The Contribution of Active Galactic Nuclei to the Excess Cosmic Radio Background at 1.4 GHz

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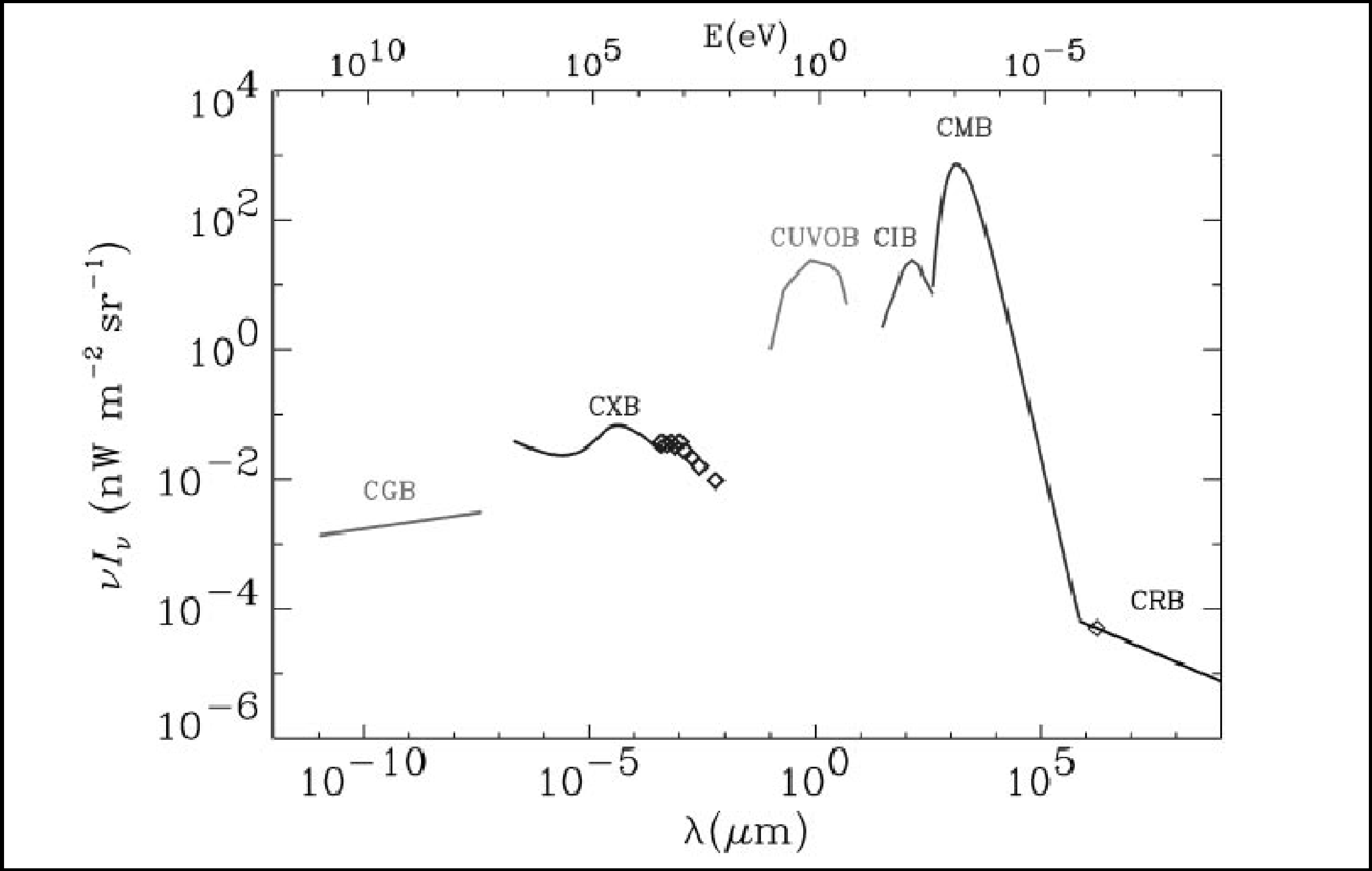
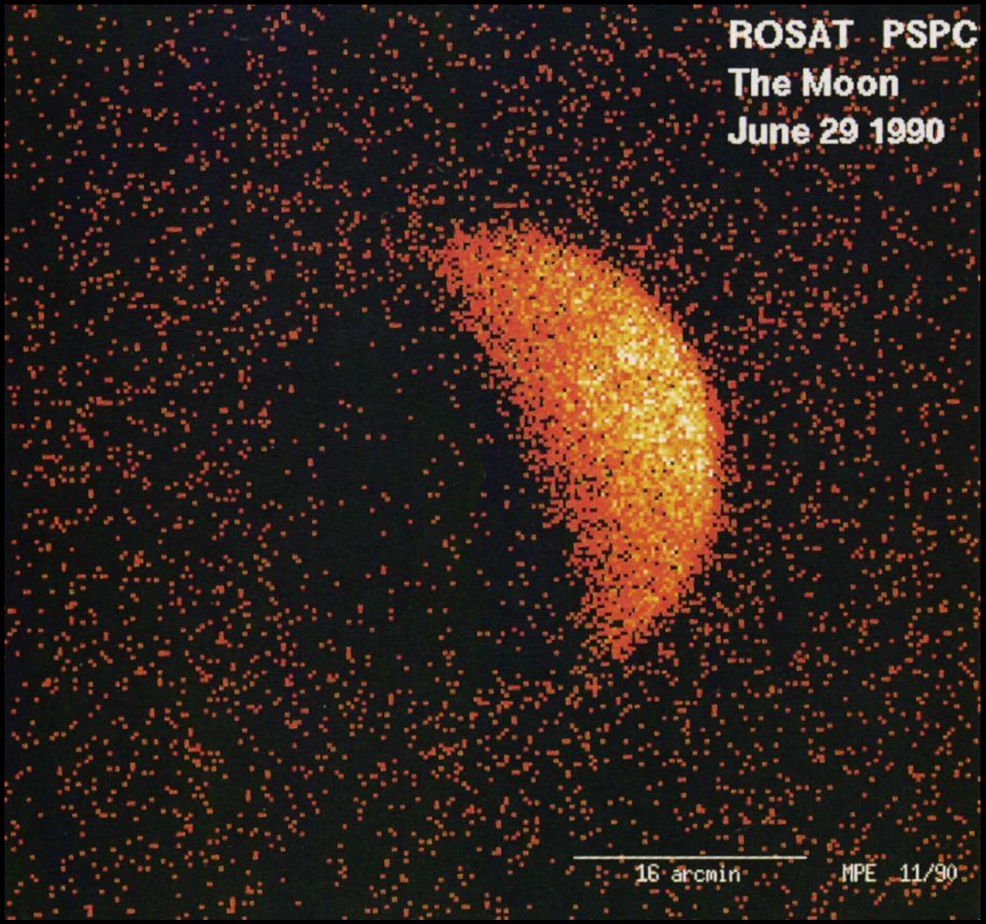
The Cosmic Backgrounds



