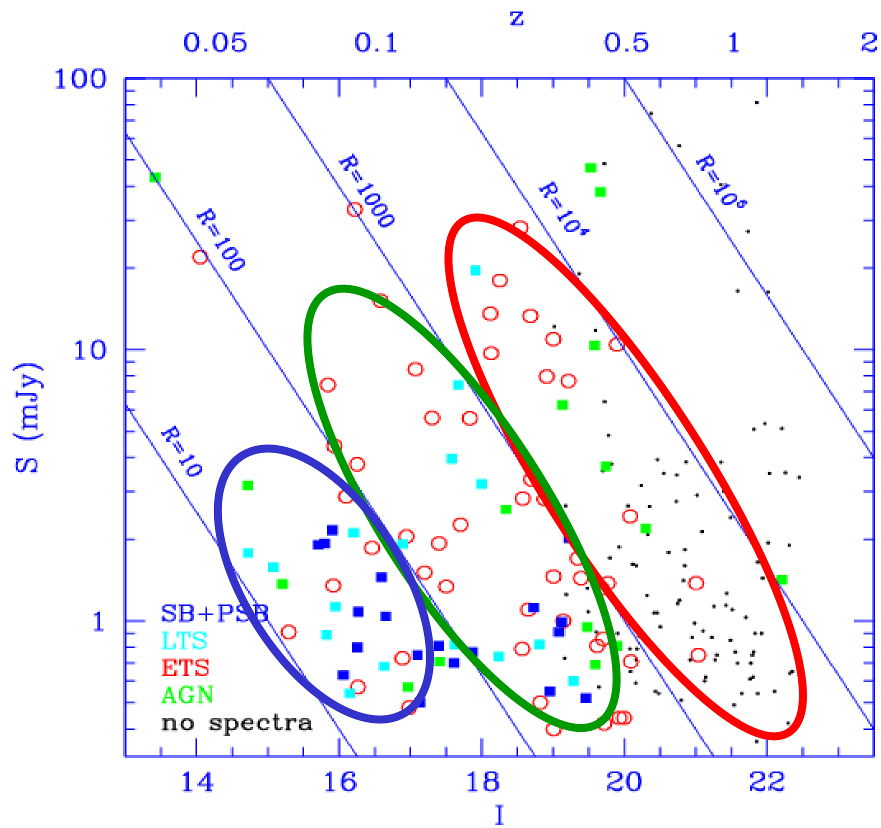


Radio to optical ratio:

$$R = S \cdot 10^{0.4(m-12.5)}$$

$R > 100 \rightarrow$ AGN / ETG

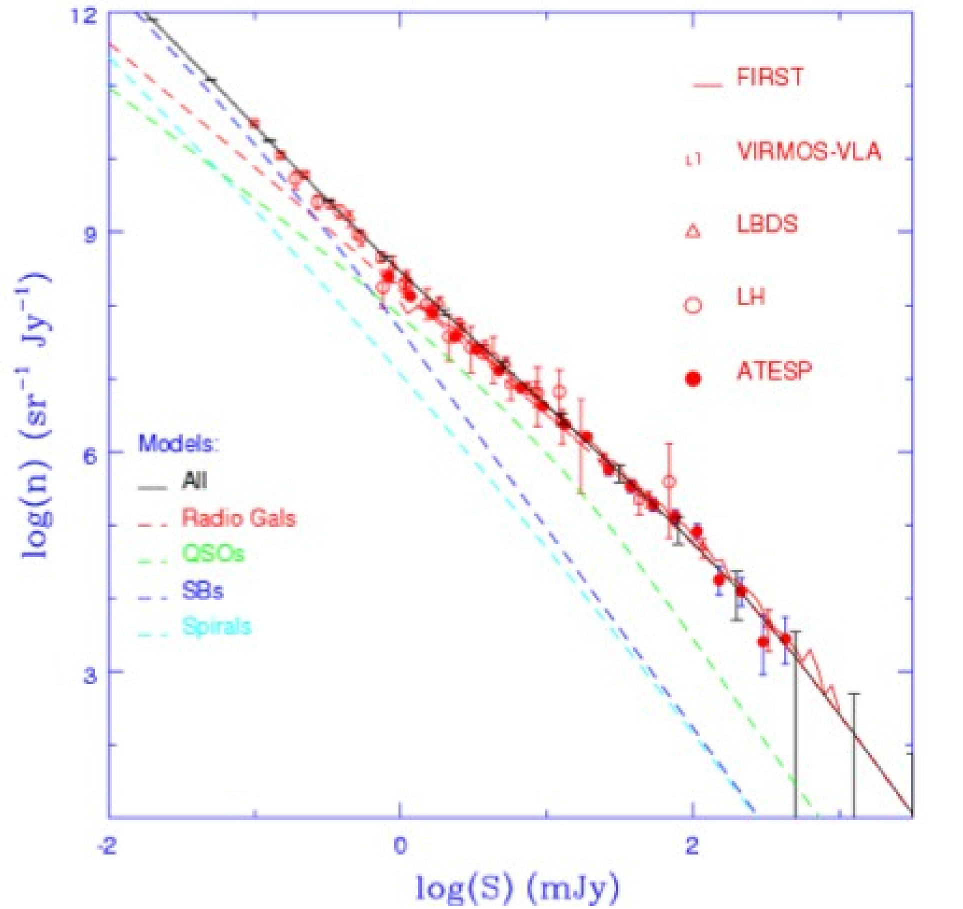
$R < 100 \rightarrow$ SFG



Something already known…. powerful radio sources are generally hosted in elliptical galaxies (and quasars), other populations of hosts shows different properties (inhomogeneous)

Source counts:

