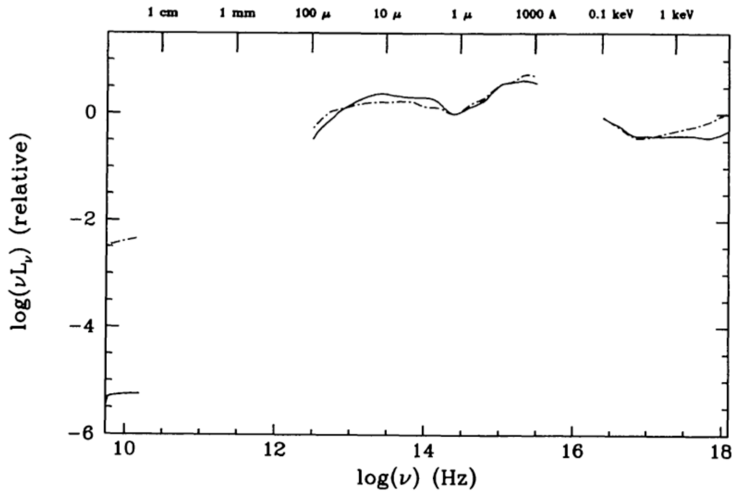
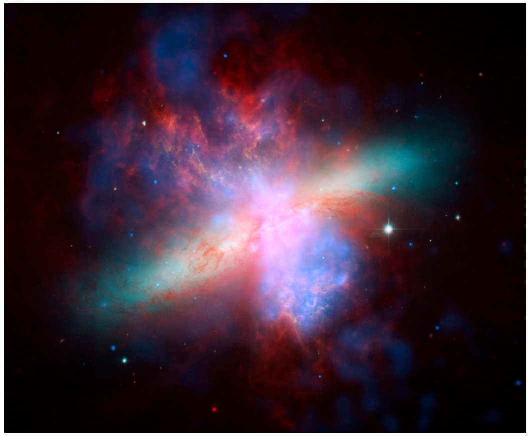




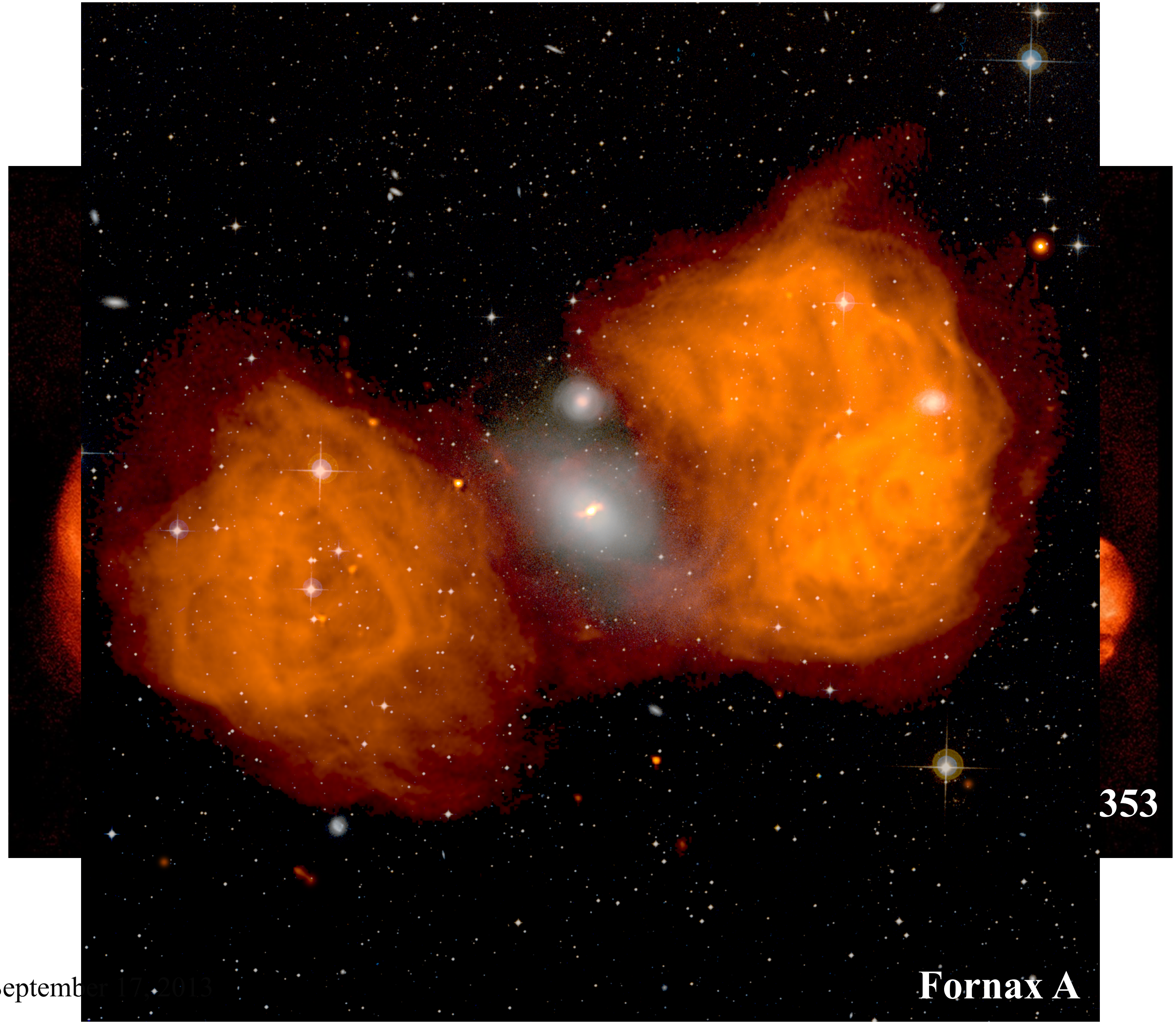
An introduction to Active Galactic Nuclei. 2.

Paolo Padovani, ESO, Germany

- Finding AGN in various bands
- Deep radio fields and the radio-loud/radio-quiet dichotomy
- The "Big Picture"
- AGN open questions

How does one find AGN?

- More complex than it sounds
- "Proper" samples are required to study relevant properties (evolution, luminosity function, etc.) on a statistically sound basis:
  - ✓ flux-limited samples
  - ✓ with high completeness (selection gets "most" AGN above the flux limit)
  - ✓ with high reliability (selection keeps contamination from other classes at "a minimum")
- In any case, <u>different bands give us very different perspectives and types of sources</u>
- Every band has its own biases: **beware of selection effects**!

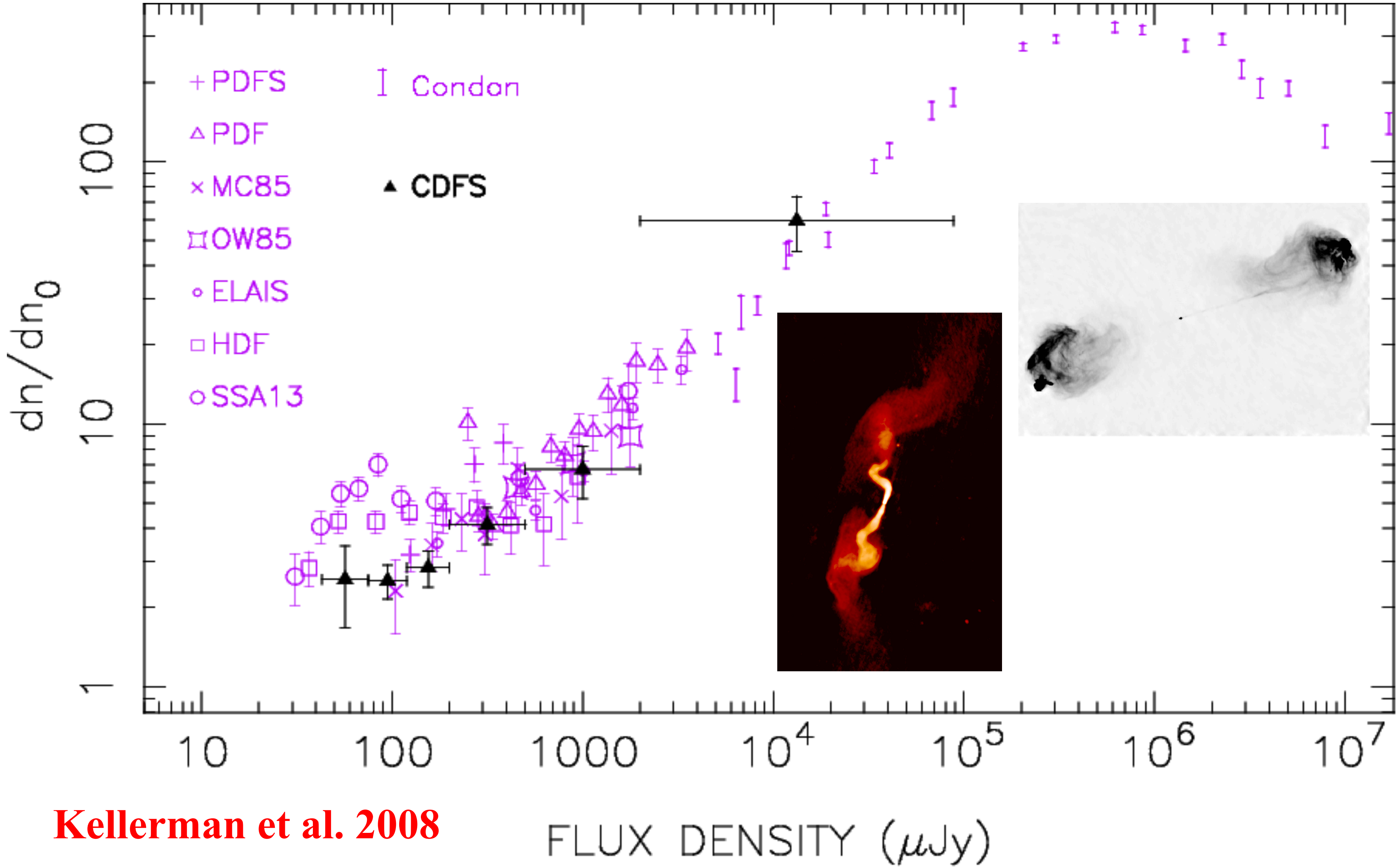

353
Fornax A

The radio sky

- Of the ~ 170,000 AGN in the Véron-Cetty and Véron (2010) catalogue, about 19,000 (~ 11%) have a radio detection (typically down to a few mJy)

- Radio flux densities: Jy = 10^{-23} erg/cm^2/s/Hz
  - ✓ $f_r \gtrsim 1$ Jy: strong
  - ✓ 1 mJy $\lesssim f_r \lesssim$ 1 Jy: intermediate
  - ✓ 1 μJy $\lesssim f_r \lesssim$ 1 mJy: weak

1.4 GHz number counts

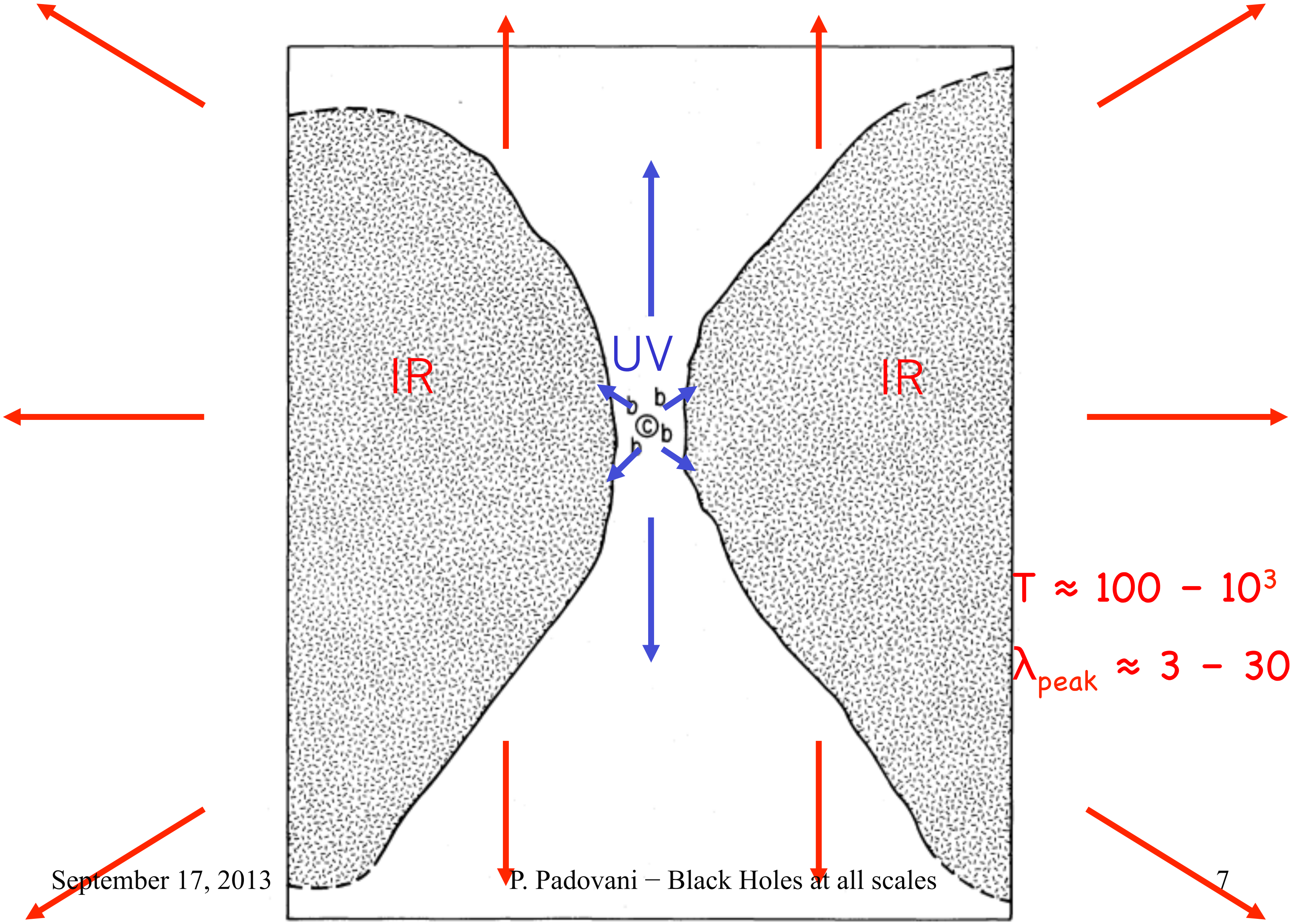


Kellerman et al. 2008

The radio band (@ ≈ 1 GHz)

- Flux densities ≳ 1 mJy:
  - ✓ selection done by just observing the sky: AGN are (basically) the only sources (only band)! (plus, stars are very weak radio emitters)
  - ✓ parameter space: radio-loud AGN [many blazars] (small fraction of the total, dominated by non-thermal emission [→ jets], elliptical hosts)
  - ✓ biases: none (but see above)
- Flux densities ≲ 1 mJy:
  - ✓ selection done by using multi-wavelength data to separate AGN (especially radio-quiet ones) from star-forming galaxies (optical counterparts faint) [more later]
  - ✓ parameter space: both radio-quiet and (decreasing fraction of) radio-loud AGN
  - ✓ biases: possible contamination from star-forming galaxies (especially if no X-ray detection); BUT: reaching the more numerous and common radio-quiet AGN with no obscuration bias!