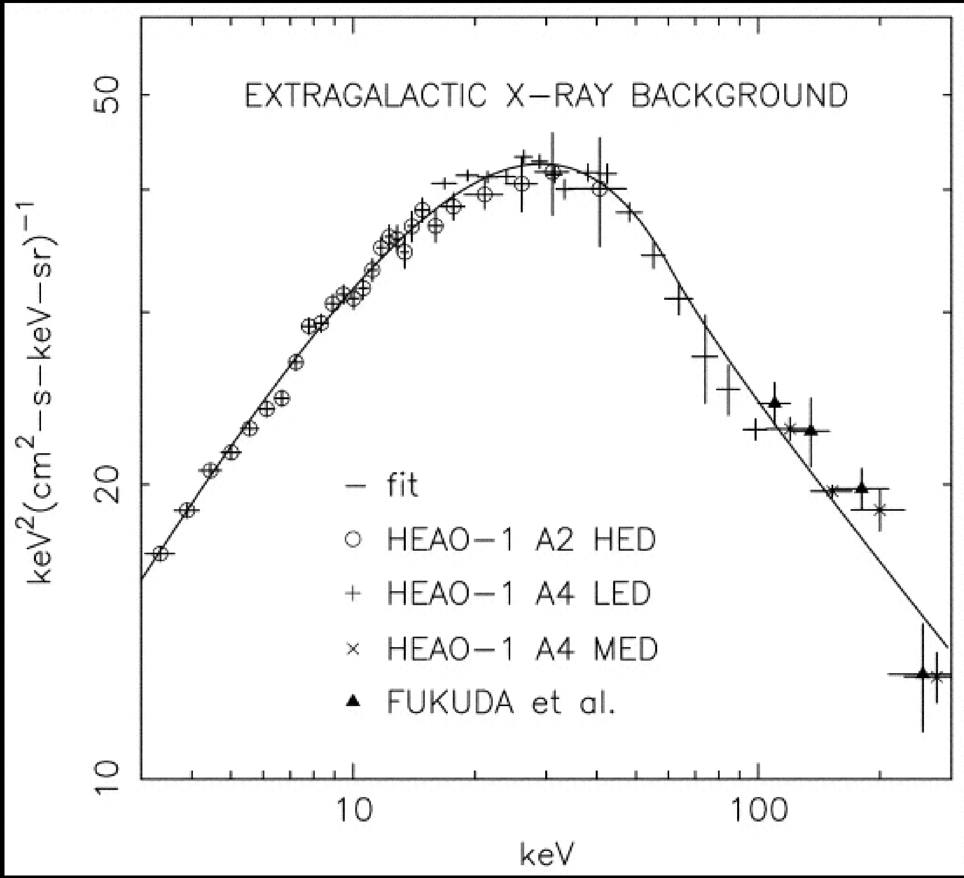
Hauser & Dwek (2001)

- XRB was the first cosmic background detected
- Discovered (along with Sco X-1) during a rocket flight that intended to detect the moon (Giacconi et al. 1962)
- Above 1-3 keV the XRB is isotropic to within a few per cent on large scales
- Strongly suggests an extragalactic origin