Log N(>S) – Log S



In case of an Euclideand Universe

$N(>S) \approx S^{-1.5}$ integral counts

$N(S) \approx S^{-2.5}$ differential counts

In a more complete & complex way

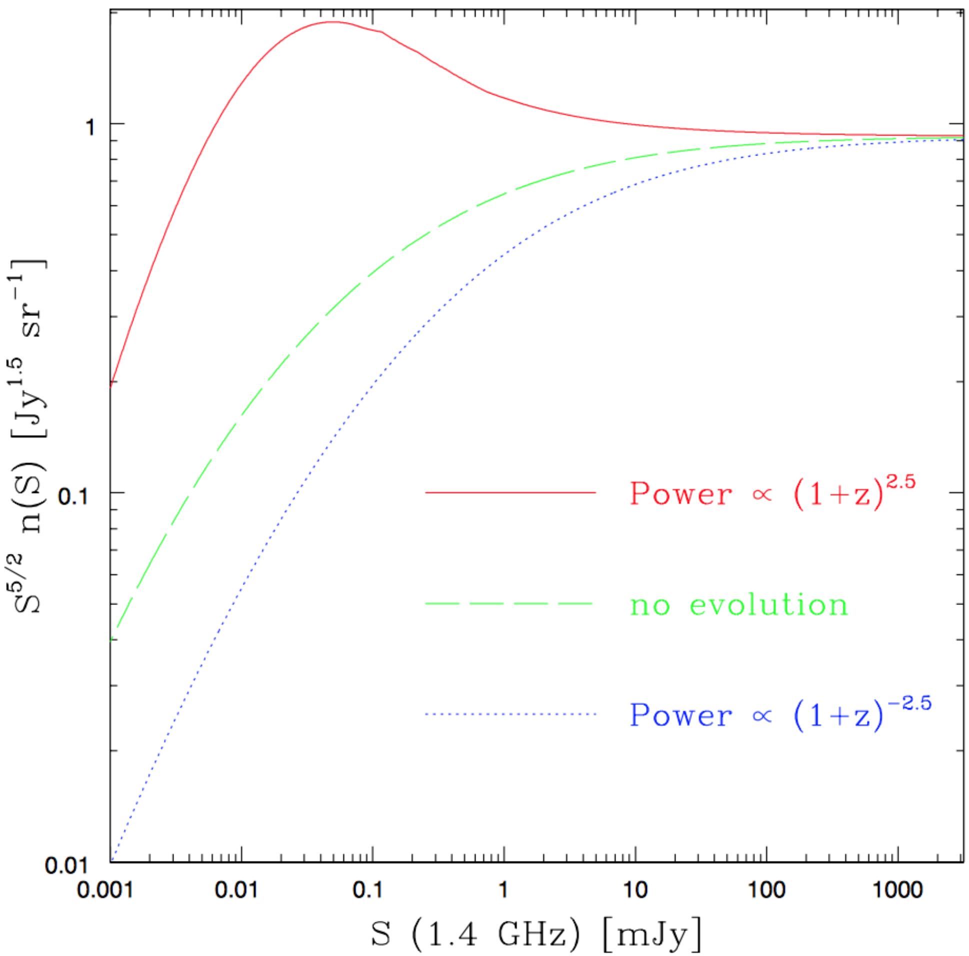
$$\frac{N(S)}{4\pi} = 4\pi \frac{c}{H_o} \int_{z_{min}}^{z_{max}} \frac{\Phi[P(S,z),z] D_L^4(z)\, dz}{(1+z)^{(3-\alpha)} \sqrt{(1+z)^2(1+\Omega_{mz}) - z(z+2)\Omega_\Lambda}}$$

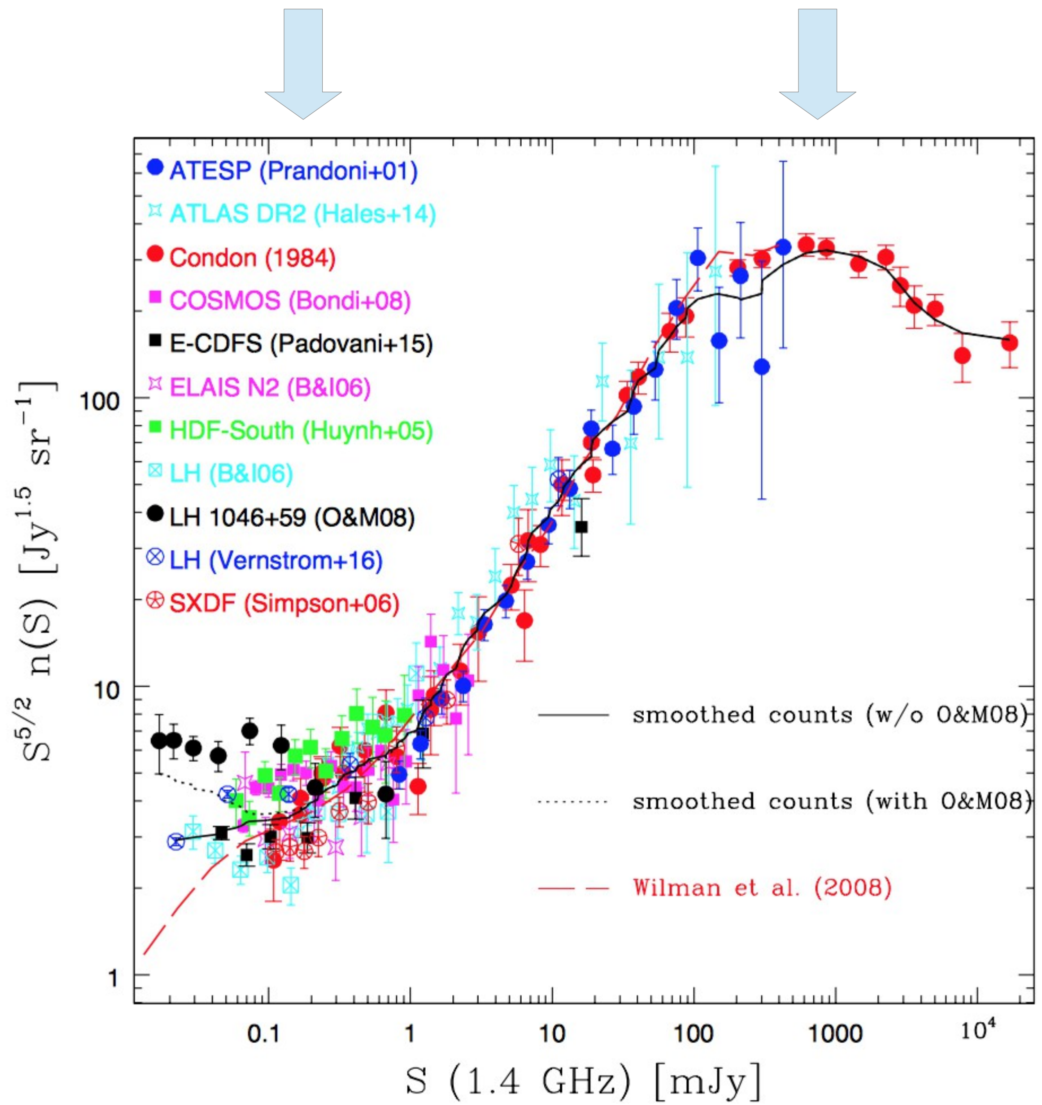
$\Phi[P(S,z),z]$ redshift dependent luminosity function: PDE, PLE? Density and/or Lumin. evol.?