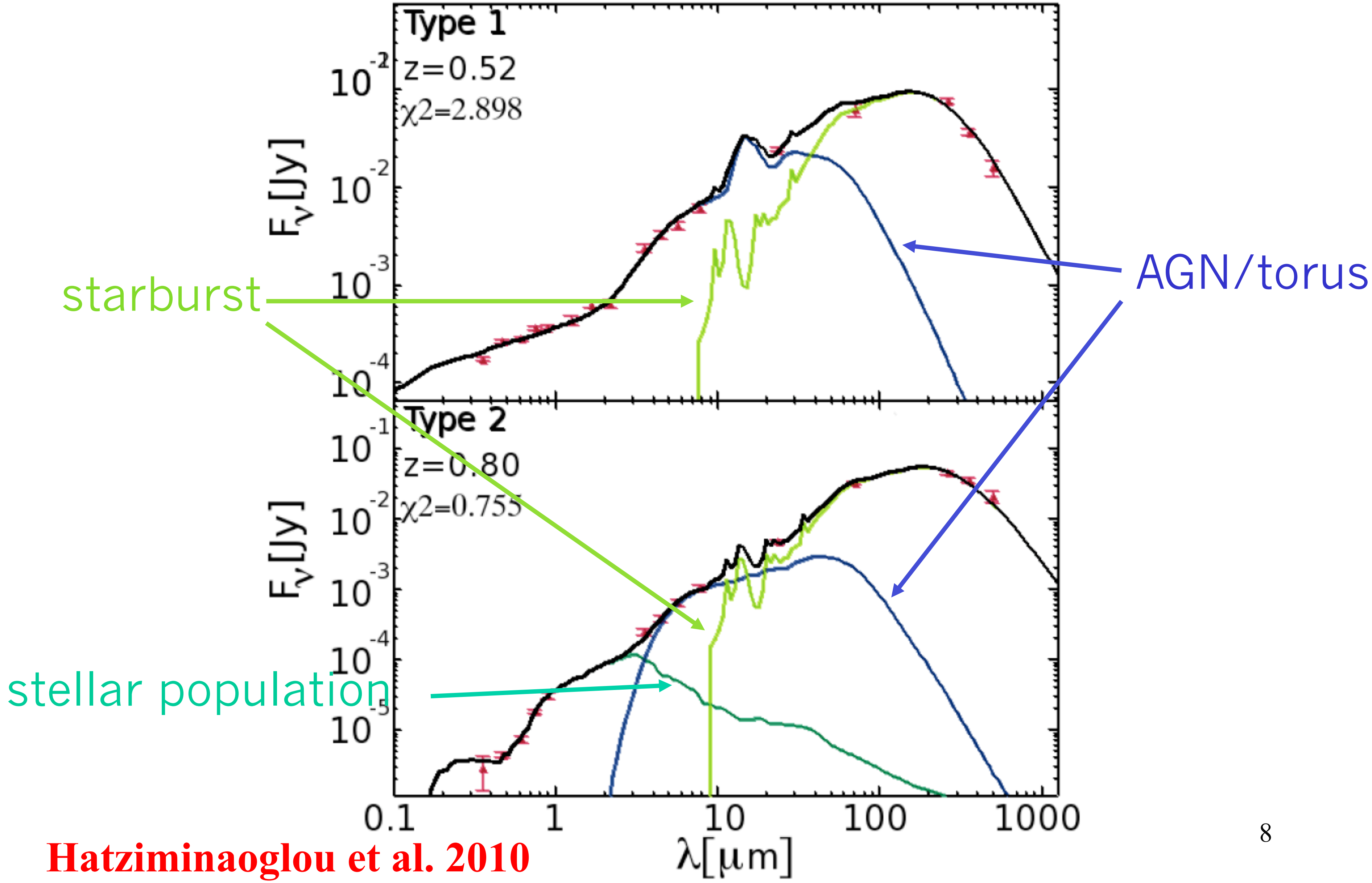
AGN torus emission



$T \approx 100 - 10^3$ K

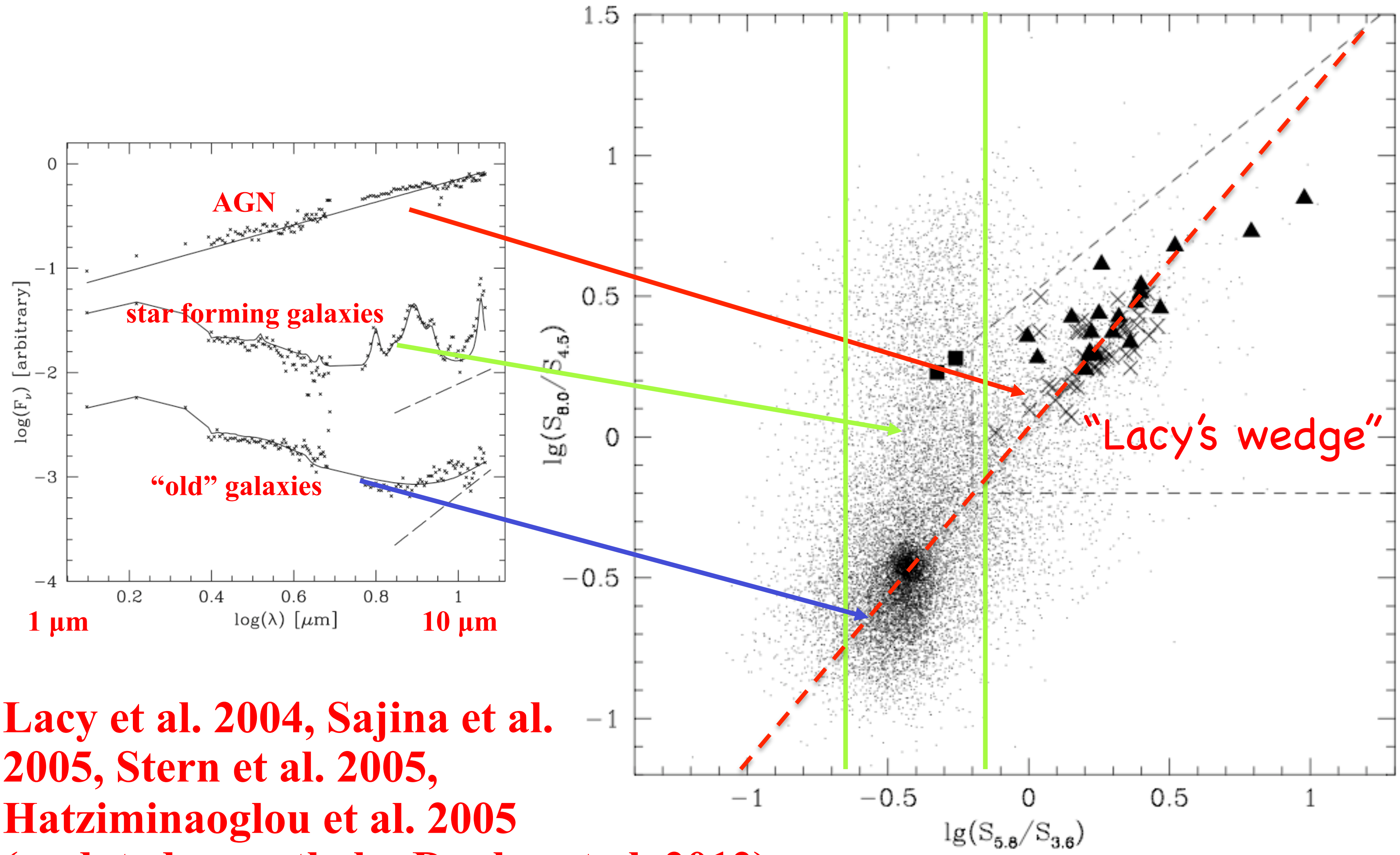
$\lambda_{peak} \approx 3 - 30 \mu m$

AGN infrared emission



Hatziminaoglou et al. 2010

The infrared band



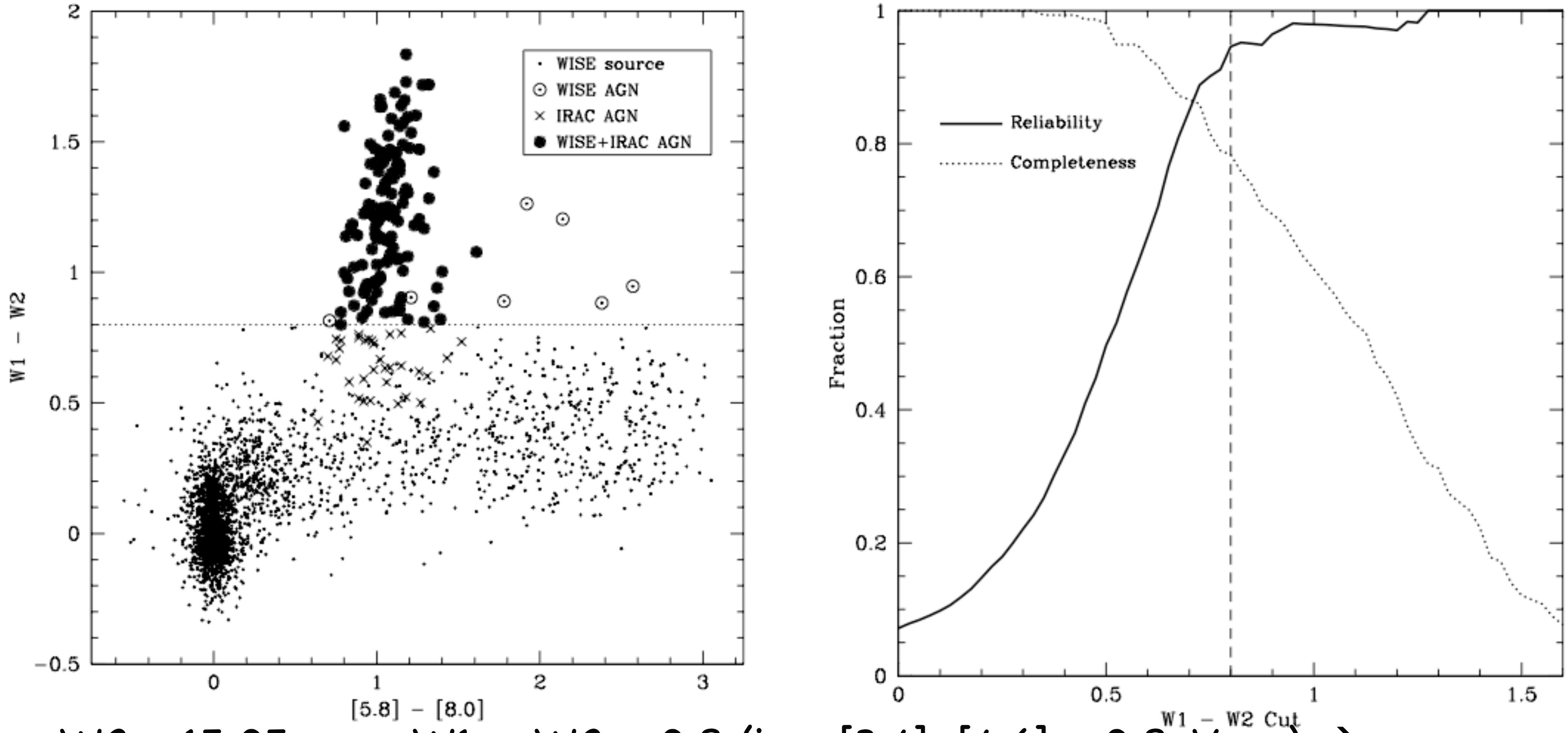
Lacy et al. 2004, Sajina et al. 2005, Stern et al. 2005, Hatziminaoglou et al. 2005 (updated recently by Donley et al. 2012)

The infrared band

- The good news:
  - ✓ sensitive to both obscured and un-obscured AGN → (almost) isotropic selection
  - ✓ sensitive to extremely obscured AGN (missed by optical and soft X-ray surveys)
- The bad news:
  - ✓ low reliability (selects also non-AGN)
  - ✓ low completeness (misses AGN above the flux limit)

The infrared band

Stern et al. 2012



W2 < 15.05 mag, W1 – W2 ≥ 0.8 (i.e., [3.4]–[4.6] ≥ 0.8, Vega) → 78% completeness, 95% reliability

BUT if W2 < 15.73 mag, W1 – W2 ≥ 0.8 → 70% completeness, 70% reliability (Assef et al. 2013)

The optical/UV band

- Unobscured radio-quiet AGN emit most of the energy in the UV band → optical/UV selection should pick up broad-line sources (quasars and Seyfert 1's)
- But stars are also strong optical/UV emitters!
- Many problems:
  - ✓ misses LOTS of obscured AGN (Type 2's)
  - ✓ misses even moderately obscured ones
  - ✓ misses many low-luminosity AGN (host galaxy light > AGN)
- Two good things:
  - ✓ crucial to study accretion disk physics
  - ✓ good to discover high redshift quasars (but together with near-IR data!)

A&A 510, A56 (2010)
DOI: 10.1051/0004-6361/200913229

Astronomy & Astrophysics

The [O III] emission line luminosity function of optically selected type-2 AGN from zCOSMOS⋆,⋆⋆

A. Bongiorno[1,2], M. Mignoli[3], G. Zamorani[3], F. Lamareille[4], G. Lanzuisi[5,6], T. Miyaji[7,8], M. Bolzonella[3], C. M. Carollo[9], T. Contini[4], J. P. Kneib[10], O. Le Fèvre[10], S. J. Lilly[9], V. Mainieri[11], A. Renzini[12], M. Scodeggio[13], S. Bardelli[3], M. Brusa[1], K. Caputi[9], F. Civano[5], G. Coppa[3,14], O. Cucciati[10], S. de la Torre[10,13,15], L. de Ravel[10], P. Franzetti[13], B. Garilli[13], C. Halliday[16], G. Hasinger[1,17], A. M. Koekemoer[18], A. Iovino[13], P. Kampczyk[9], C. Knobel[9], K. Kovač[9], J. -F. Le Borgne[4], V. Le Brun[10], C. Maier[9], A. Merloni[1,19], P. Nair[3], R. Pello[4], Y. Peng[9], E. Perez Montero[4,20], E. Ricciardelli[21], M. Salvato[17,19,22], J. Silverman[9], M. Tanaka[11], L. Tasca[10,13], L. Tresse[10], D. Vergani[3], E. Zucca[3], U. Abbas[10], D. Bottini[13], A. Cappi[3], P. Cassata[10,23], A. Cimatti[14], L. Guzzo[16], A. Leauthaud[10], D. Maccagni[13], C. Marinoni[24], H. J. McCracken[25], P. Memeo[13], B. Meneux[1], P. Oesch[9], C. Porciani[9], L. Pozzetti[3], and R. Scaramella[26]

(Affiliations can be found after the references)

Received 2 September 2009 / Accepted 17 November 2009

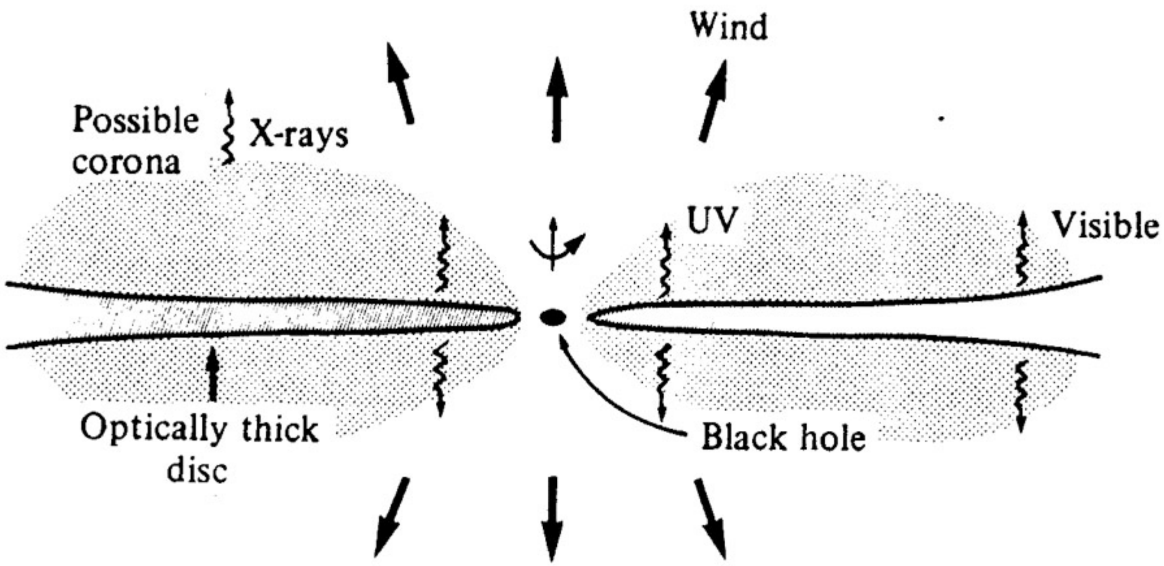
ABSTRACT

Aims. We present a catalog of 213 type-2 AGN selected from the zCOSMOS survey. The selected sample covers a wide redshift range ($0.15 < z < 0.92$) and is deeper than any other previous study, encompassing the luminosity range $10^{5.5}\ L_\odot < L_{[\rm OIII]} < 10^{9.1}\ L_\odot$. We explore the intrinsic properties of these AGN and the relation to their X-ray emission (derived from the XMM-COSMOS observations). We study their evolution by computing the [O III]λ5007 Å line luminosity function (LF) and we constrain the fraction of obscured AGN as a function of luminosity and redshift.

Methods. The sample was selected on the basis of the optical emission line ratios, after applying a cut to the signal-to-noise ratio (S/N) of the relevant lines. We used the standard diagnostic diagrams ([O III]/Hβ versus [N II]/Hα and [O III]/Hβ versus [S II]/Hα) to isolate AGN in the redshift range $0.15 < z < 0.45$ and the diagnostic diagram [O III]/Hβ versus [O II]/Hβ to extend the selection to higher redshift ($0.5 < z < 0.92$).

X-ray emission

UV photons + Inverse Compton from relativistic electrons ($T \approx 10^9$ K) → X-ray photons



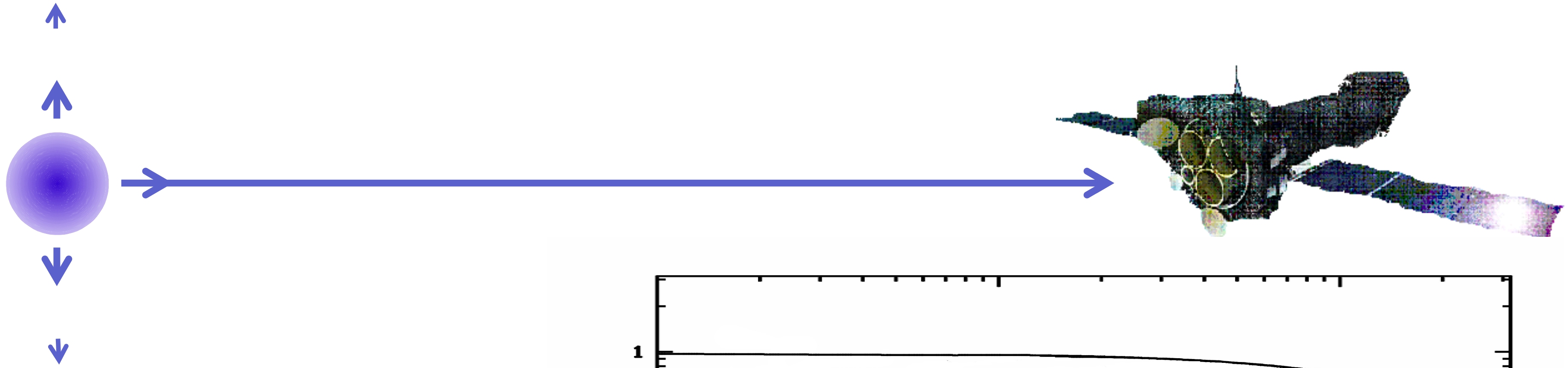
Wiita 1991

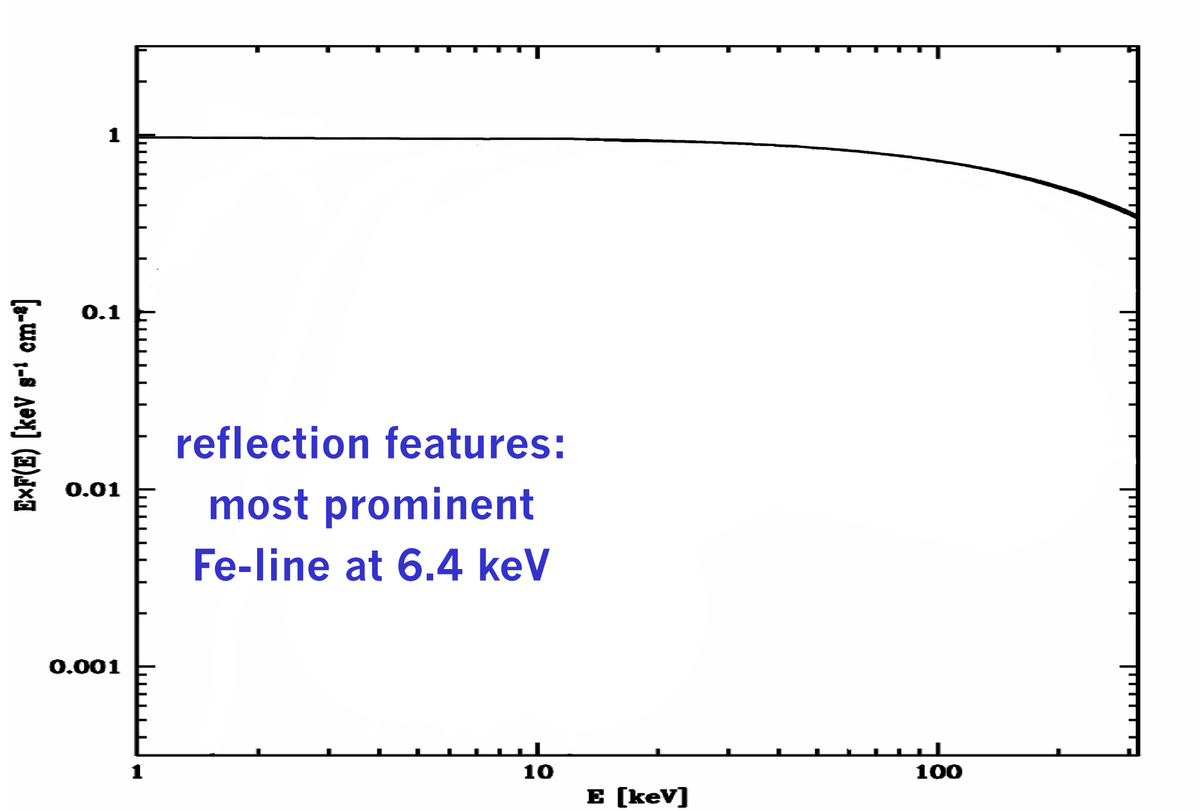
X-ray emission

- Universal in AGN
- Accounts for ≈ 1 – 10 % of the bolometric power
- Strongly variable → small emitting region
- Radio-loud AGN are somewhat stronger in X-rays than radio-quiet AGN (jet emission)
- Frequency/energy expressed in keV (1 keV = 2.418×10^{17} Hz)