The Background Spectrum

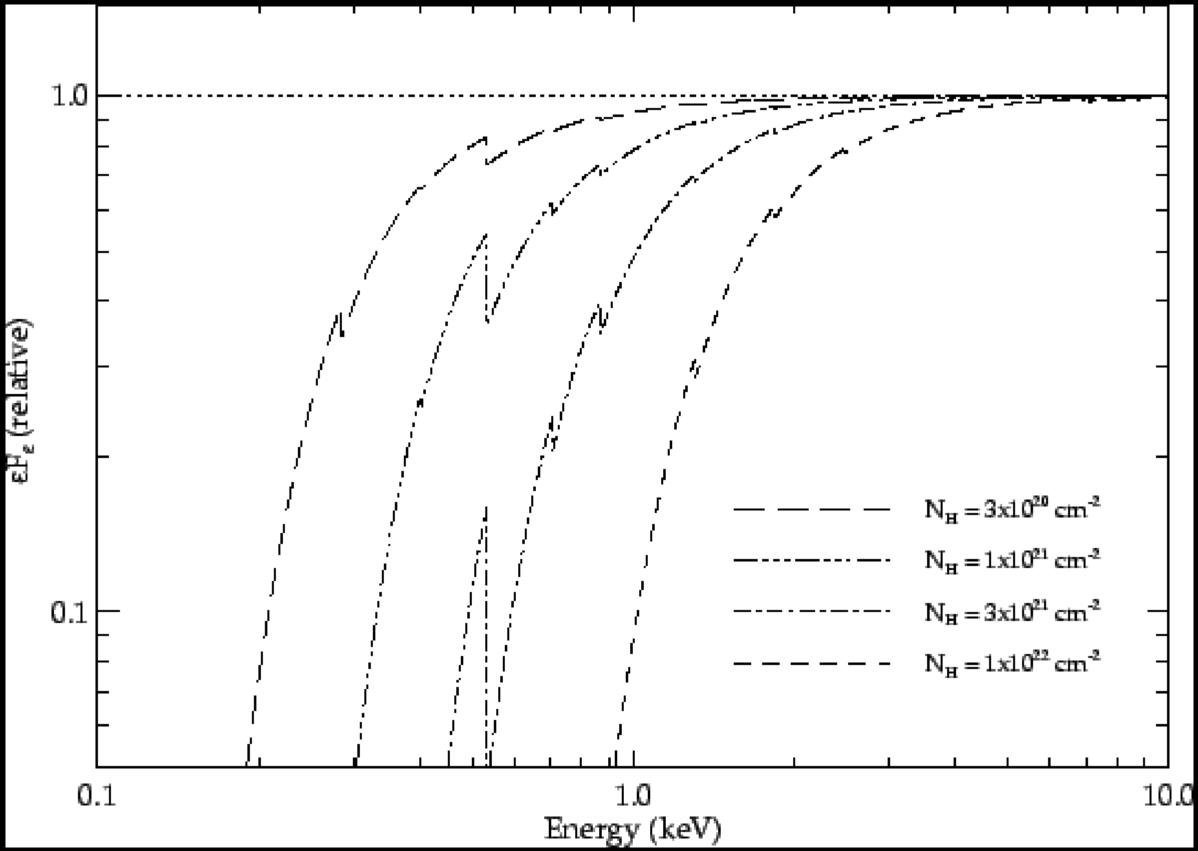
- spectrum peaks at 30-40 keV
- between ~1 and 20 keV the spectrum is well fit with a power-law with photon index, $\Gamma = 1.4$ (photon-flux $\propto E^{-\Gamma}$)
- no obvious spectral features -> no z info



Gruber et al. (1999)