$z_{min}, z_{max}, D_L^4(z), H_o$ $\rightarrow$ clear influence from cosmology!

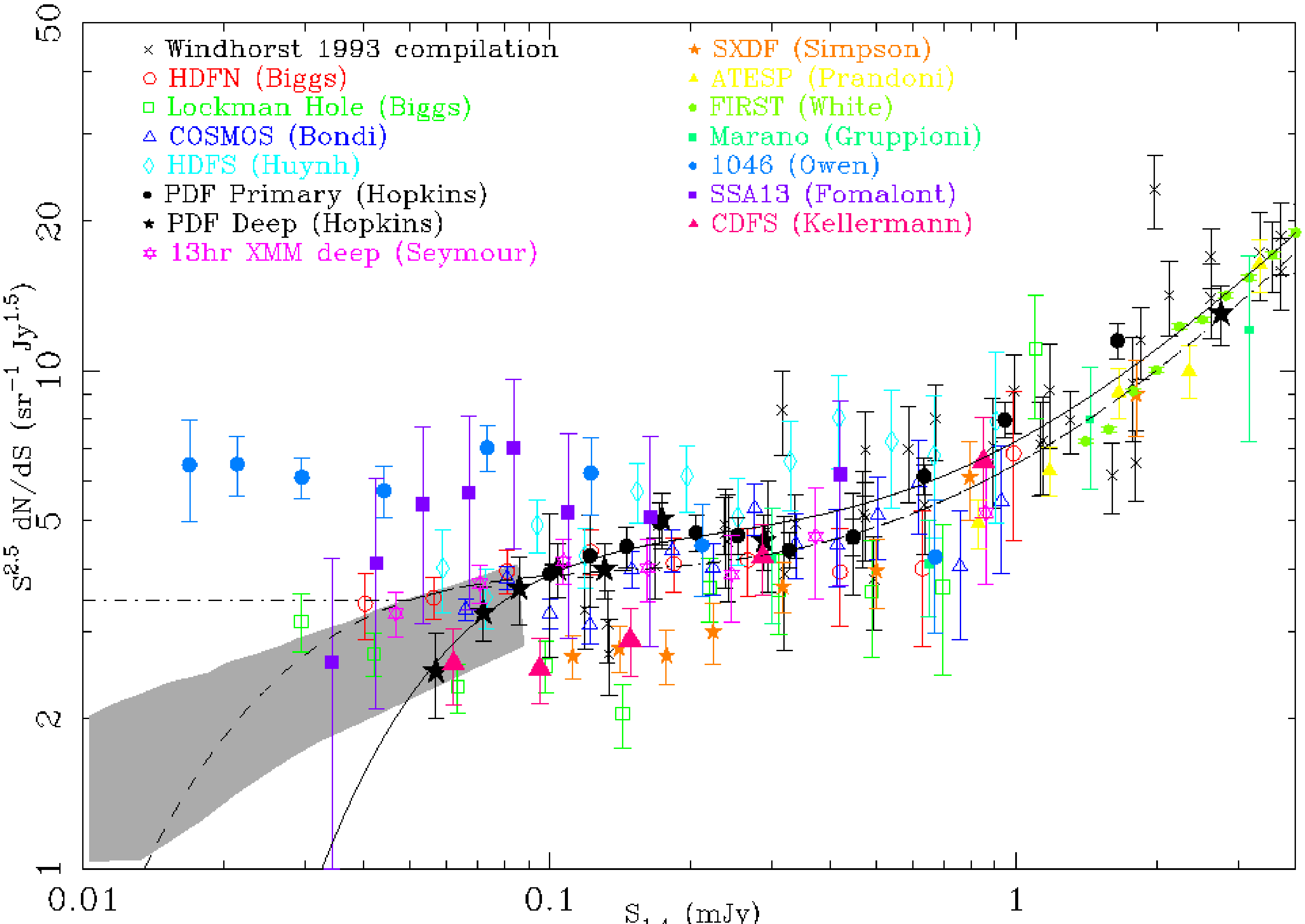
Source counts and evolution

SFGalaxies *AGN*





Radio Faint Population: the importance of the optical identification



Flux interval 1.4 GHz (μJy)	Early type	Late type	Starburst	Total
$S < 60$	29%	34%	37%	80%
$60 \leq S < 100$	34%	32%	34%	84%
$100 \leq S < 150$	42%	32%	26%	90%
$150 \leq S < 500$	48%	33%	19%	95%
$S \geq 500$	61%	20%	19%	95%

Radio ~~Quiet~~ Faint Population

Radio quiet AGN: ~90% of total

Low radio-to-optical ratio (<10), but can have $P_{1.4\,GHz} \leq 10^{24}\,W\,Hz^{-1}$