Absorption in the X-ray band

X-ray unabsorbed AGN (type I AGN)



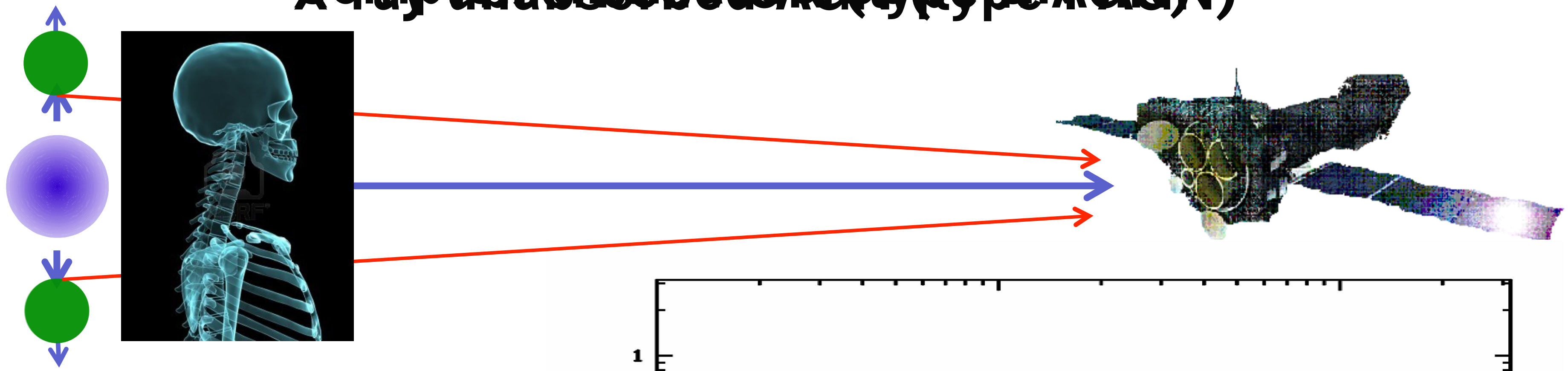


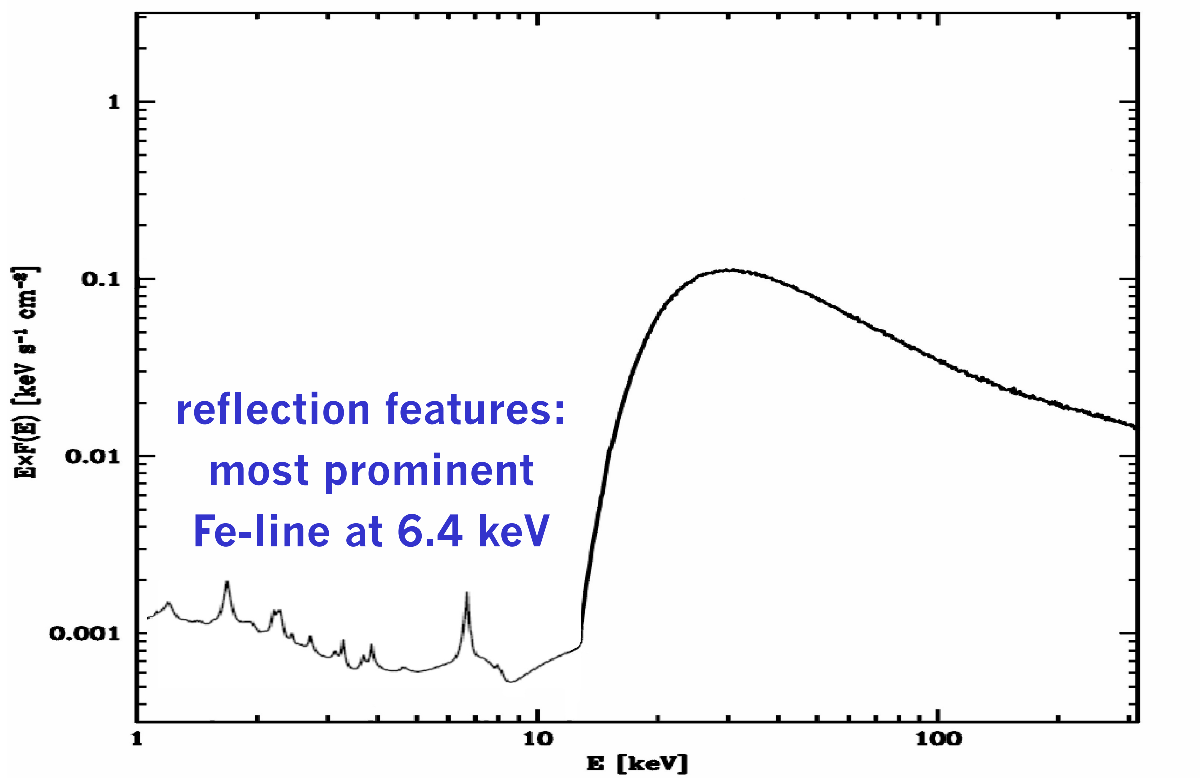
courtesy of Mirko Krumpe

Absorption in the X-ray band

Compton-thick AGN

X-ray unabsorbed AGN (type 1 AGN)





amount of absorbing material can be measured in AGN X-ray spectrum ⇨ classification

$A_V \succcurlyeq 500$

courtesy of Mirko Krumpe

The X-ray band

- The good news:
  - ✓ sensitive to (more) obscured AGN (especially in the hard X-rays)
  - ✓ good reliability (> 80% in the hard band)
  - ✓ identification done using a variety of X-ray related parameters (L_x, α_x, variability, f_x/f_{opt}, etc.) plus optical spectroscopy
- The (moderately) bad news:
  - ✓ need sensitive hard X-ray missions to detect extremely obscured AGN
- NuSTAR (launched June 2012; 3 – 79 keV) > 100x improvement with respect to previous missions (but still not comparable [sensitivity-wise] to *Chandra* and XMM: $f_{6-10\ keV}$ (1 Ms, 3σ) ≈ 2 x 10^{-15} c.g.s.) [Harrison et al. 2013]

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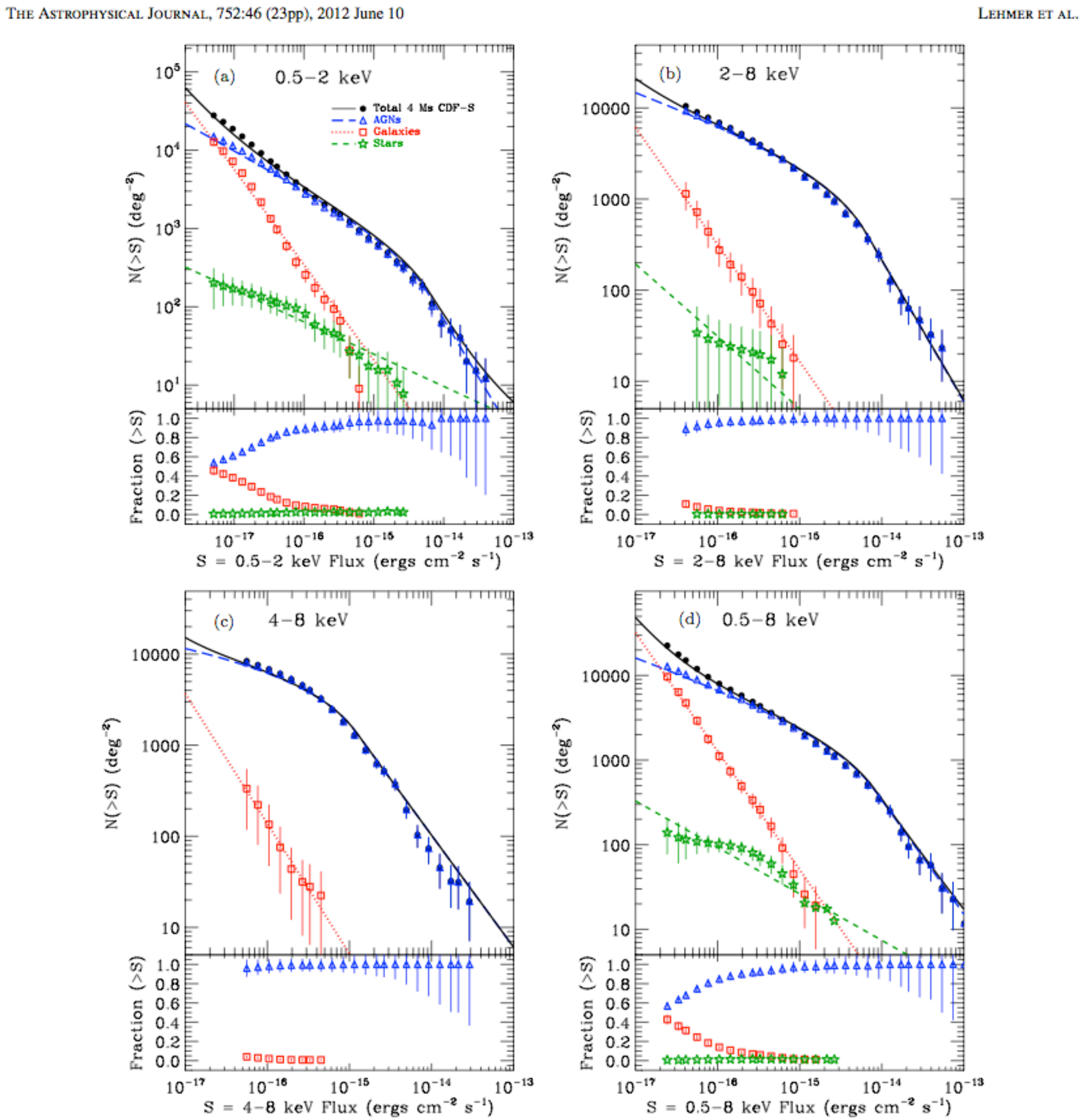
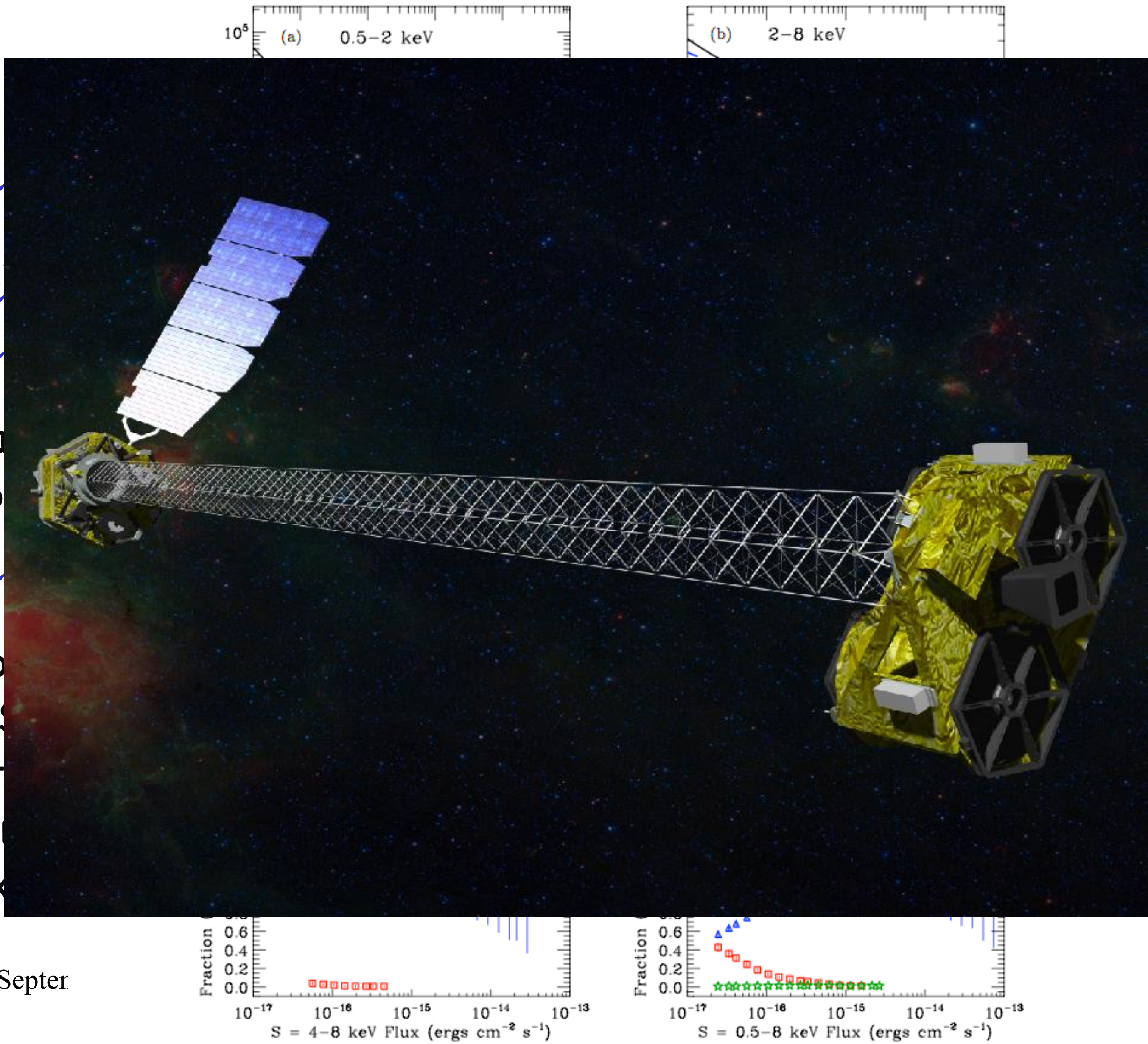
- NuSTA ... vement with r ... ble [sensit ... r) ≈ 2 x 10



THE ASTROPHYSICAL JOURNAL, 752:46 (23pp), 2012 June 10 LEHMER ET AL.



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The γ-ray band: 2nd Fermi Source Catalogue (Nolan et al. 2012)

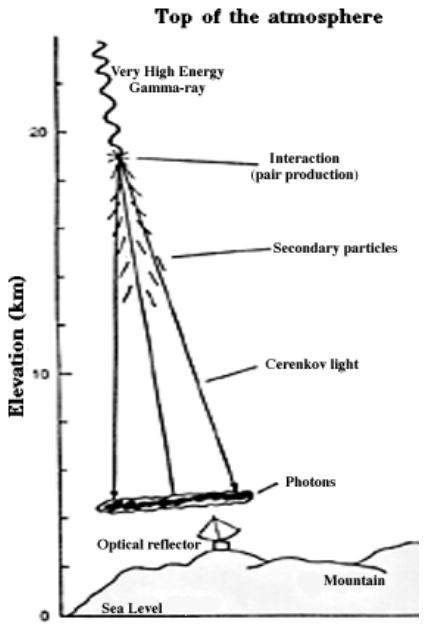
- 1873 sources detected all-sky above 100 MeV and up to 100 GeV (2.4×10^{22} – $2.4\ 10^{25}$ Hz)

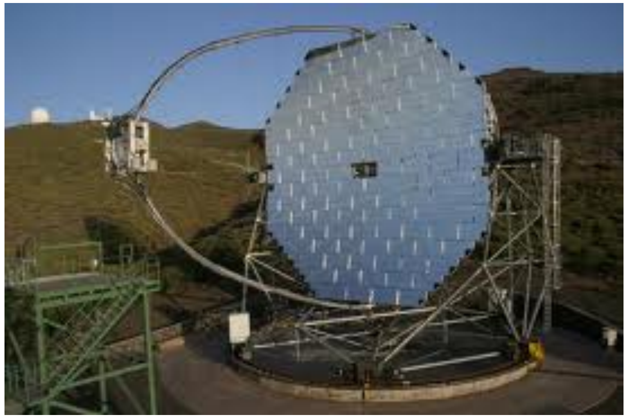
Galactic sources (pulsars, SNR, etc.)	**195**	**10.4%**
Blazars	**806**	**43.0%**
Other/uncertain AGN (mostly blazar candidates)	**286**	**15.3%**
Normal and star-forming galaxies	**10**	**0.5%**
Unclassified	**576**	**30.8%**

- AGN (blazars) make up ≈ 60% (< 90%) of the MeV – GeV γ-ray sky
- γ-ray AGN sky ≈ radio-bright AGN sky!