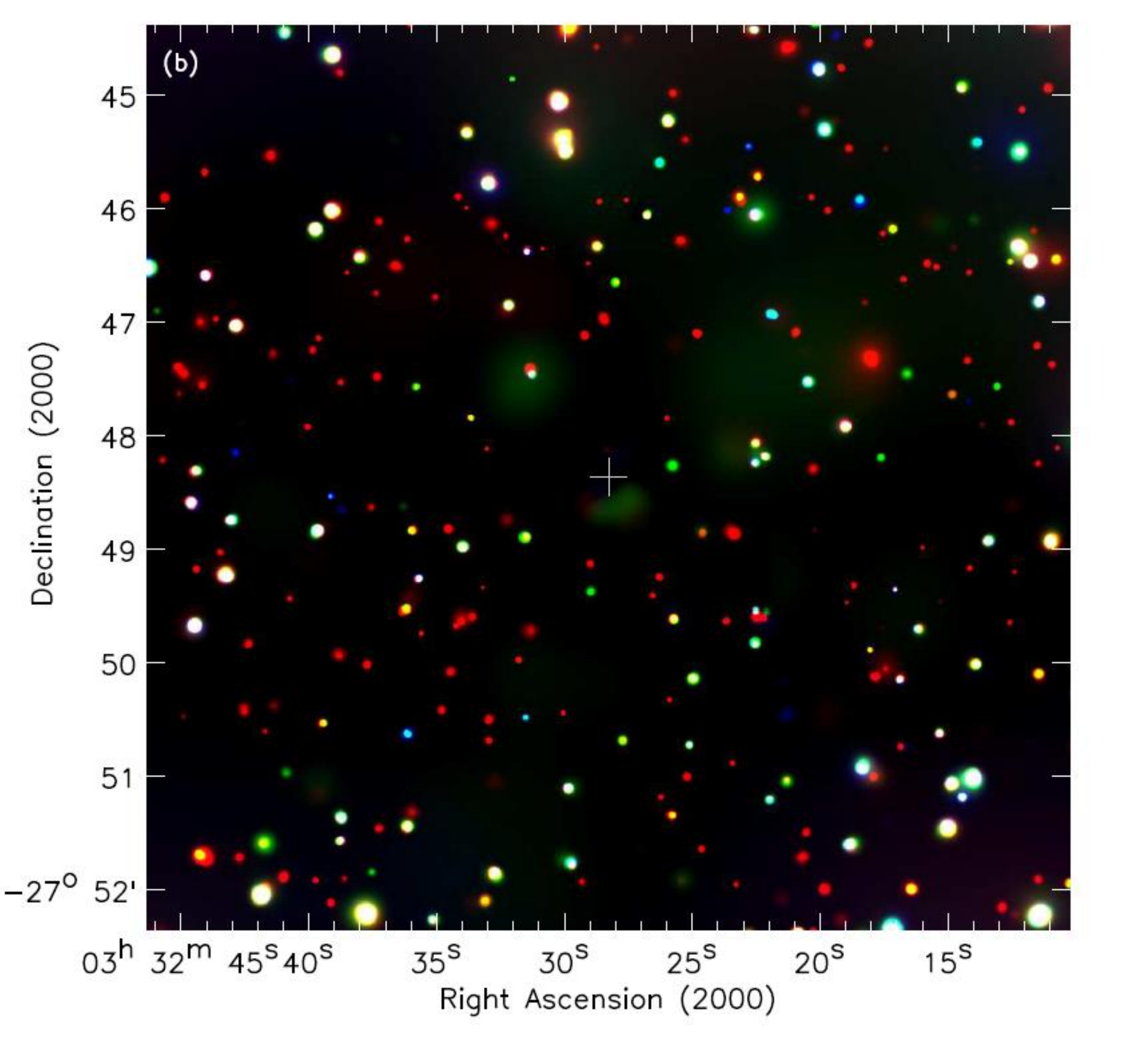
Discrete Models of the XRB

- the most common hard extragalactic X-ray sources are AGN
- they have power-law spectra above 2 keV
- but the average observed photon-index of AGN is $\Gamma \sim 1.7$

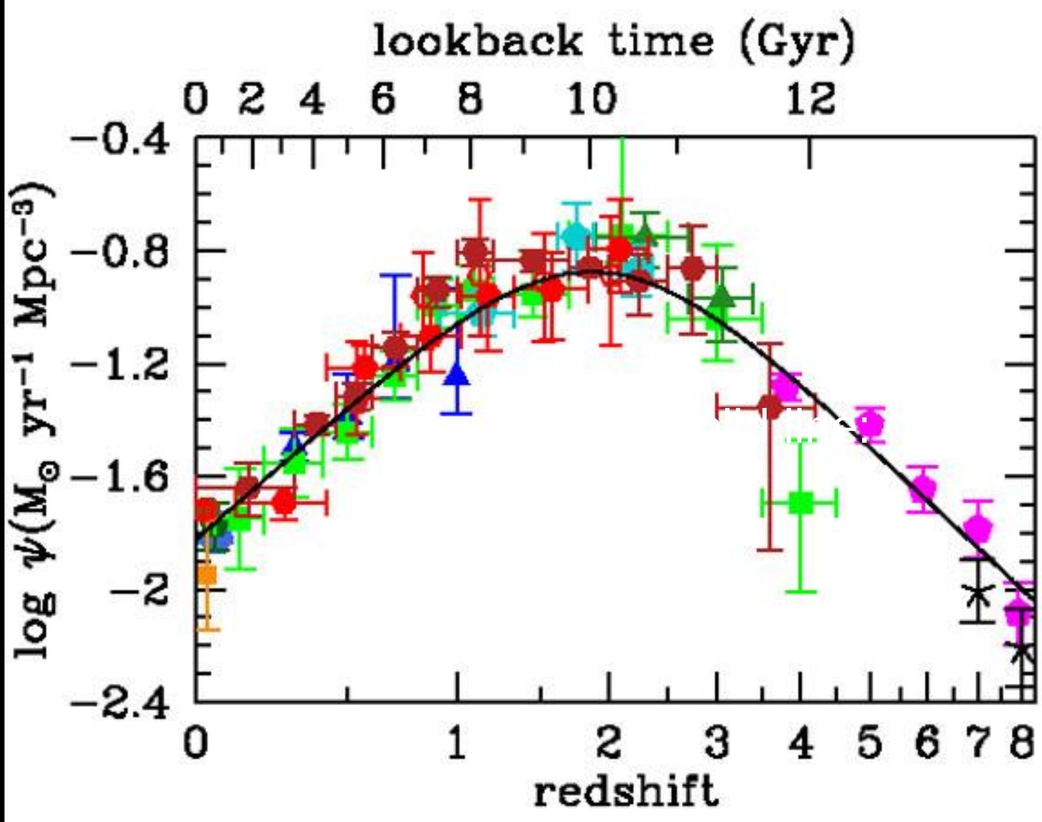


- Setti & Woltjer (1989) proposed that the XRB was comprised of the sum total of emission from mostly obscured AGN over a range of luminosity, redshift and absorbing column
- they were inspired by the AGN unification model