Intrisically different from RL

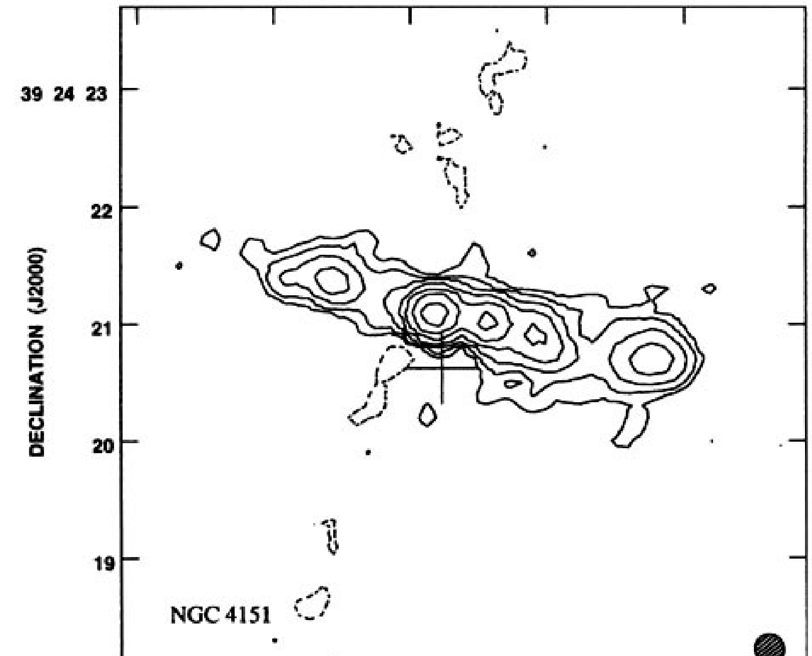
RL

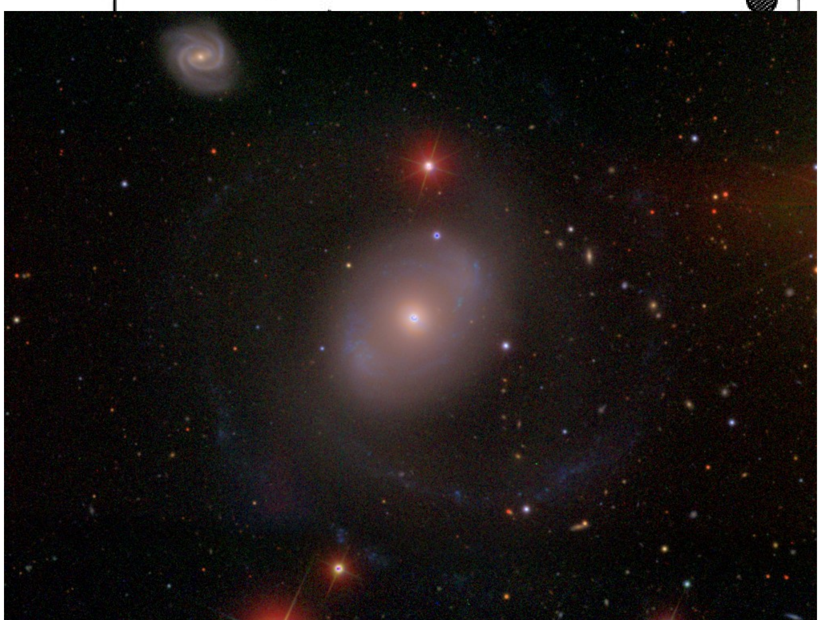
- mostly non-thermal emission
- bulge dominated host galaxy ($L_{bulge} / L_{host} > 0.5$)

RQ

- Mostly thermal emission
- Host galaxy with a variety of morphologies

- Also in RQ the type I/II AGN distinction holds (example: Seyfert galaxies)





Radio ~~Quiet~~ Faint Population

Kimball + 2011 ($0.2 < z < 0.3$), Condon + 2013 ($1.8 < z < 2.5$)

⇨ Sample of SDSS RQs

Peak of the distribution of radio powers:

$$P_{6\,GHz} \sim 10^{23}\ W\ Hz^{-1}$$

• • • Consistent with being powered by SF

Zakamska + (2016) ($z < 0.8$)

$S > 1$ mJy

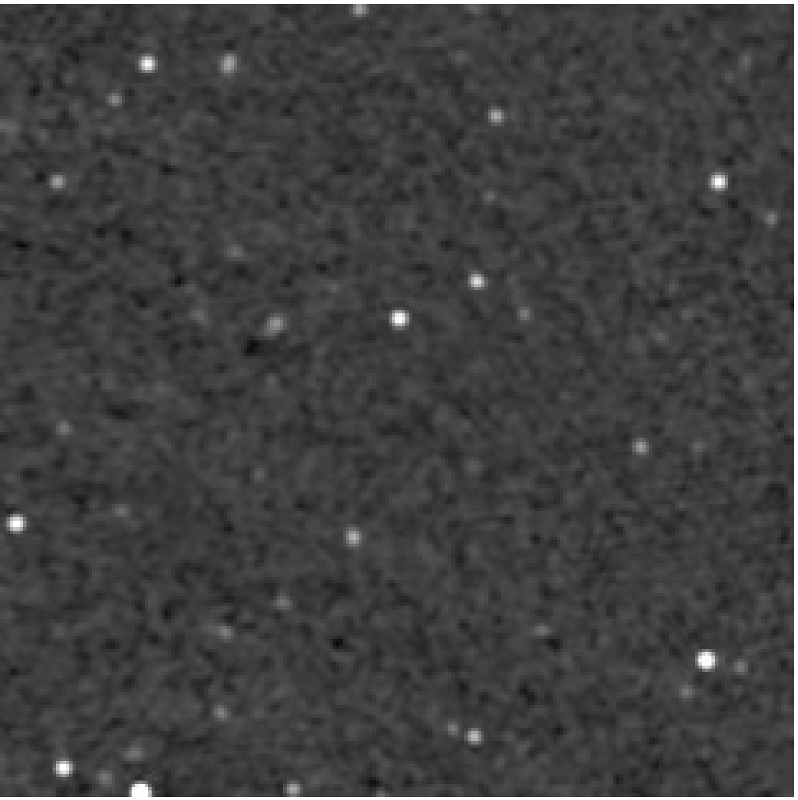
At least part of the radio emission is powered by the AGN

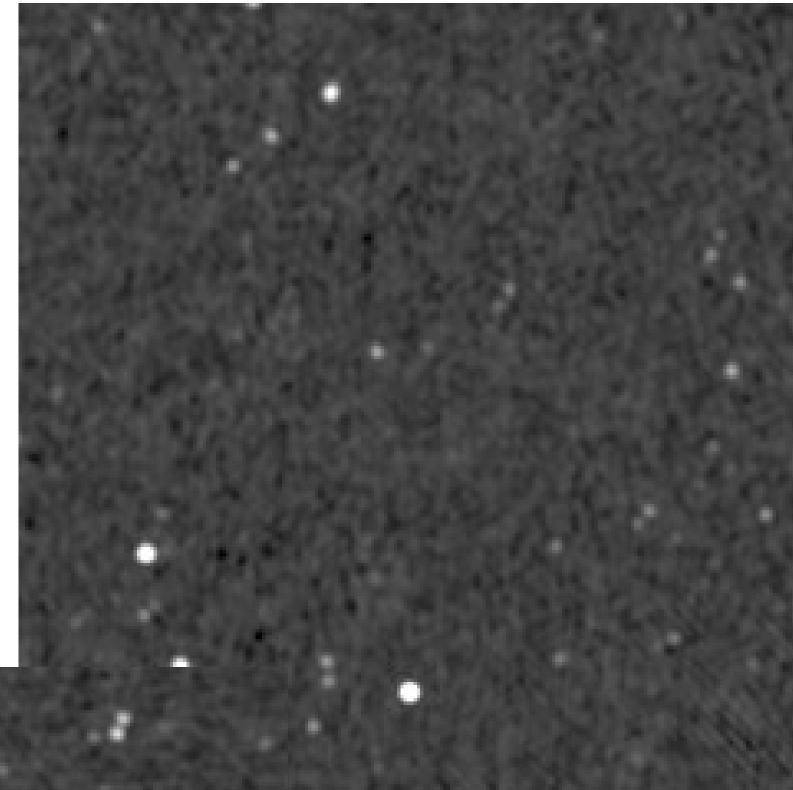
Still open issue (longstanding debate since the '60ies)