The γ-ray band: TeV sources

• Approximately 150 sources detected at TeV energies (> 2.4 10^{26} Hz) by Cherenkov telescopes [from the ground]





• AGN (blazars) make up > 1/3 of the TeV γ-ray sky

The γ-ray band: TeV sources

- Approximately 150 sources detected at TeV energies (> 2.4 10^{26} Hz) by Cherenkov telescopes [from the ground]

Source: TeVCat

Galactic sources (pulsars, etc.)	60	42%
Blazars	52	36%
Other AGN	3	2%
Star-forming galaxies	2	1%
Unclassified	27	19%

- AGN (blazars) make up > 1/3 of the TeV γ-ray sky

The γ-ray band

✓selection done by identifying the radio/optical counterparts via, e.g., correlated variability and positional coincidence (*Fermi* median 95% radius ~ 6′)

✓parameter space: mostly blazars (preferred angle, small fraction, dominated by non-thermal emission [→ jets], elliptical hosts)

✓biases: radio-loud AGN only; however, *very* unlikely that radio-quiet AGN emit in the γ-ray band

✓probes extremely high-energy processes

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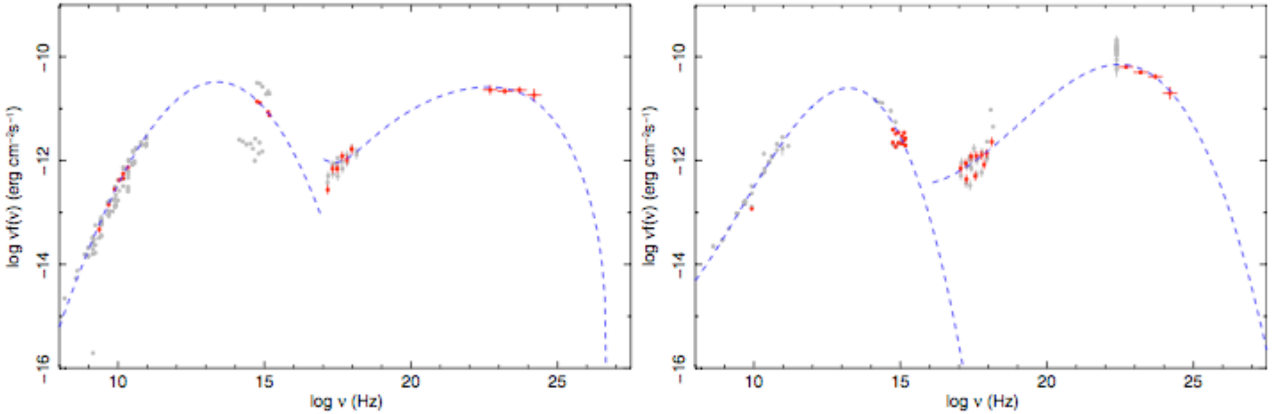


Figure 2. SED of 0FGL J0137.1+4751 = S40133+47 (left) and of 0FGL J0210.8−5100 = PKS0208-512 (right).
(A color version of this figure is available in the online journal.)

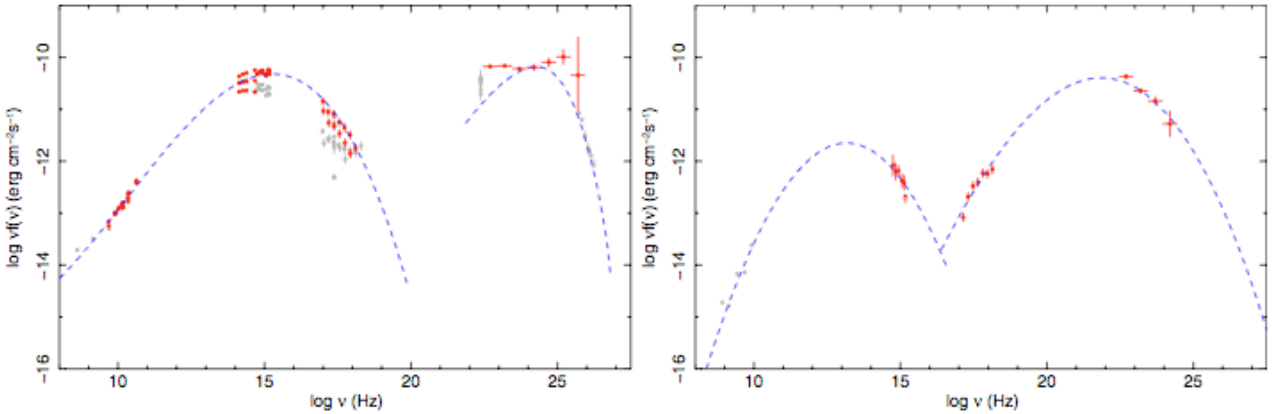


Figure 3. SED of 0FGL J0222.6+4302 = 3C 66A (left) and of 0FGL J0229.5−3640 = PKS0227-369 (right).
(A color version of this figure is available in the online journal.)

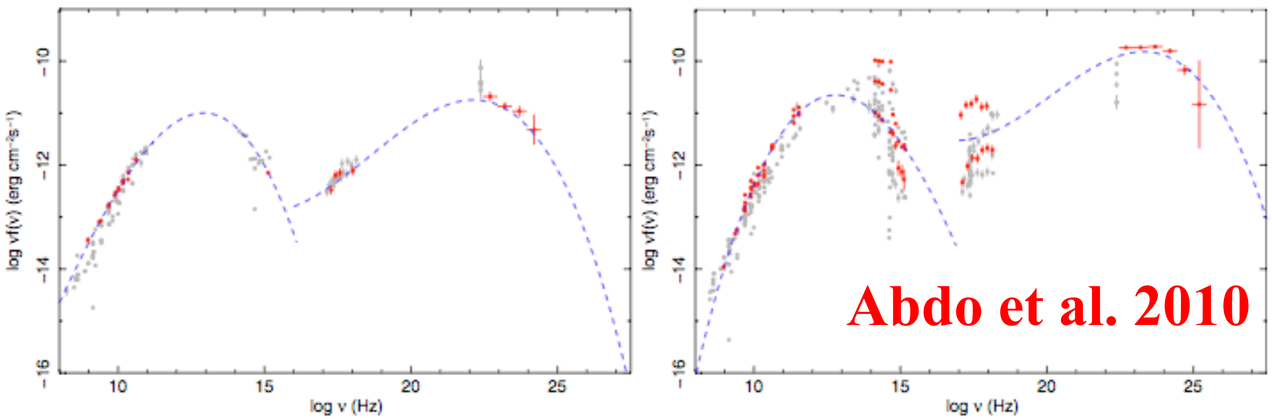
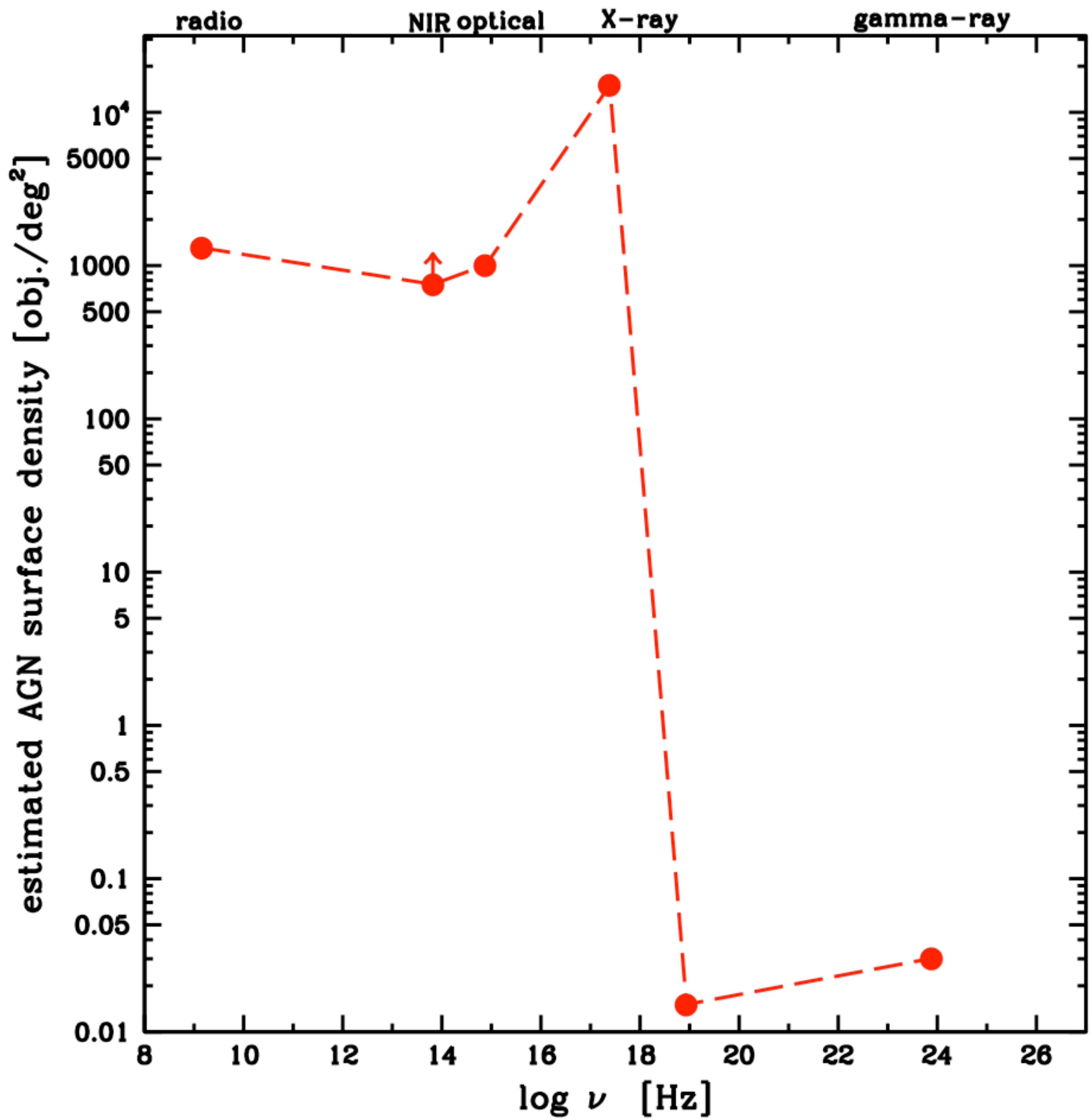


Figure 4. SED of 0FGL J0238.4+2855 = 4C28.07 (left) and of 0FGL J0238.6+1636 = PKS0235+164 (right).

AGN surface densities

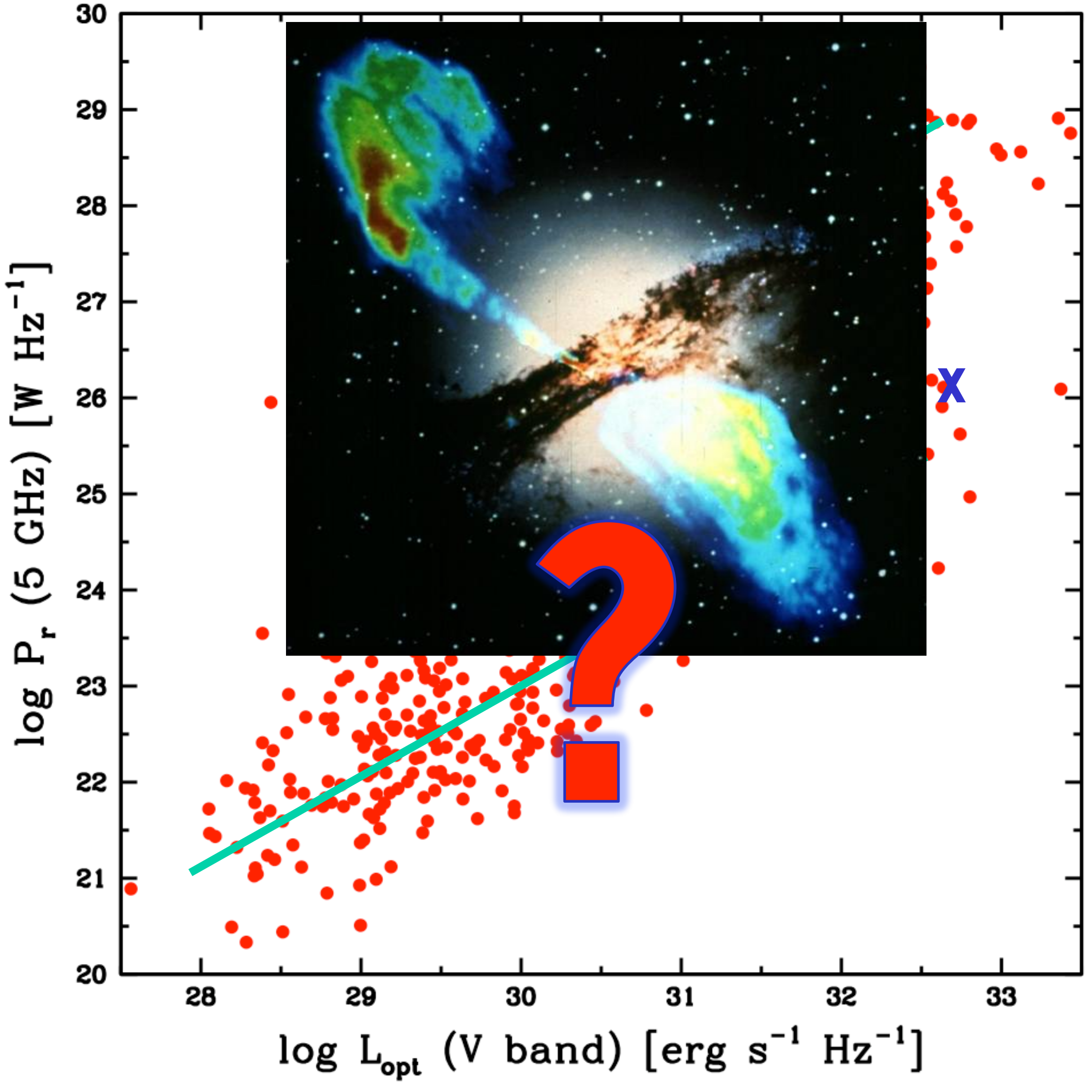


How many AGN are there?

My estimate (PP 2011): ≈ 2 x 10^4/deg^2 → 800 million!

(≈ 1 million known ...)

The puzzle of radio quiet quasars

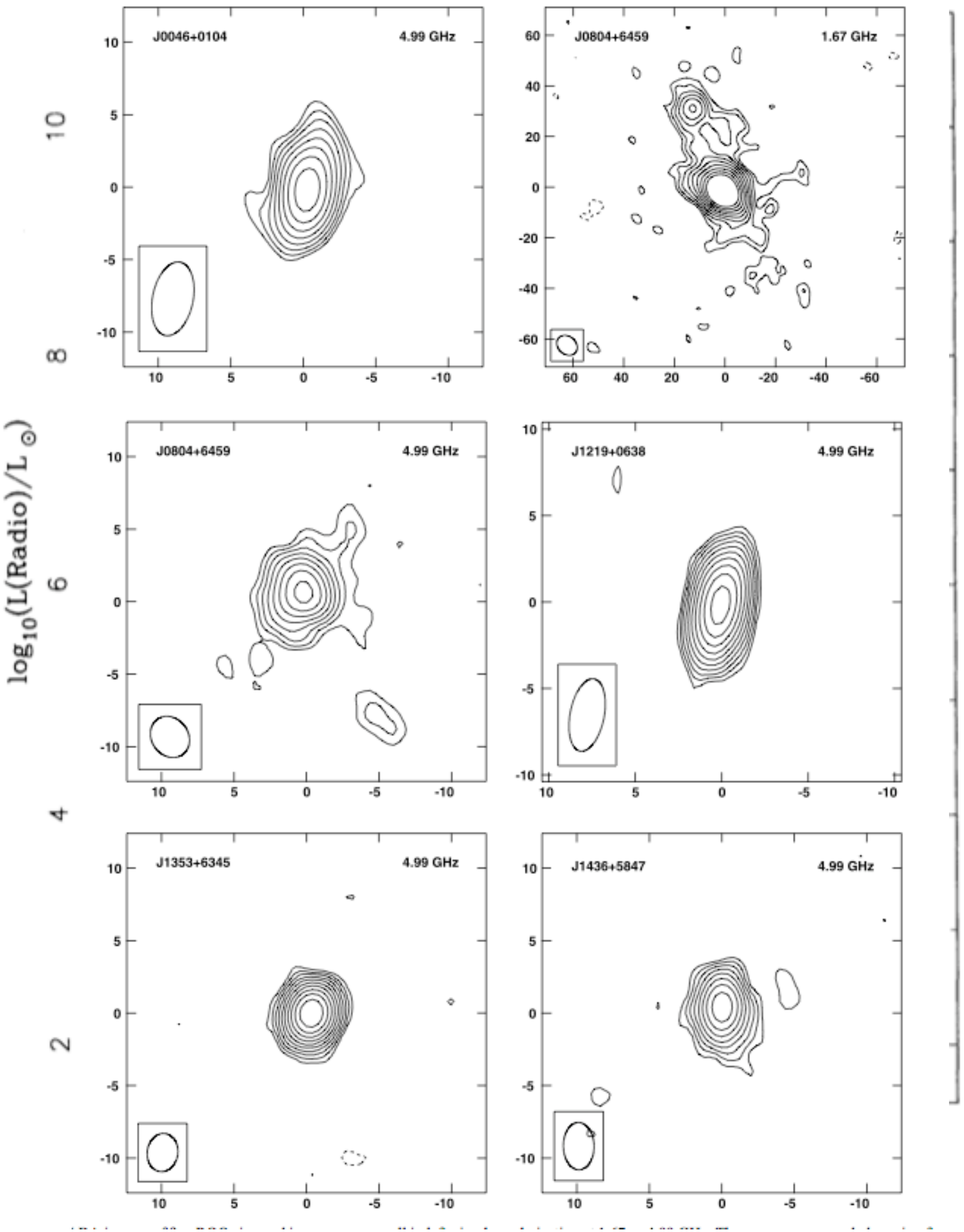


Radio emission in radio-quiet AGN

- Matter of debate since the discovery of quasars. For example:
  - ✓ scaled down version of radio-loud AGN (Ulvestad et al. 2005)
  - ✓ star formation related (far-IR/radio correlation: Sopp & Alexander 1991)
  - ✓ slowly rotating black holes (Wilson & Colbert 1995)
  - ✓ magnetically heated coronae (Laor & Behar 2008)
  - ✓ and more …