7 Ms *Chandra* Deep-Field South (Luo et al. 2017)



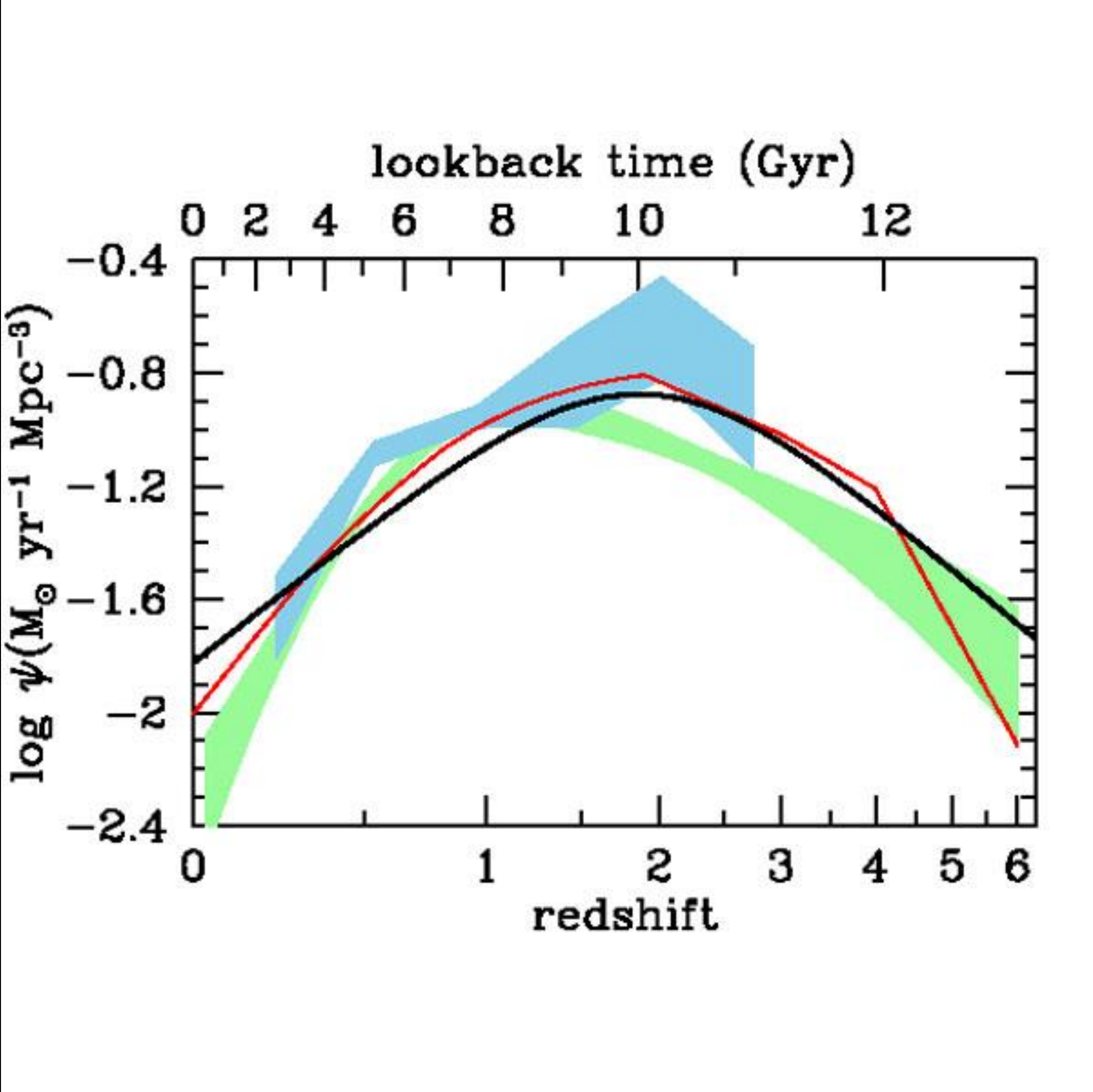
Connection to Star-Formation History?



Madau & Dickinson (2014)

$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}} \ \mathrm{M_\odot \ year^{-1} \ Mpc^{-3}}$$

Connection to Star-Formation History?



Red, green and blue lines/areas are estimates of the black hole accretion rate density scaled up by 3,300.