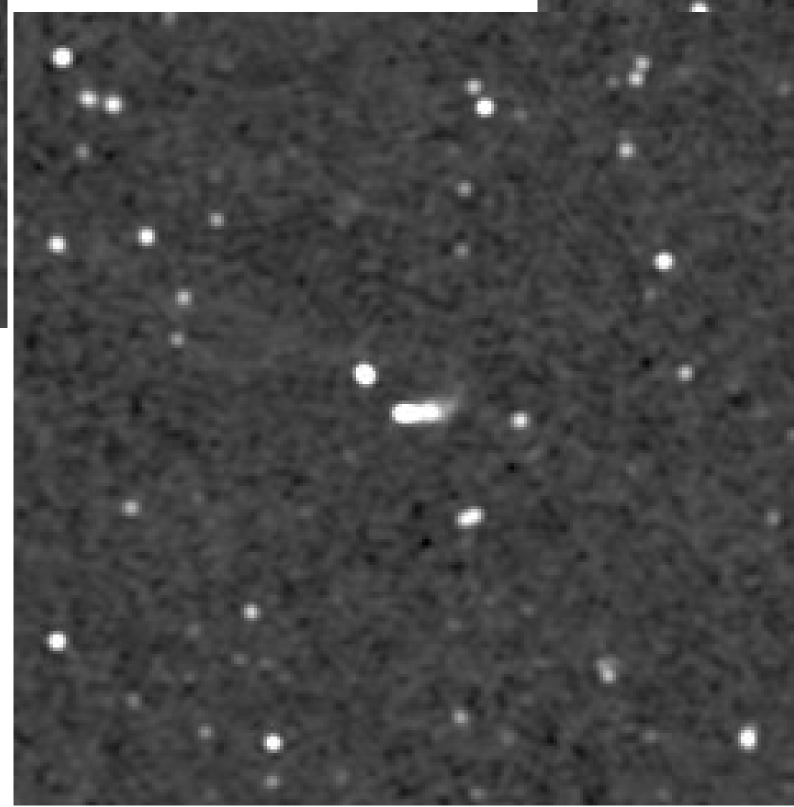
Radio ~~Quiet~~ Faint Population

Radio source surveys:

>80% of the sources are unresolved at 45″



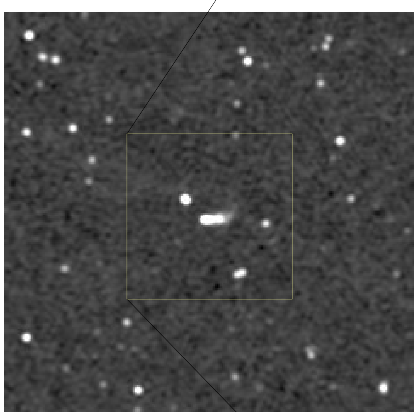


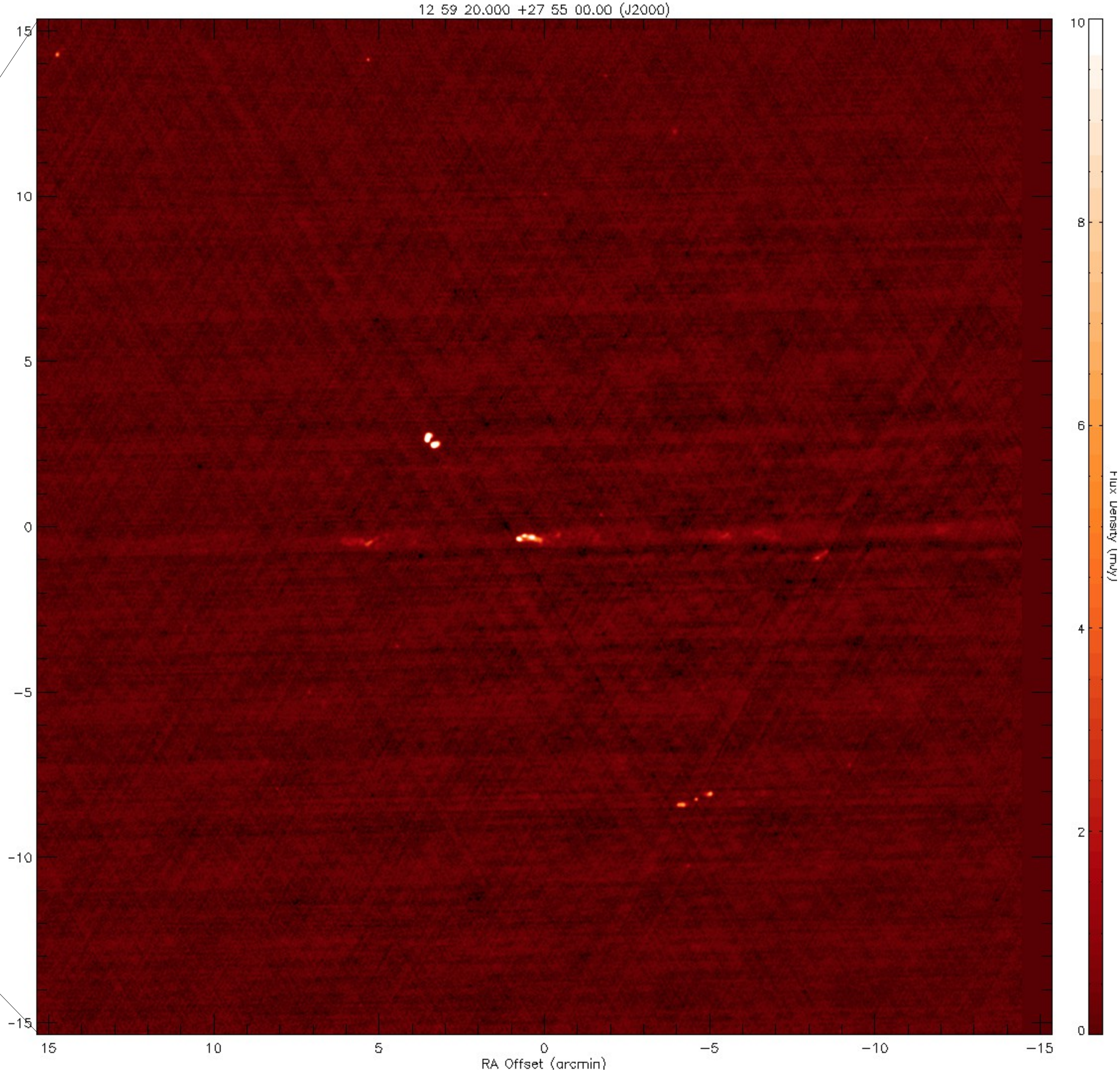


Radio ~~Quiet~~ Faint Population

Radio source surveys:

Relevance of angular resolution





References

- •*Radio source populations*

- *Windhorst, 2003, NAR, 47, 357-365*
  "The microJansky and nanoJansky population"

- *Padovani, 2016, A&AR, 24, 13 (61 pages, alternatively arXiv:1609.00499 36 pages)*
- *"The faint radio sky: radio astronomy becomes mainstream"*

AGN radio emission

Quick Overview of the radio source interpretation "bias":

What are radio galaxies and radio quasars (very dominant fraction at high flux densities)

FR I & II ! Is that all?

Ambient is relevant (cluster weather), pressure balance?

Does size matters? Is that related to individual radio source evolution?

Consider radio galaxies only (no significant beaming) and a self-similar growth:

Radio spectrum evolution: turnover to lower and lower frequencies, then break frequency does the same: various names for various stages

Radio luminosity evolution: as long as in a dense environment, luminosity increases, then when > 1 to a few kpc slow decline. May be a function of the accretion rate.

"Normal" Galaxies

$P_{1.4\,GHz} \leq 4 \times 10^{20}\,W\,Hz^{-1}$ - ($10^{21}\,W\,Hz^{-1}$ e.g. M81)

Synchrotron emission (CR +H in the ISM): mostly spirals, no ellipticals/S0s

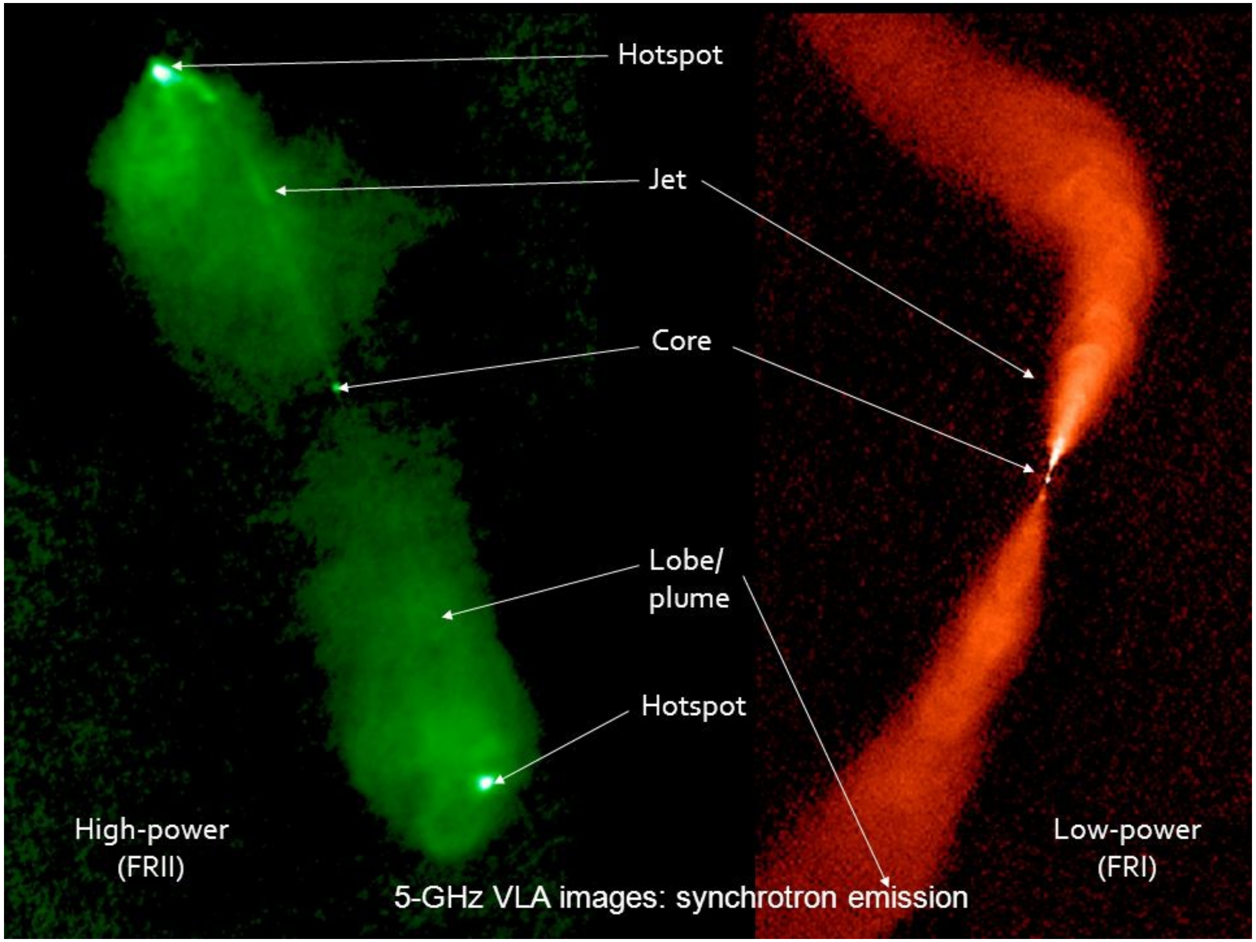
Radio Galaxies , aka AGNs and the Unified Scheme Models (**JETTED RADIO SOURCES**)

$P_{1.4\,GHz} > 10^{22}\,W\,Hz^{-1}$ (up to 10^{28})

Synchrotron emission in (cores), **jets**, (H-Ss), lobes: hosted in E (& QSOs)

FR – I & FR – II classification based on morphology, but also physical!