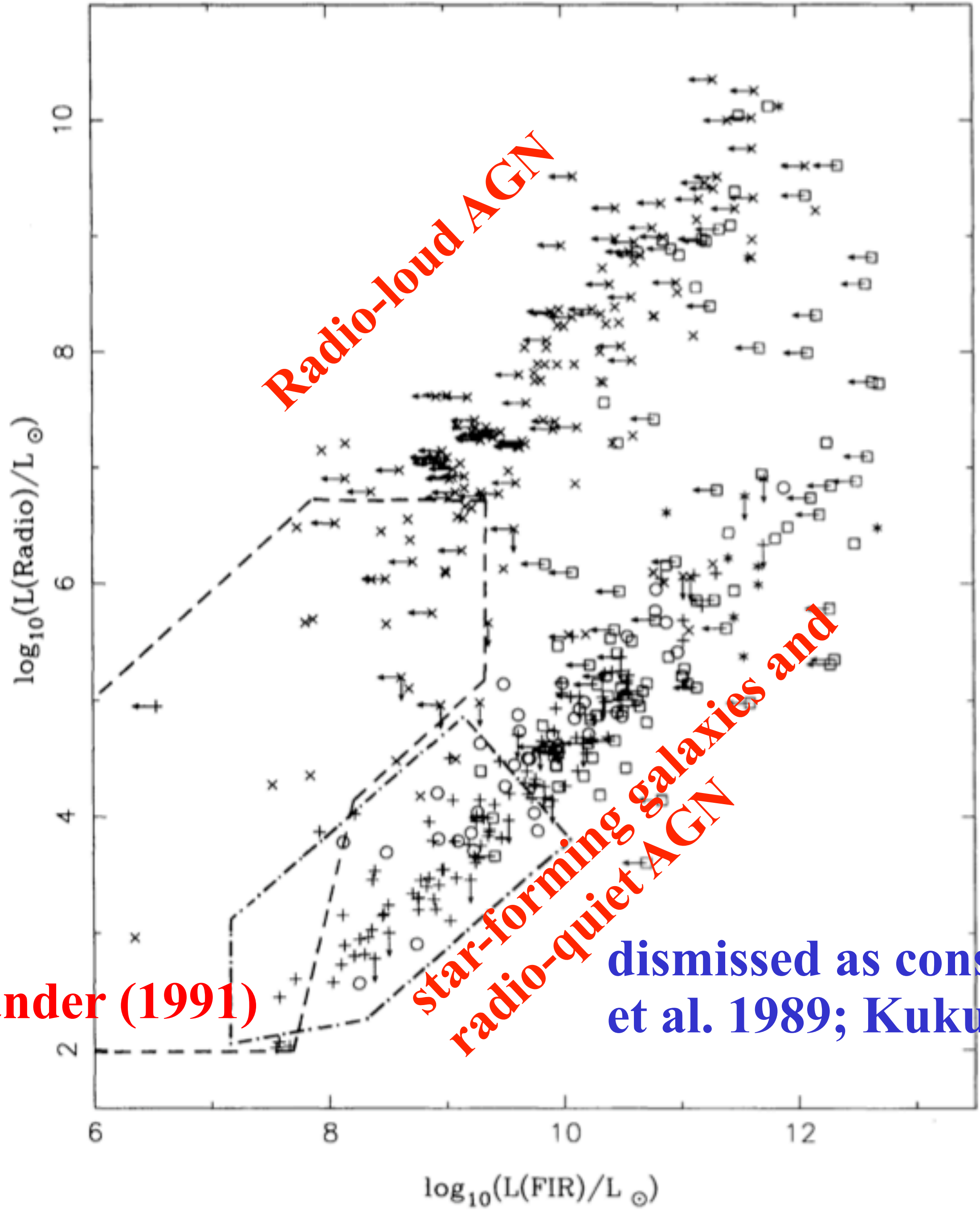
Radic ... et AGN

- Matter ... quasars.
  For ex...
  ✓ scal ... N (Ulvestad
    et al
  ✓ star ... relation:
    Sopp
  ✓ slow ... olbert 1995)
  ✓ mag ... ehar 2008)
  ✓ and



Radic ... et AGN

- Matter ... quasars. For ex...
  - scal ... N (Ulvestad et a...
  - star ... relation: Sopp...
  - slow ... olbert 1995)
  - mag ... ehar 2008)
  - and

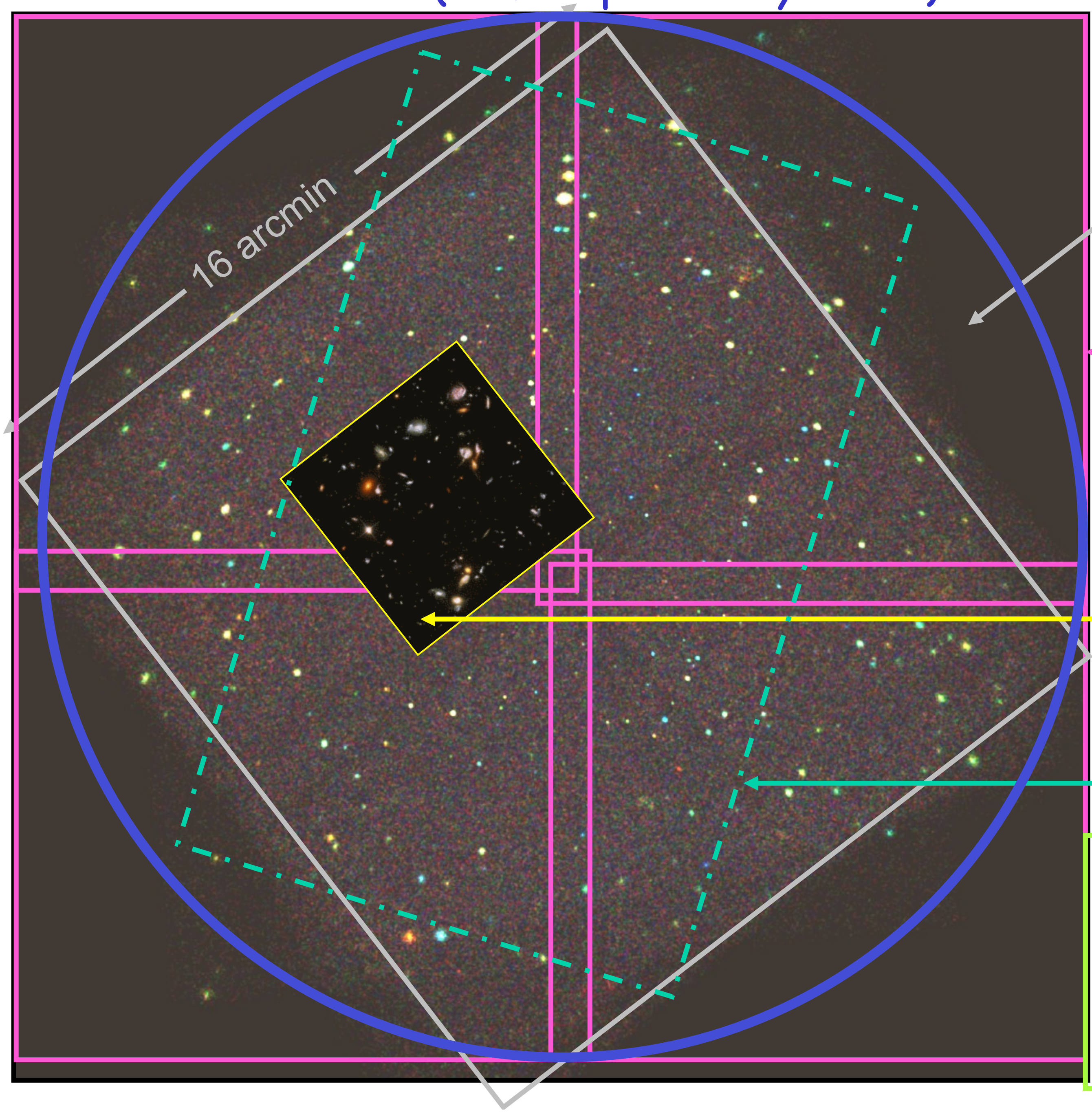


Sopp & Alexander (1991)

dismissed as conspiracy: Sanders et al. 1989; Kukula et al 1998

The Chandra Deep Field South
VLA data (30% sensitivity level)

now 4 Ms (1.5 month)



Chandra Data
942 ks exposure
366 X-ray sources
5 x 10^{-17} ergs/sec

Extended CDFS
250 ks per field

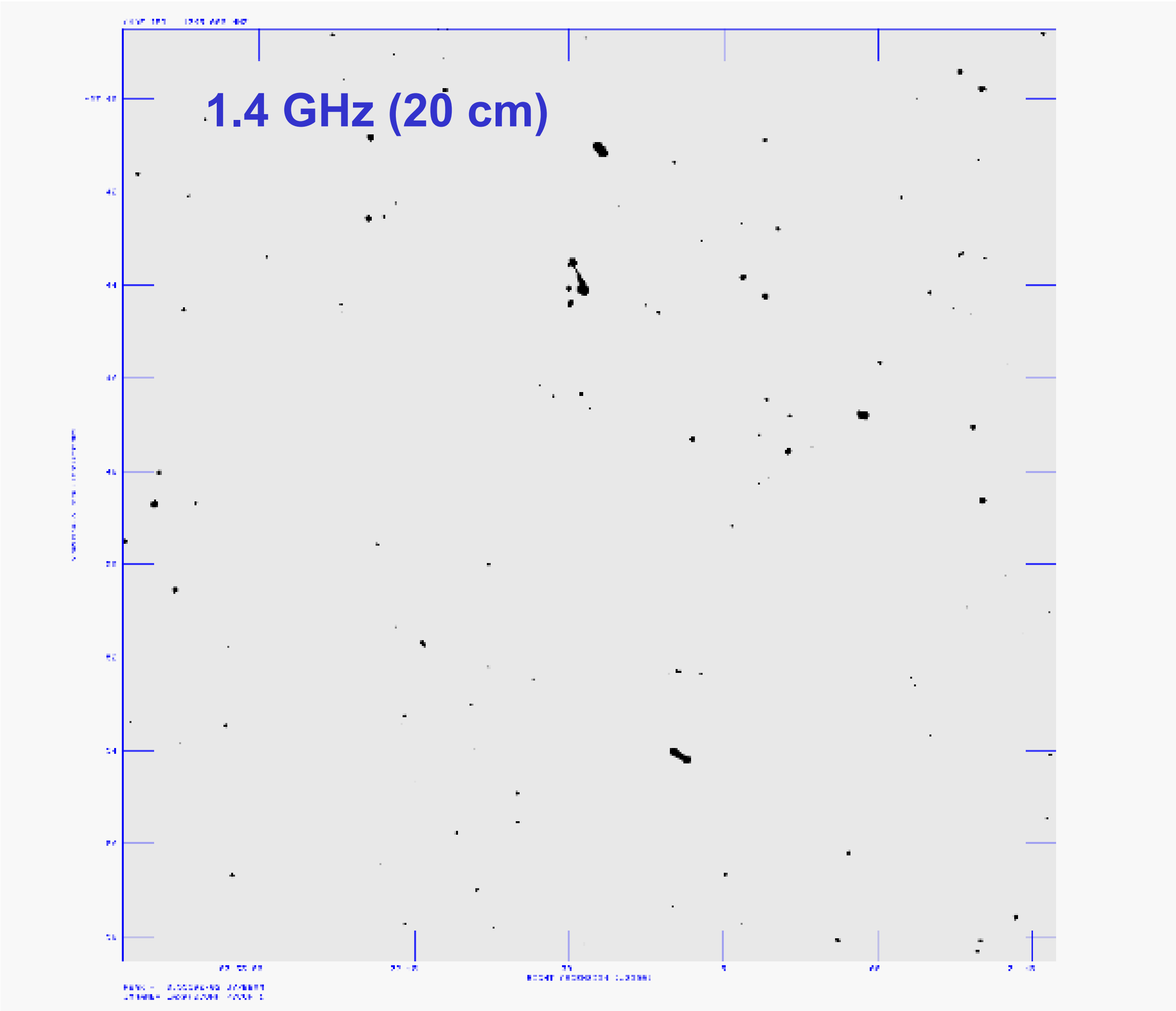
Hubble UDF
976 ks exposure
B, V, I, z
10,000 galaxies
mag 29

GOODS ACS
B, V, i, z
I < 28

GEMS/ACS, VLT/FORS + ISAAC, Subaru, NTT/SOFI, ESO2.2m/WFI, Spitzer/IRAC +MIPS

Very Large Array (VLA) Observations

Kellermann et al. (2008)



20 & 6 cm (50 & 32 h)

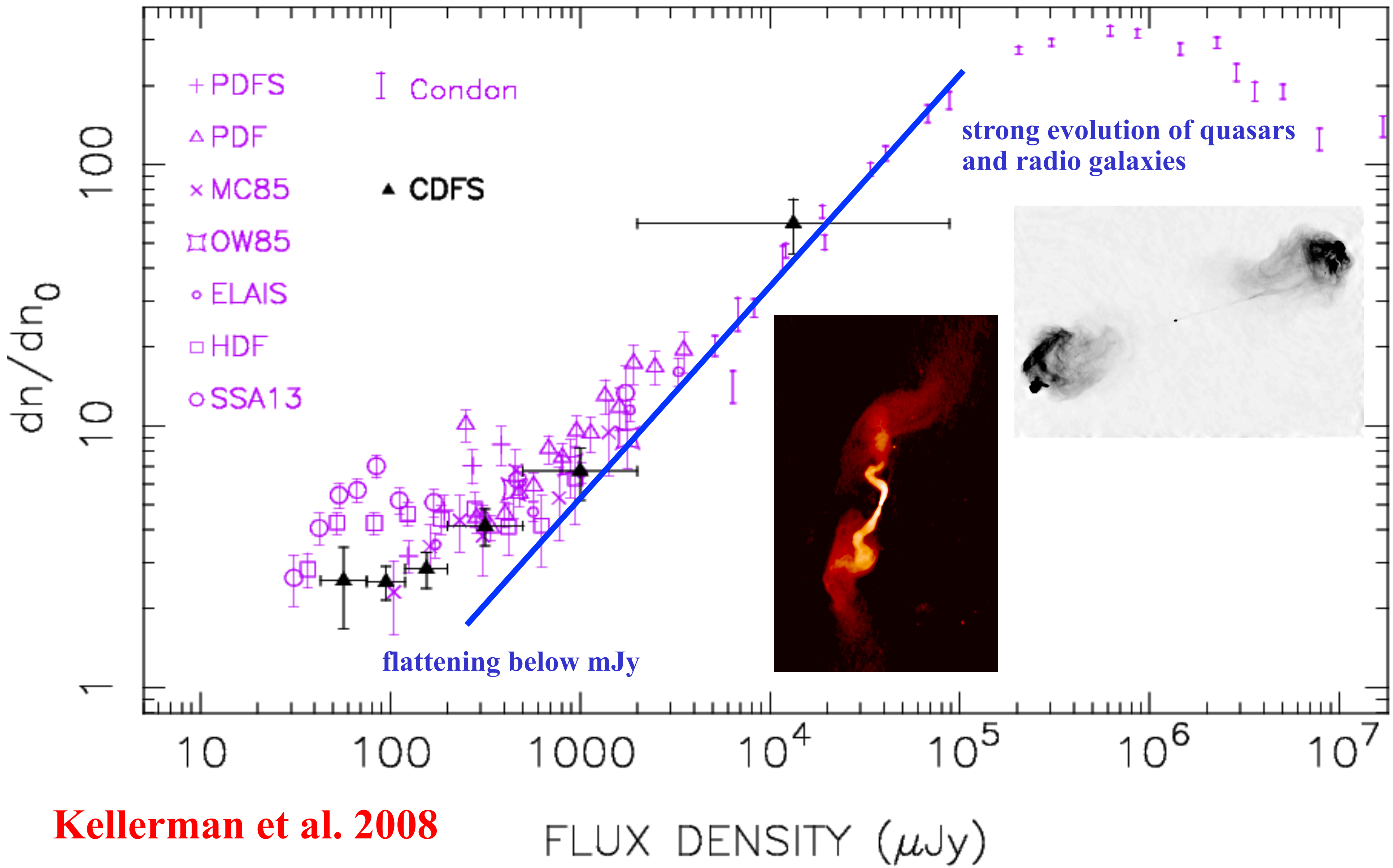
θ = 3.5”, 0.2 sq. deg.