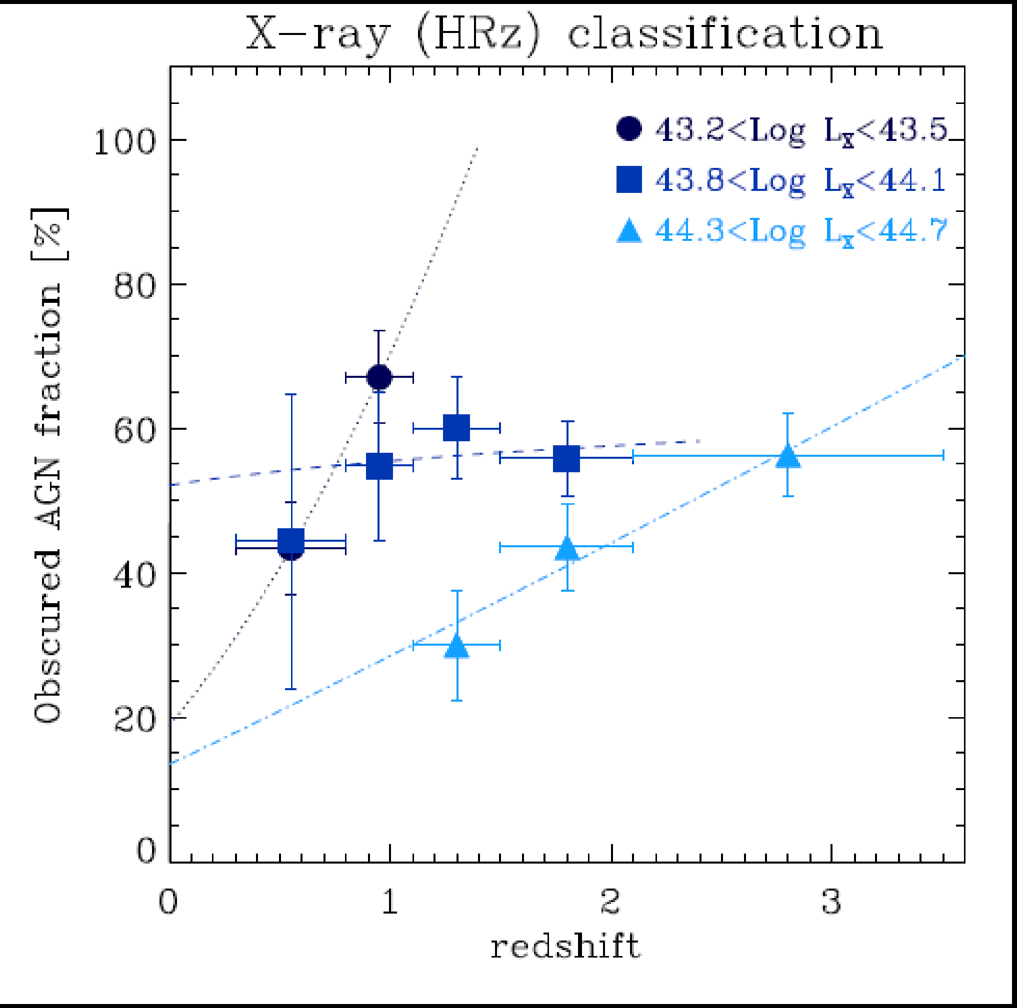
Madau & Dickinson (2014)

Hypothesis:

There exists an increase in obscured AGN to z~1-2 that is directly related to the increase in the cosmic SF rate.

- That is, the obscuration around the AGN is regulated by the host galaxy SF rate -> it must evolve with z
- If this is correct, then studying how the environment around an AGN evolves and changes with luminosity and redshift will give important information on the galaxy assembly process.

Prediction: *An AGN Type 2/Type 1 ratio that evolves with z*



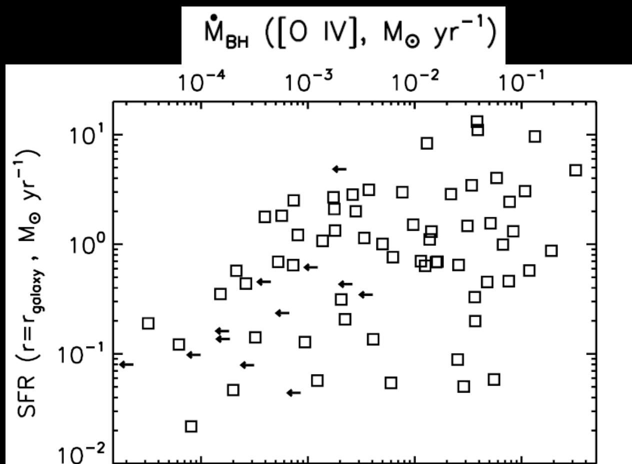
Merloni et al. (2013)

Now good evidence for this:

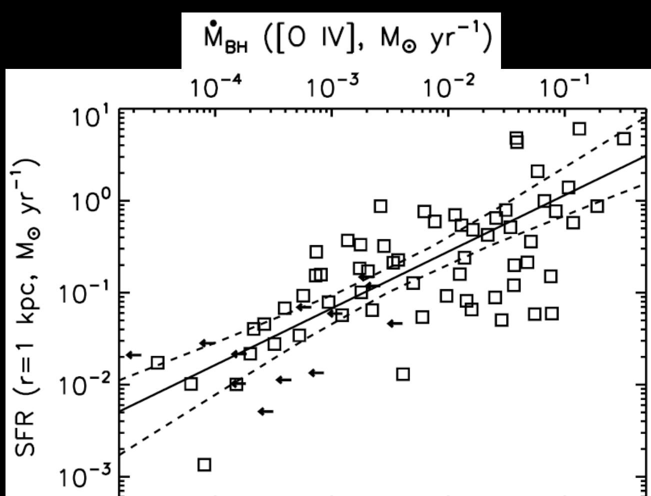
Ballantyne et al. (2006) found that a Type 2 fract. $\propto (1+z)^{0.3}$ can fit the XRB and X-ray number counts.