Small fraction of the overall population of radio sources in surveys/catalogs



5-GHz VLA images: synchrotron emission

Radio Source Populations

FR – I & FR – II

based on morphology, but also physical!

$P_{178\,MHz} = 10^{26}\,W\,Hz^{-1}$ Is the threshold

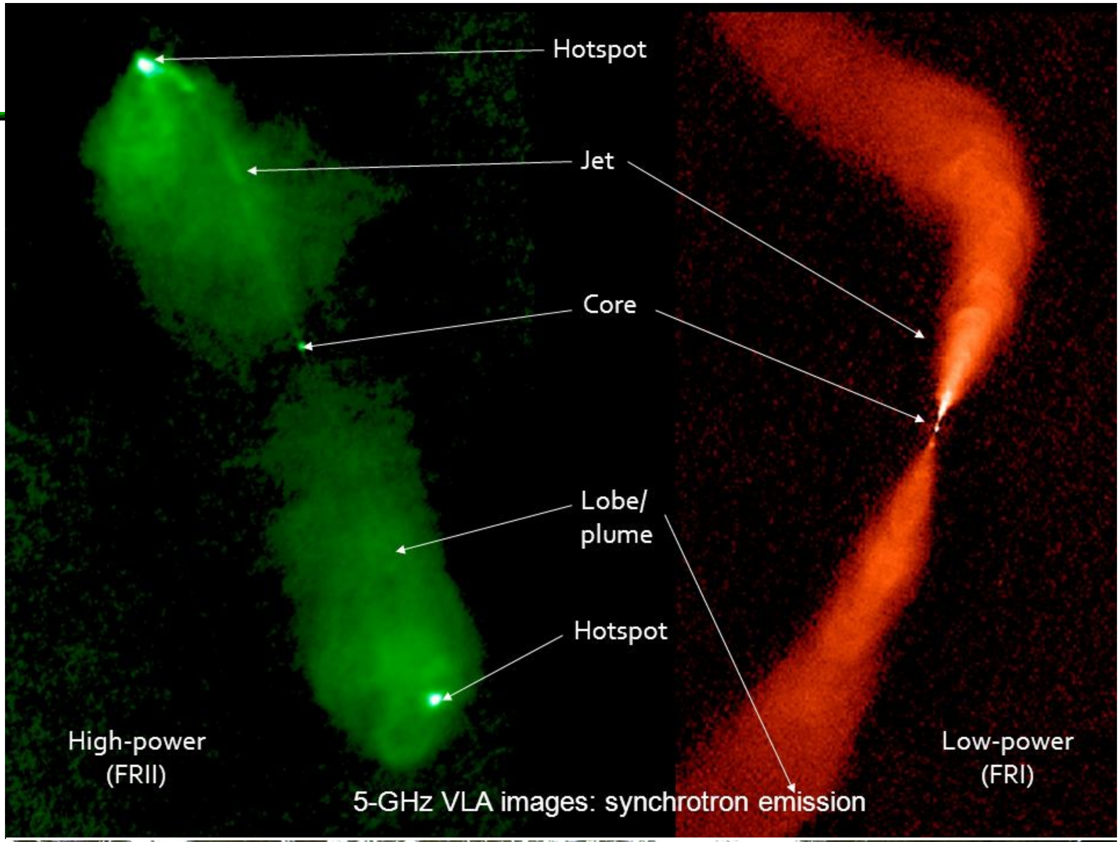
Other different properties:

FR – I

- Low z aka low radio power
- In groups/clusters
- "slow" kpc scale jets (low efficiency)

FR – II

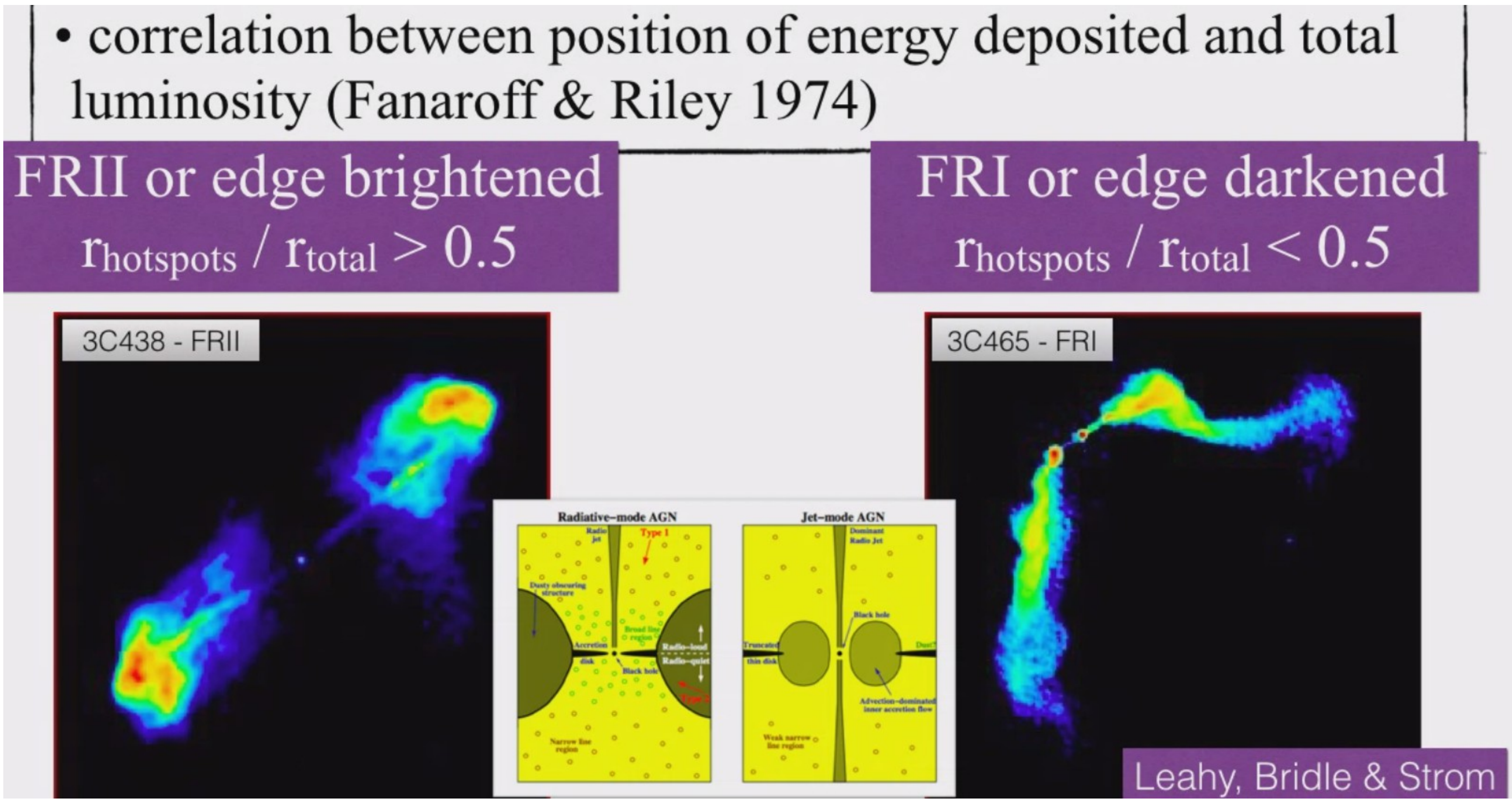
- High z aka high radio power
- Isolated
- "relativistic" bulk motions up to Mpc scales