σ_{20} = 8 μJy

266 radio sources

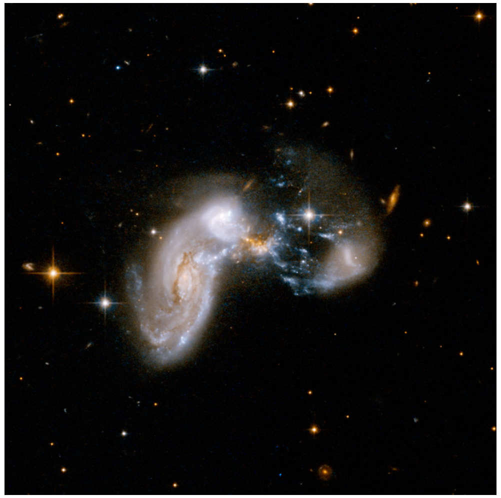
Complete sample:
198 sources reaching
S_{20} = 43 μJy (5σ)

1.4 GHz number counts



Kellerman et al. 2008

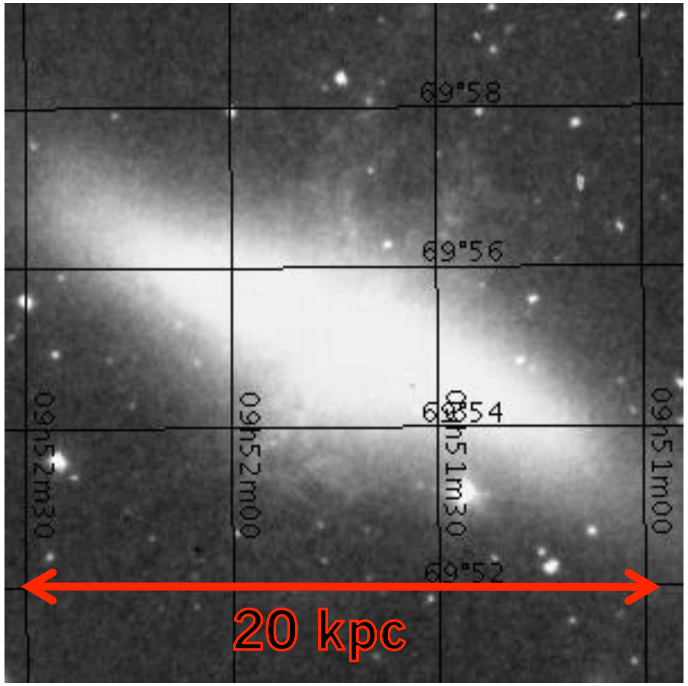
Star forming galaxies

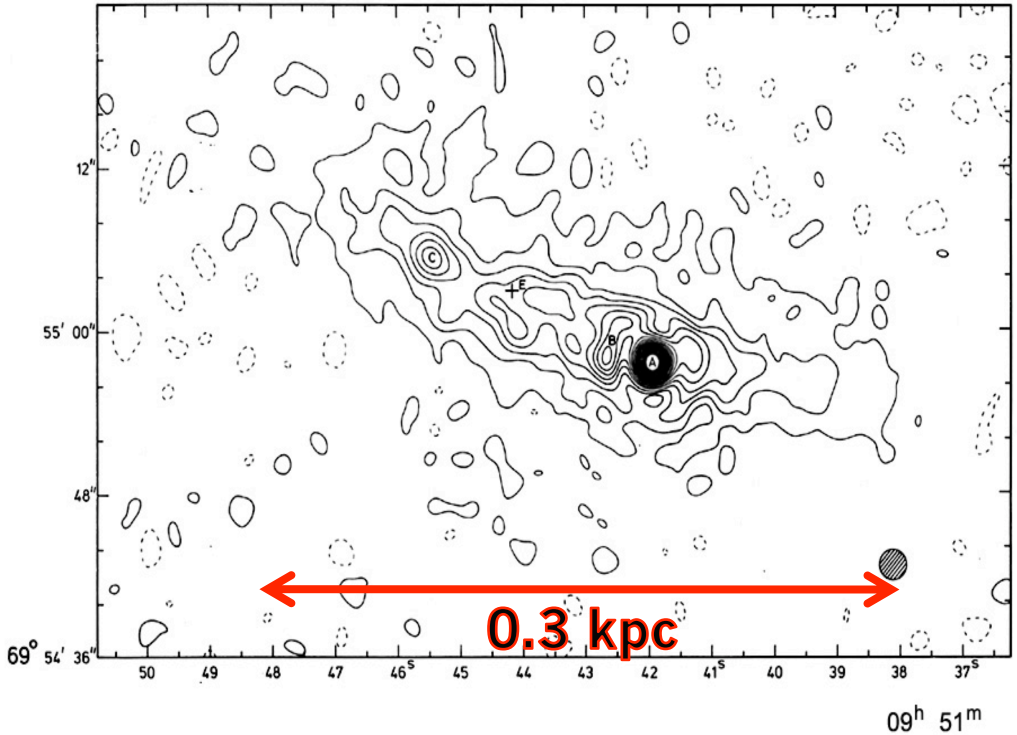


NON active galaxies →
no (or dormant) black hole
(e.g. the Milky Way)

Star forming galaxies

M 82





Optical

Radio
mostly synchrotron emission
from SN remnants; $P_r < 10^{24}$ W/Hz

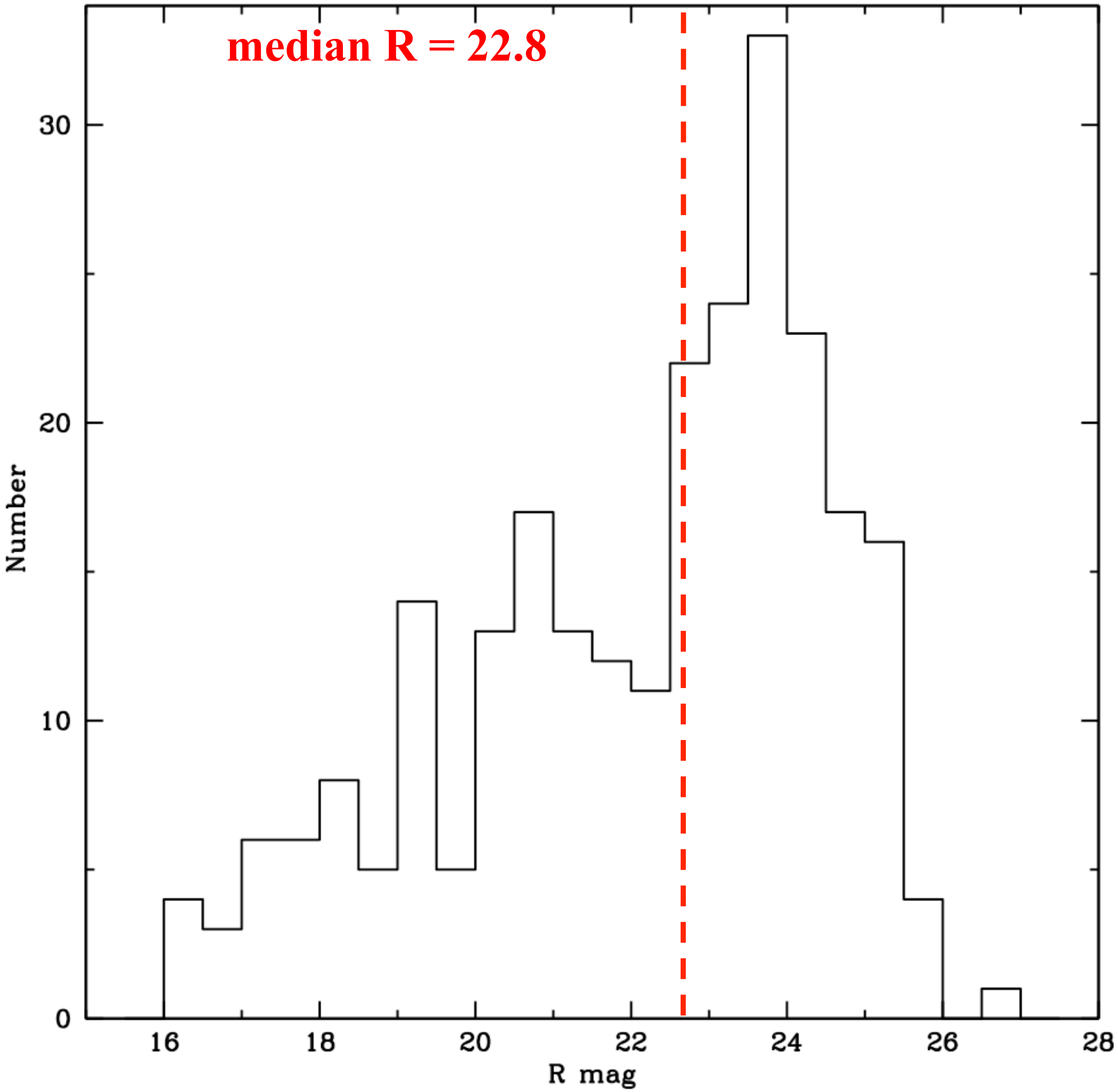
Source identification in modern surveys

- First astronomical surveys were relatively shallow; e.g.:
  - ✓ Third Cambridge Catalogue of Radio sources (3CR, 60's – 70's): radio band (178 MHz), $f_r \gtrsim 10$ Jy, ~ 300 sources, typical $V_{mag} \approx 18 - 19$
  - ✓ *Einstein* Medium Sensitivity Survey (EMSS, 90's): X-ray band (0.3 – 3.5 keV), $f_x \gtrsim 5 \times 10^{-13}$ erg/cm^2/s, 835 sources, typical $V_{mag} \approx 16 - 17$
- Modern surveys reach much fainter fluxes (VLA-CDFS ≈ 50,000 deeper & CDFS ≈ 10,000) and therefore much fainter magnitudes (and are also *much* bigger)

Source identification in modern surveys

- Implications of faint counterparts:
  - ✓ Hard to get spectra (8/10m telescopes needed)
  - ✓ Hard to get classification
  - ✓ **Optical spectra can sometimes give only limited information** (especially for strongly absorbed sources)
- Proper source classification requires multi-wavelength data!

Classifying faint radio sources



VLA-CDFS: main ancillary data*

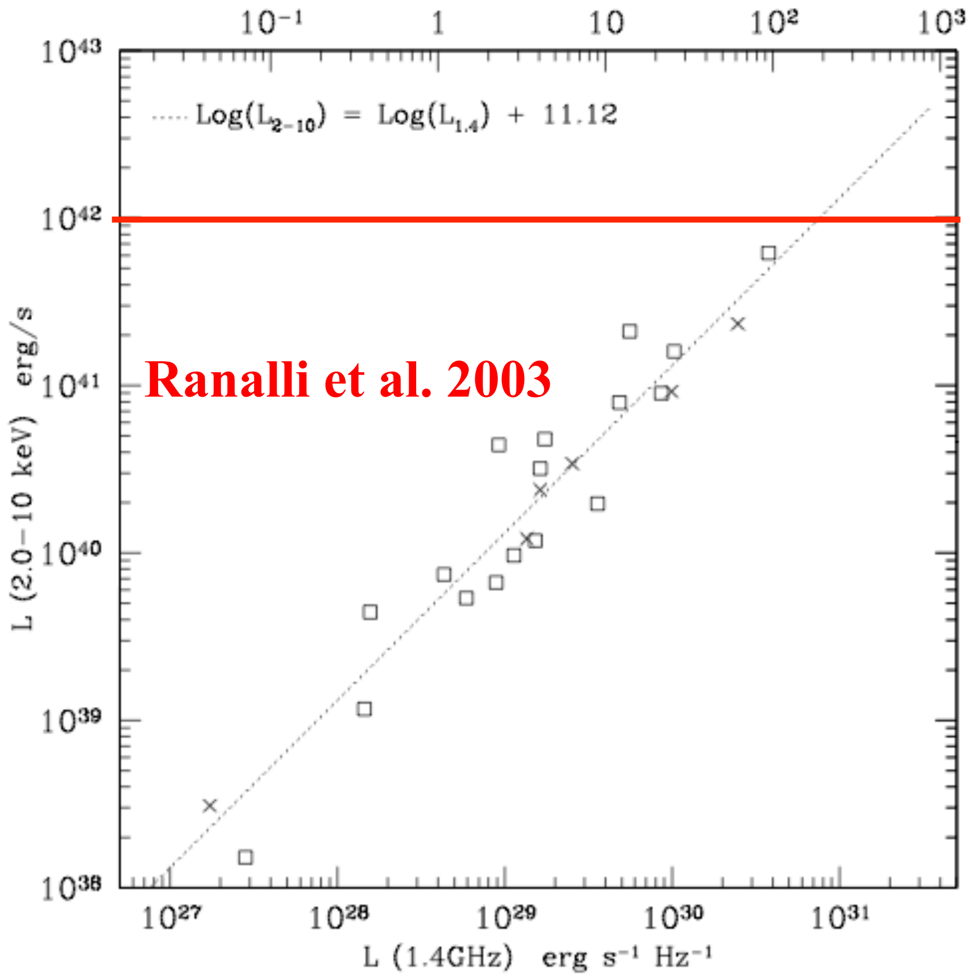
1. Reliable optical/near-IR IDs for 94% of the radio sources
2. Optical morphological classification for 68% of the sample
3. Redshift information for 92% of the objects (74% spectroscopic); <z> = 1.1 [0.04 – 4.5]
4. IRAC (3.6 – 8 μm) detections for 96% of the radio sources
5. MIPS (70 μm) detections for 50% of the objects, upper limits for all the others
6. X-ray detections for 38% of the objects, upper limits for all the others

*complete sample

Use everything we have and we know about AGN to identify them!

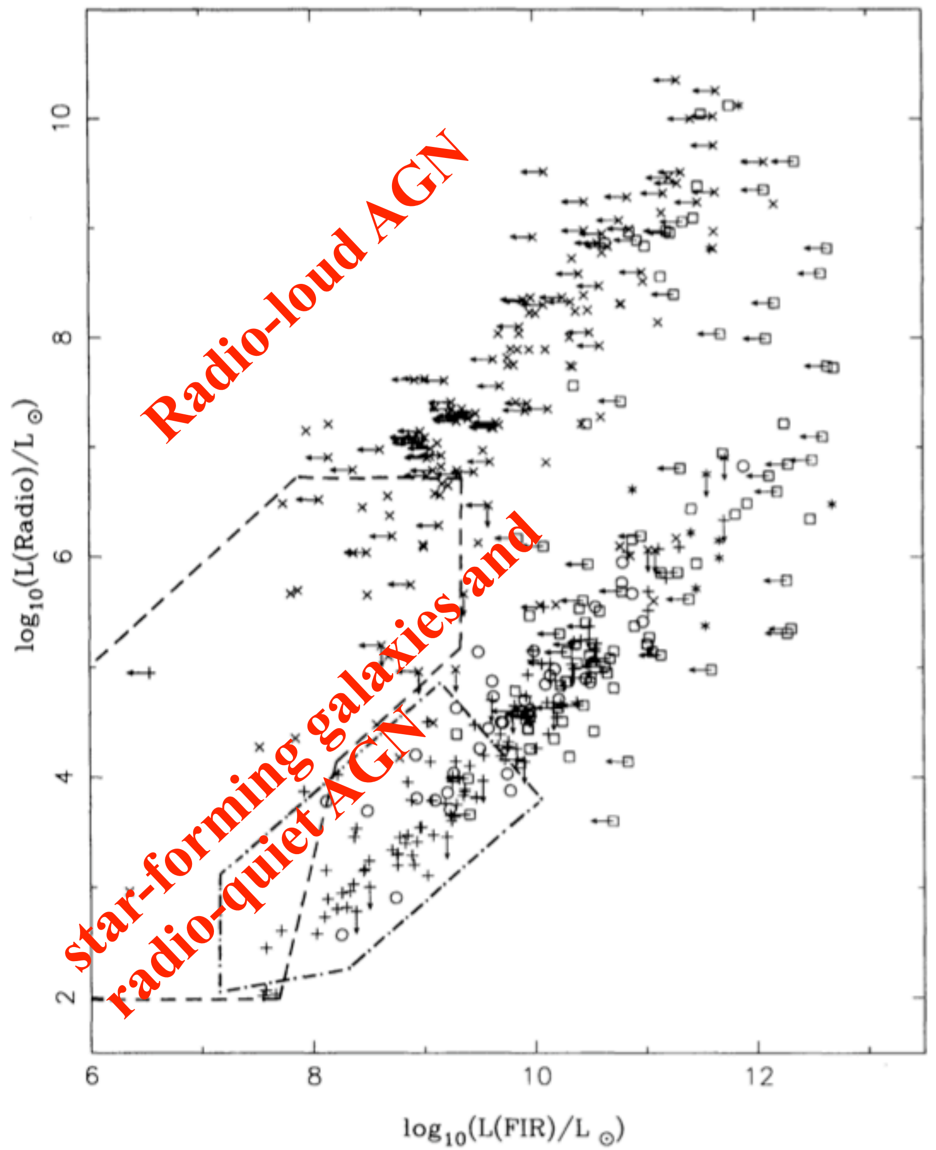
Selecting star-forming galaxies (SFGs)

SFGs have relatively low X-ray powers (AGN are strong X-ray emitters): $L_x < 10^{42}$ erg/s



Selecting star-forming galaxies

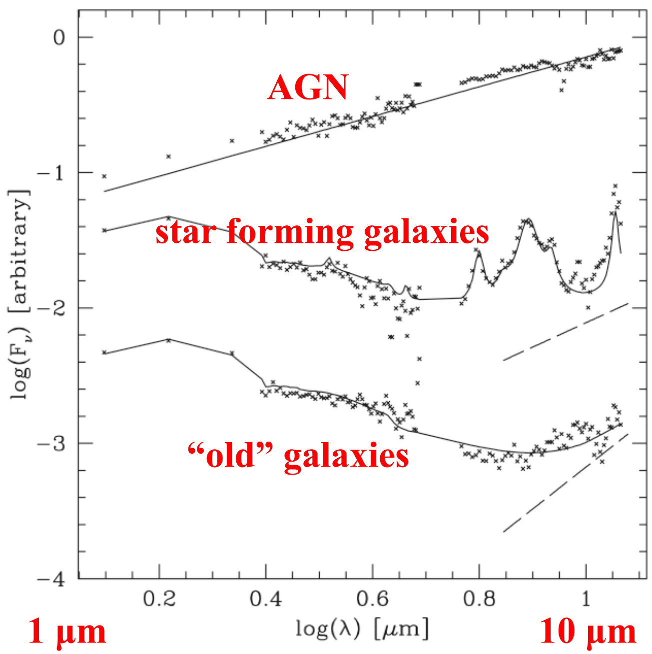
SFGs follow the radio – far IR correlation