Confirmed by Treister & Urry (2006) [0.4], Hasinger (2008) [0.6], and Ueda et al. (2014) [0.48].

Zooming Into the Nucleus



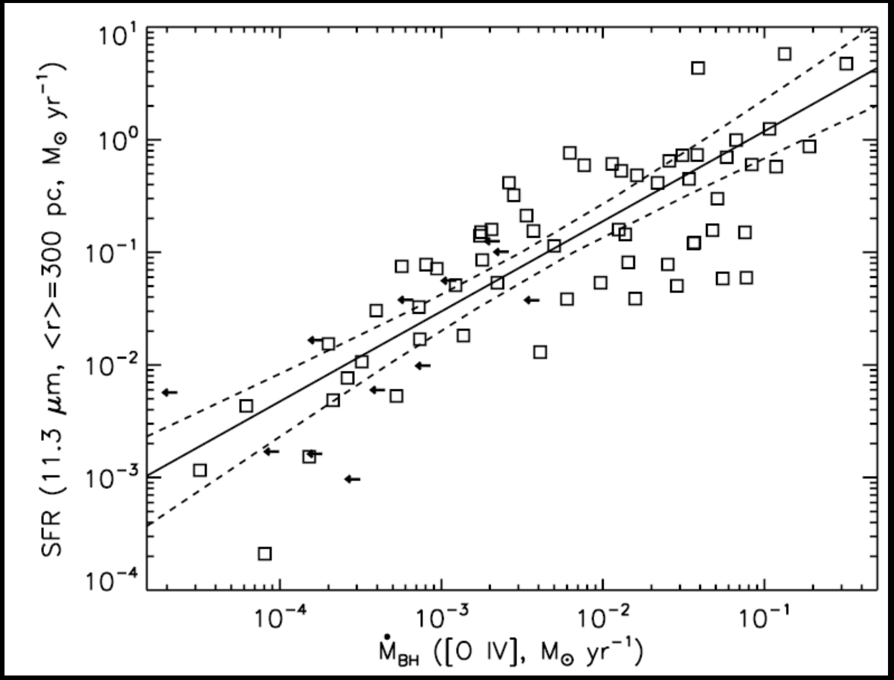
Galaxy scale



kpc scale