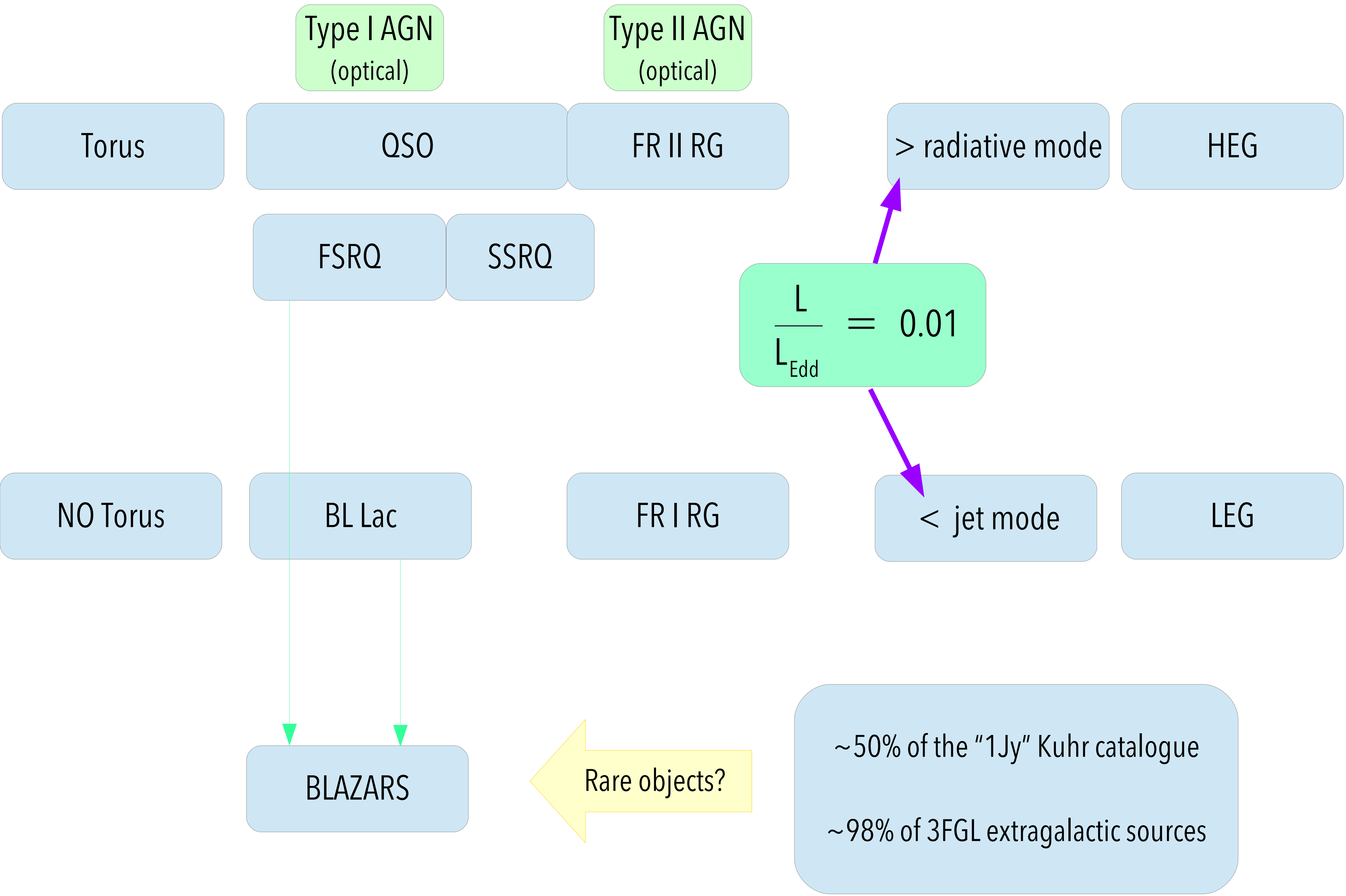
Bernie Fanaroff & Julia Riley, Cambridge, 2013. Photo Credit: Sarah White https://www.eso.org/public/videos/eso1907h/

https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=11821

https://www.nasa.gov/feature/goddard/2021/peering-into-a-galaxys-dusty-core-to-study-an-active-supermassive-black-hole



Unified scheme (radio loud)



Radio Sources/Galaxies

- About 10% of the AGN population has substantial radio emission (from AGN activity)
- Radiative ages are at most a few in 10^{8} yr
- Linear sizes reach a few Mpc
- Ambient is relevant (isolated/groups/clusters)
- Hosts are in Ellipticals (+ quasars)
- Morphological classification consistent with Unified Scheme Model(s)
- Most of the present day information is based on FR–I & FR–II populations but it is not the whole story!