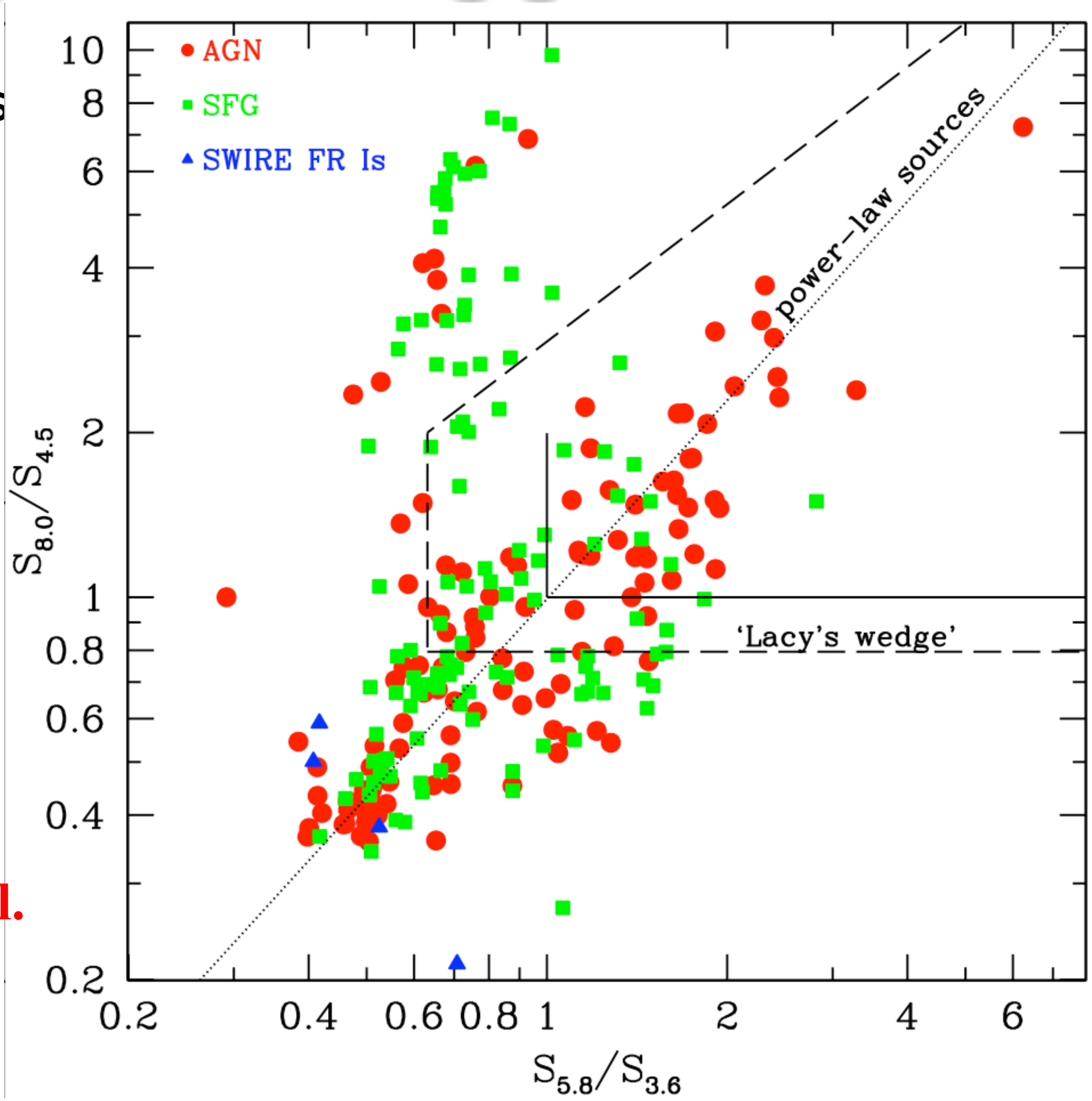


Sopp & Alexander (1991)

Selecting star-forming galaxies

SFGs have (somewhat) dis



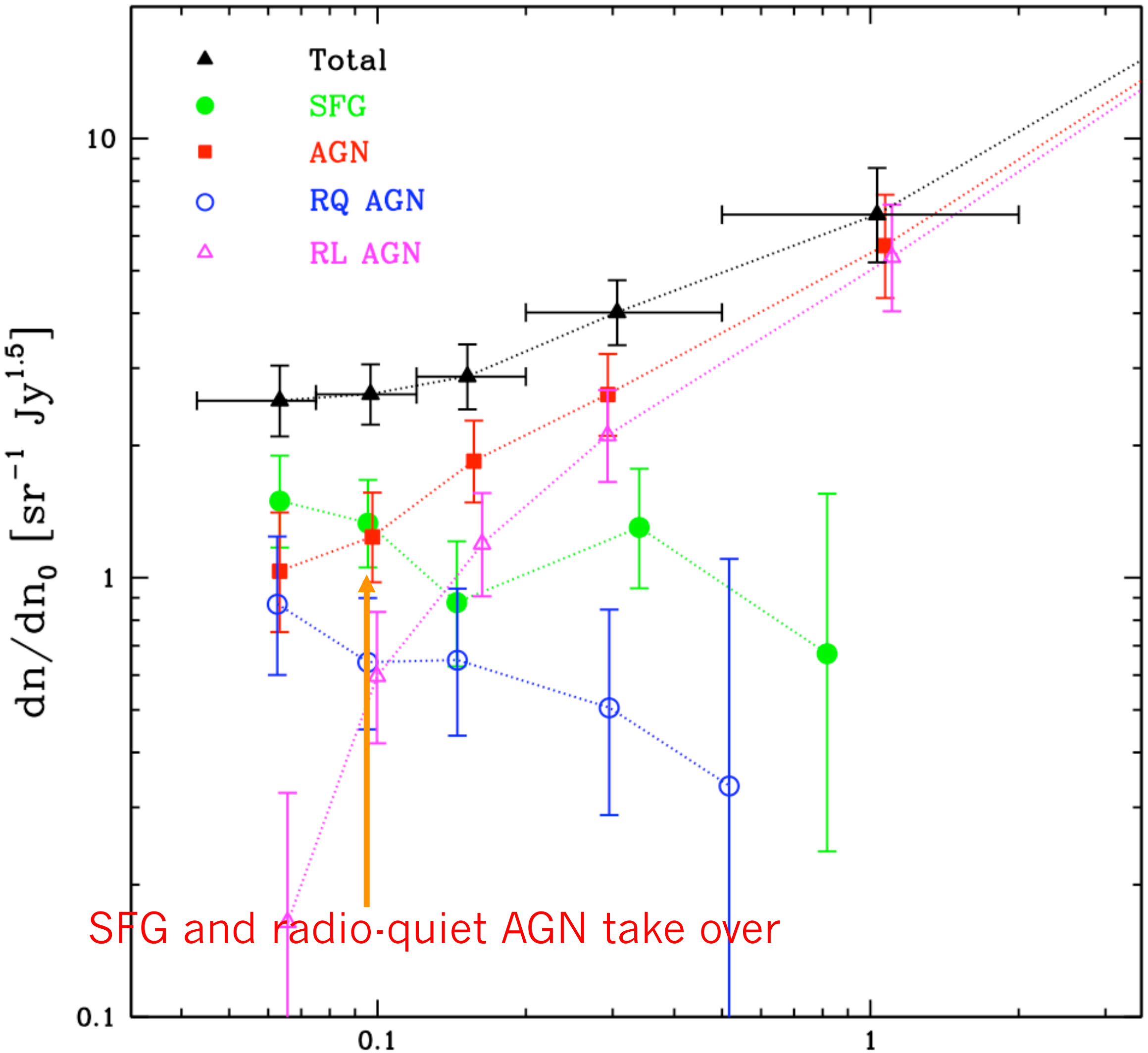


Lacy et al. 2004, Sajina et al. 2005, Stern et al. 2005, Hatziminaoglou et al. 2005

Selecting radio-quiet AGN

1. Have low radio-to-optical luminosity ratios: $R = \log(P_r/L_{opt}) < 1.4$ (Kellermann et al. 1989)
2. Follow the FIR – radio correlation: $q \geq 1.7$ (vital for radio galaxies)

Sub-mJy populations



Sub-mJy sources:

≈1/2 SFG

≈1/2 AGN

≈1/2 radio-loud (mostly low-power radio galaxies)

≈1/2 radio-quiet

Below 0.1 mJy the radio sky is dominated by star-formation-related processes!

Going beyond number counts: evolution of sub-mJy sources

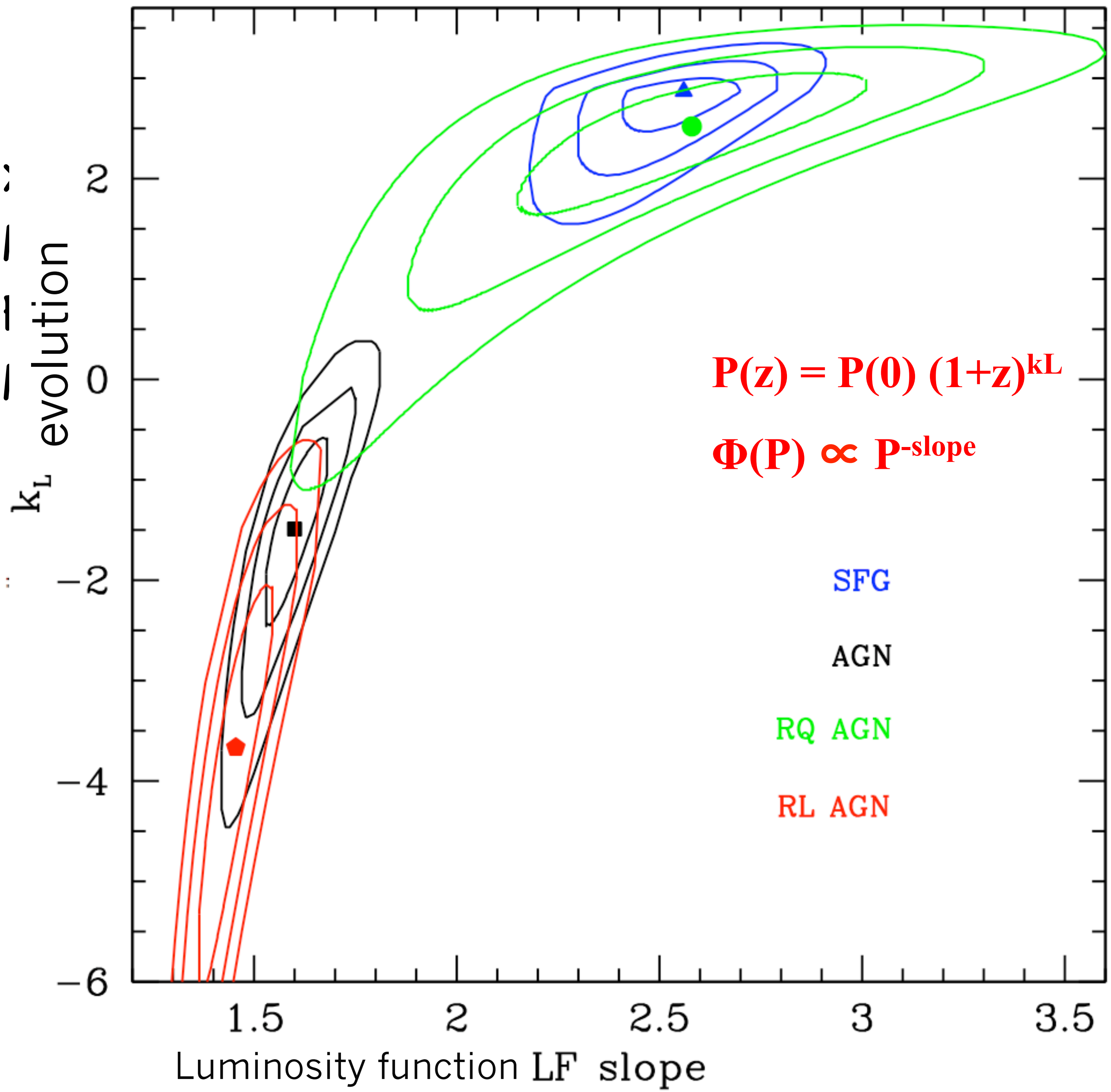
Sample	<z>	$<V_e/V_a>$	$P_{evolution}$	k_L	k_D
Star-forming galaxies	0.90	0.655±0.034	> 99.9%	2.5±0.3	
All AGN	1.44	0.479±0.026	65.6%	…	
Radio-quiet AGN	1.73	0.727±0.048	> 99.9%	2.5±0.3	

Pure luminosity evolution $P(z) = (1+z)^{k_L}$

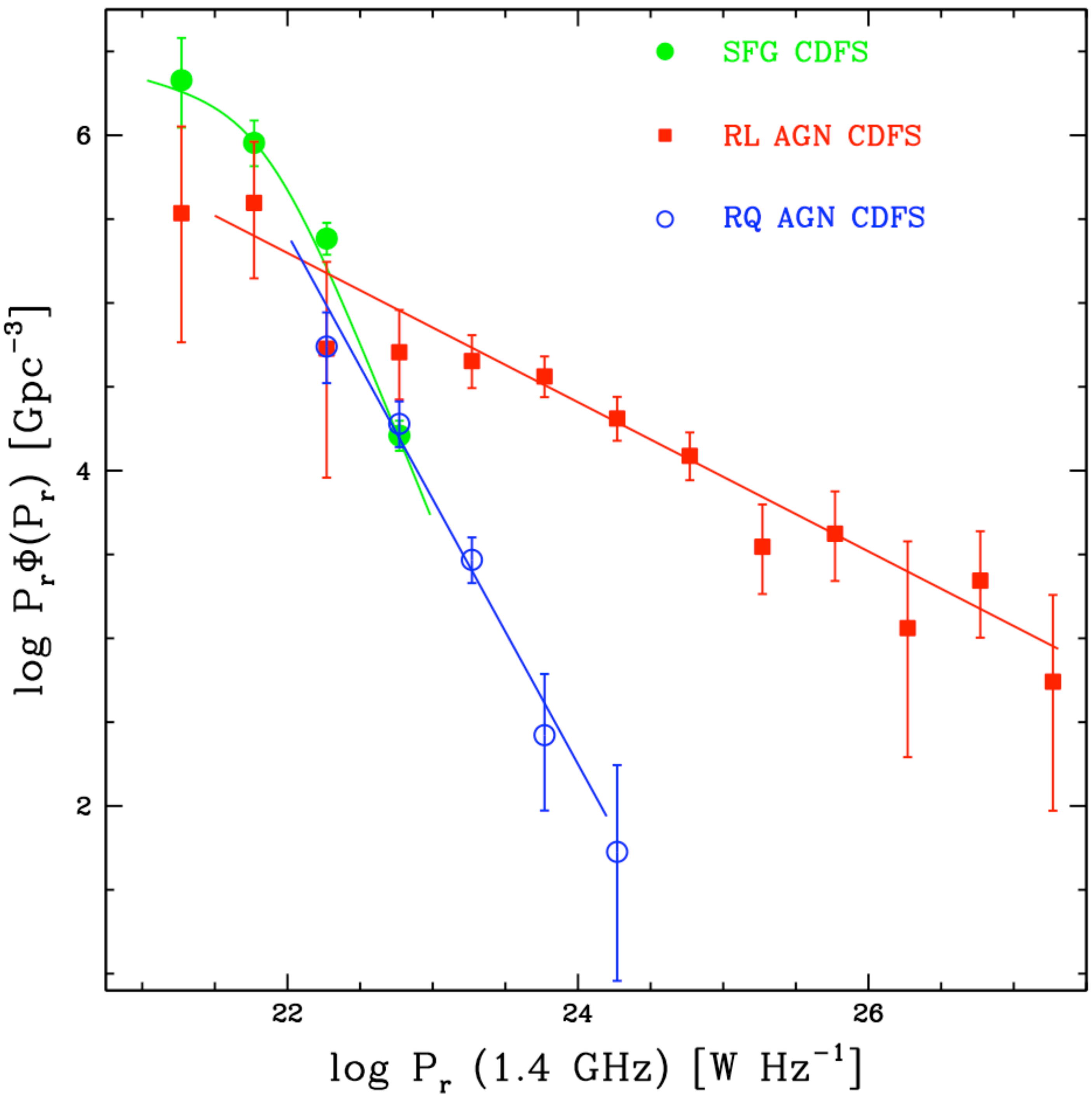
Pure density evolution $\Phi(z) = (1+z)^{k_D}$

- Ma

S



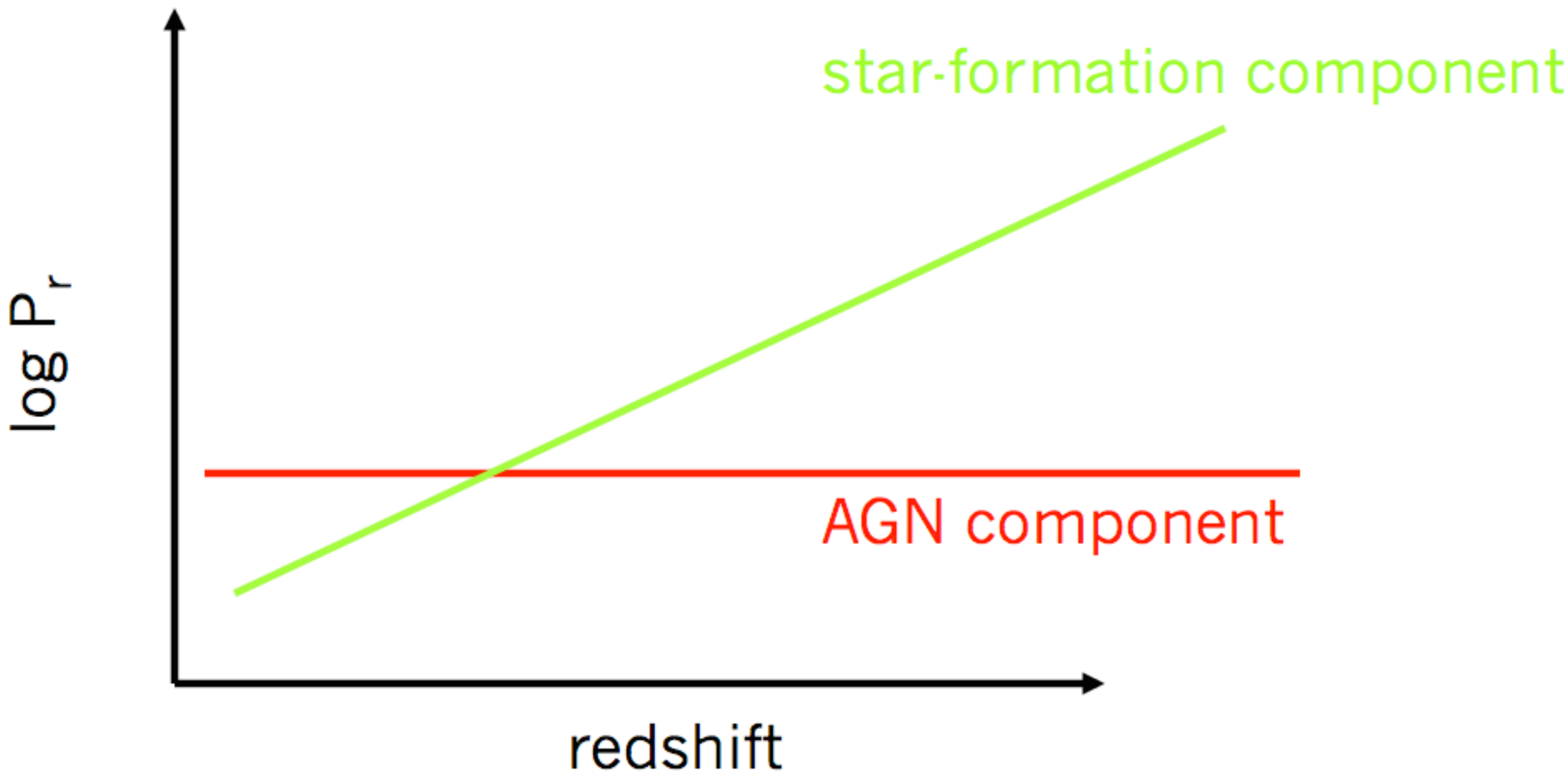
k_L evolution
Luminosity function LF slope
$P(z) = P(0)\,(1+z)^{kL}$
$\Phi(P) \propto P^{-slope}$
SFG
AGN
RQ AGN
RL AGN
2
0
−2
−4
−6
1.5
2
2.5
3
3.5


SFG CDFS
RL AGN CDFS
RQ AGN CDFS
6
4
2
22
24
26
log $P_r\Phi(P_r)$ [Gpc^{-3}]
log P_r (1.4 GHz) [W Hz^{-1}]

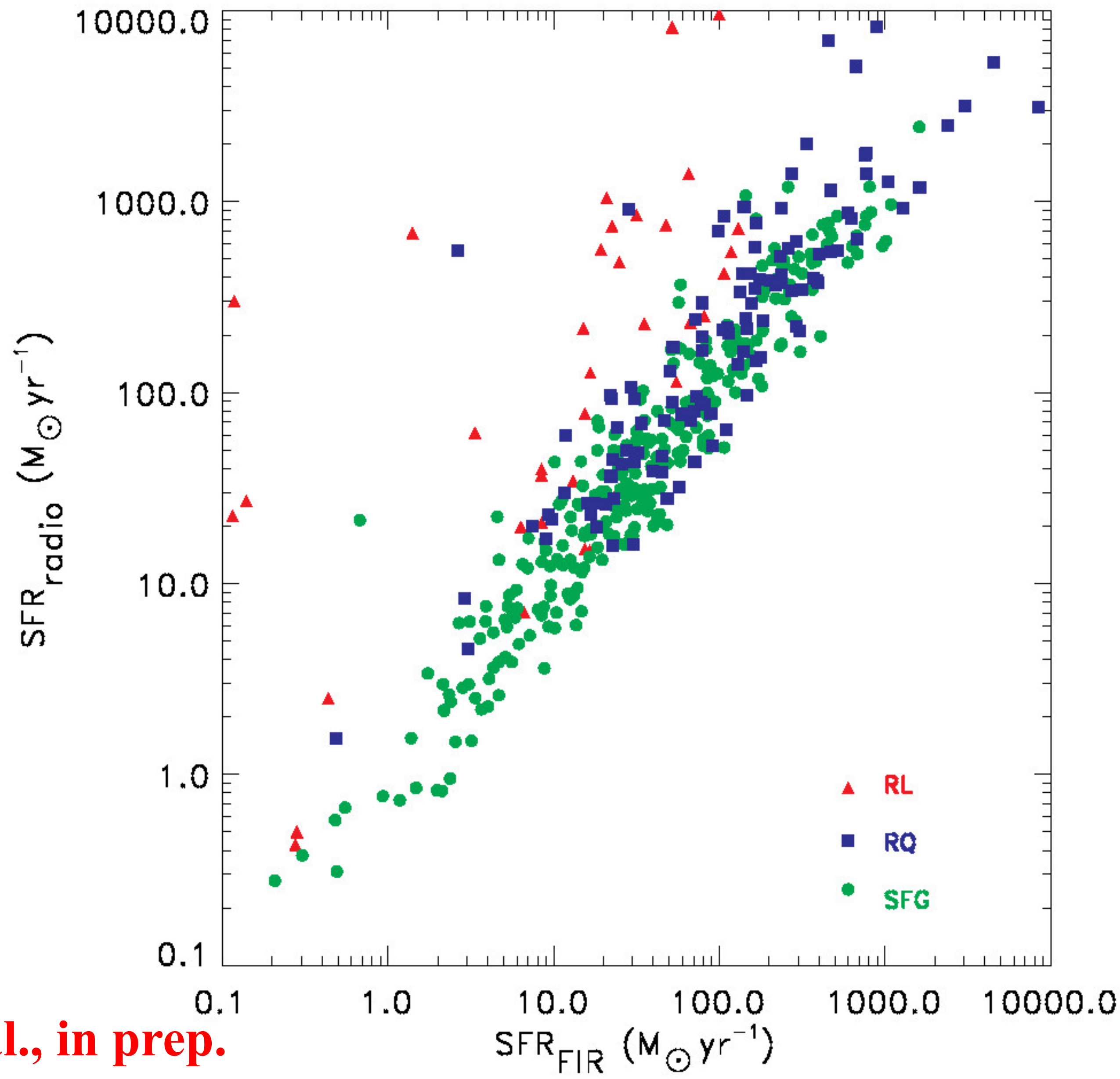
Radio emission in radio-quiet AGN

- Radio emission in radio-quiet AGN at $z \approx 2$ is *star-formation related*
- Compact radio cores?
  - ✓ Compact component ≈ 70% of total (Kellermann et al. 1989; Kukula et al. 1998) or less (Giroletti & Panessa 2009) → room for extended (non-nuclear) emission
  - ✓ Two components: AGN-related component non-evolving (as in low-power RL AGN) and star formation related component evolving (as in SFG)
  - ✓ High-z sources SF dominated while local AGN-dominated: 30% SF locally → ≈ 5 x at $\langle z \rangle = 1.7$

Radio emission in radio-quiet AGN



Radio emission in radio-quiet AGN



Bonzini et al., in prep.

Based on the following VLA-CDFS papers:

- *The VLA Survey of the CDFS. I. Overview and the radio data,* Kellermann, Fomalont, Mainieri, PP, Rosati, Shaver, Tozzi, Miller, 2008, ApJS, 179, 71
- *The VLA Survey of the CDFS. II. Identification and host galaxy properties of sub-mJy sources,* Mainieri, Kellermann, Fomalont, Miller, PP, Rosati, Shaver, Silverman, Tozzi, Bergeron, Hasinger, Norman, Popesso, 2008, ApJS, 179, 95
- *The VLA Survey of the CDFS. III. X-ray spectral properties of radio sources,* Tozzi, Mainieri, Rosati, PP, Kellermann, Fomalont, Miller, Shaver, Bergeron, Brandt, Brusa, Giacconi, Hasinger, Lehmer, Nonino, Norman, Silverman, 2009, ApJ, 698, 740
- ***The VLA Survey of the CDFS. IV. Source Population,*** PP, Mainieri, Tozzi, Kellermann, Fomalont, Miller, Rosati, Shaver, 2009, ApJ, 694, 235
- ***The VLA Survey of the CDFS. V. Evolution and Luminosity Functions of sub-mJy radio sources and the issue of radio emission in radio-quiet AGN,*** PP, Miller, Kellermann, Mainieri, Rosati, Tozzi, 2011, ApJ, 740, 20

plus VLA-ECDFS work in progress

AGN and star formation in the Universe

- A complex relationship
  - ✓accreting gas feeding black hole *might* trigger starbursts
  - ✓black hole feeds energy back through winds and jets:
    - jets/winds *might* accelerate star formation (gas compression)
    - jets/winds *might* blow away all gas (stopping accretion and star formation)
- AGN thought to play major role in galaxy evolution

→**AGN Feedback** (e.g., Cattaneo et al. 2009)

AGN Feedback: a simple estimate (adapted from Fabian 2012)

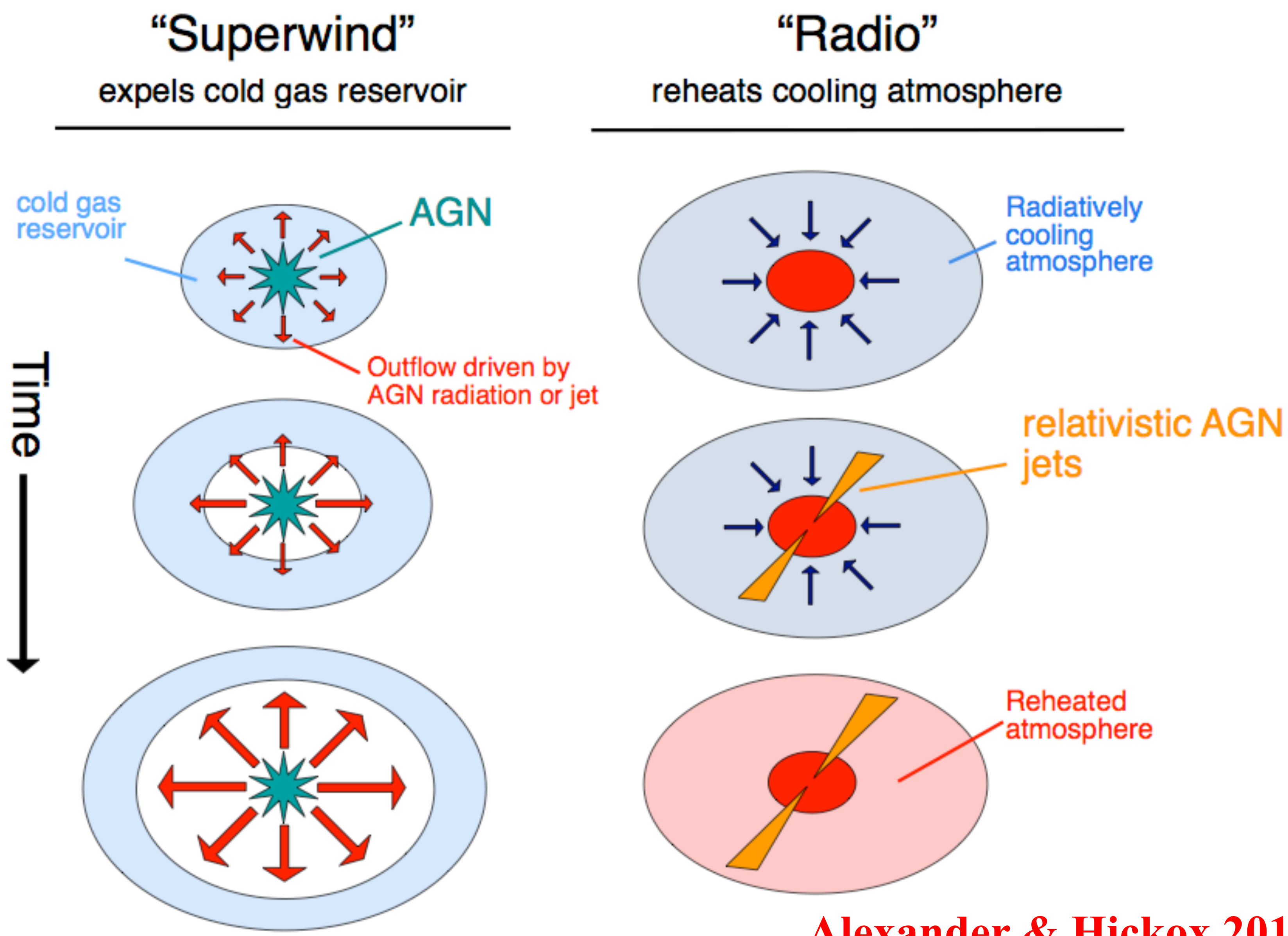
$$E_{\rm gal} \approx M_{\rm gal}\sigma^2 (\text{from U} \sim GM^2/R \text{ and taking } GM/R \approx \sigma^2)$$

$$E_{\rm BH} = \int L(t)dt = \eta c^2 \int \dot{m} dt = \eta M_{\rm BH} c^2$$

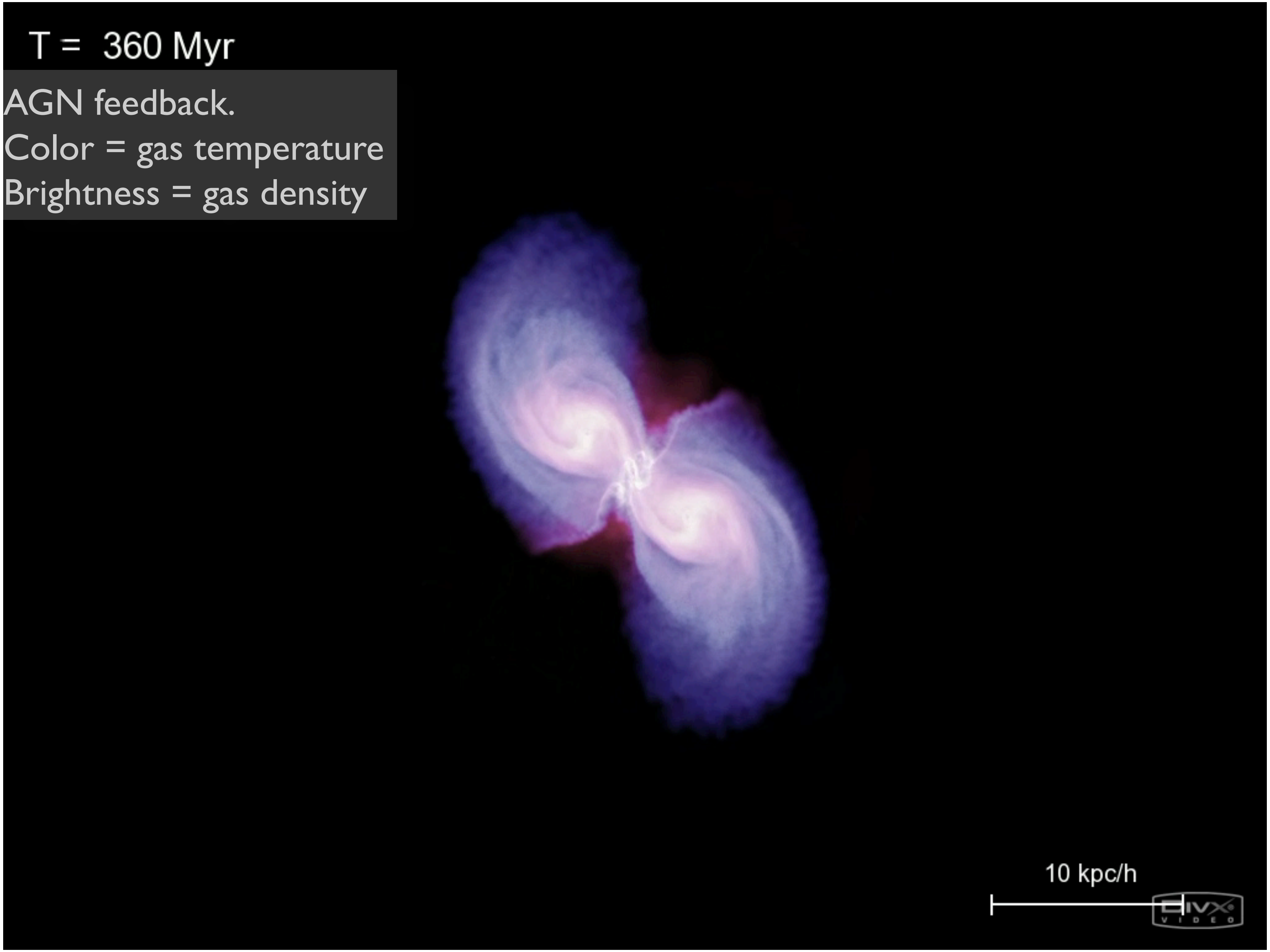
$$M_{\rm BH} \approx 5 \times 10^{-3} M_{\rm gal} \text{ (Kormendy \& Ho 2013)}$$

$$E_{\rm BH}/E_{\rm gal} \approx (\eta/0.1)\ 5 \times 10^{-4} (c/\sigma)^2$$

$$\sigma < 400 \text{ km/s} \rightarrow E_{\rm BH}/E_{\rm gal} > 280$$



Alexander & Hickox 2012


T = 360 Myr
AGN feedback.
Color = gas temperature
Brightness = gas density
10 kpc/h

Things to remember

- *AGN emit over the whole electromagnetic spectrum*
- *Different bands give us complementary views of their inner structure and physics*
- *Be aware of selection effects: know your samples!*
- *Radio emission in radio-quiet AGN at $z \approx 2$ is due to star formation*
- *AGN play an important role in the life of their host galaxies*

AGN selection: a view on their physics

- radio: jet ($\gtrsim$ 1 mJy) and star-formation in the host galaxy ($\lesssim$ 1 mJy)
- IR: obscuring material (mid-IR) and star-formation in the host galaxy (far-IR) [*jet*]
- optical/UV: accretion disk [*jet*]
- X-ray: hot corona (?) close to the disk [*jet*]
- γ-ray: jet

AGN (main) Open Questions

- Why do only a few % of AGN have jets while the majority do not? How are jets launched?
- What does an AGN *really* look like on sub-pc scales?
- How does the radiative and mechanical energy of an AGN *really* affect its host galaxy?

Want to know more about AGN?

Read this book: →
Q/A with 50 AGN researchers