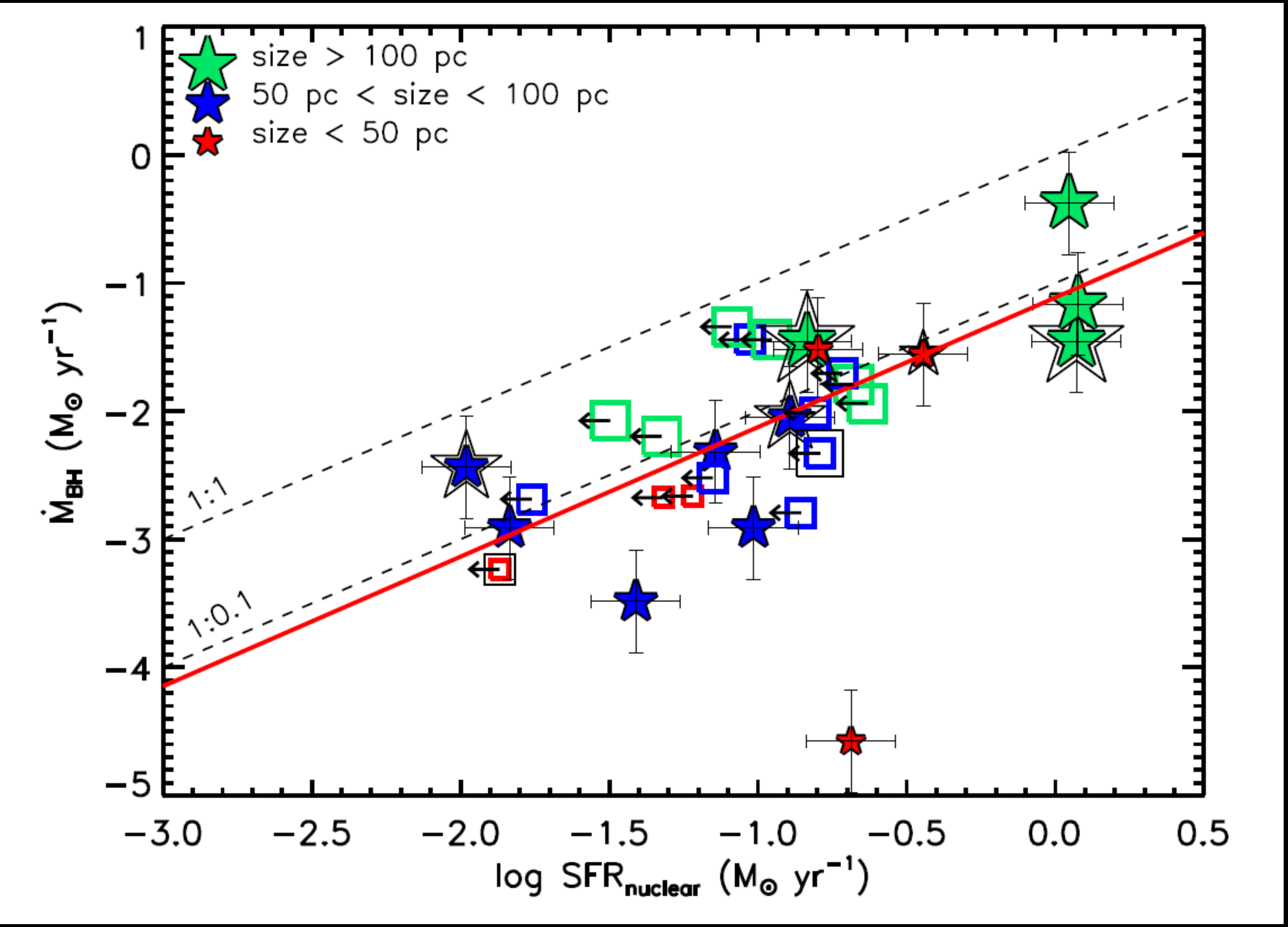
PAH emission + 24 μm in local Seyferts

Diamond-Stanic & Rieke (2012)



300 pc scale

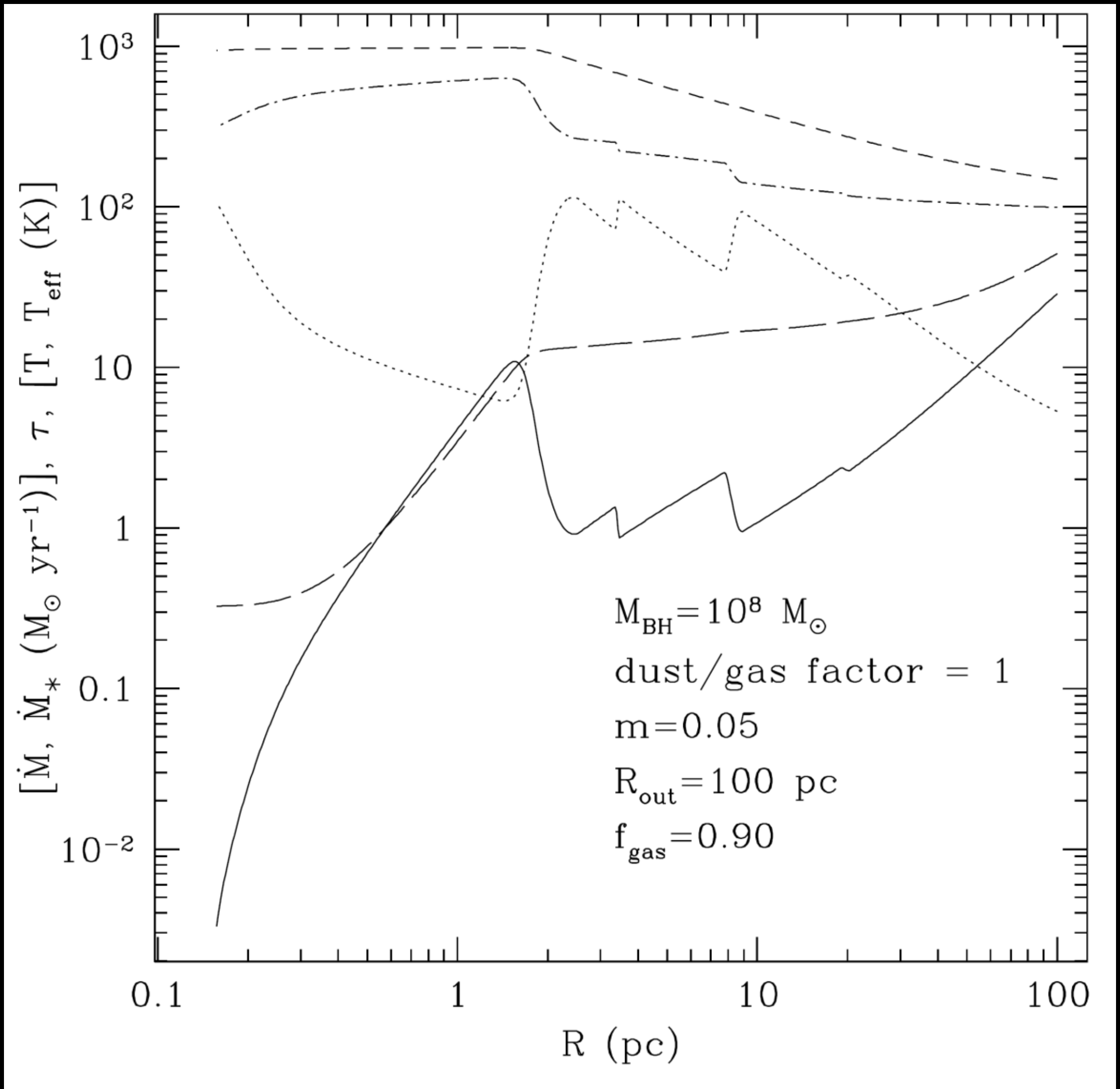
…and even closer…



Esquej et al. (2013)

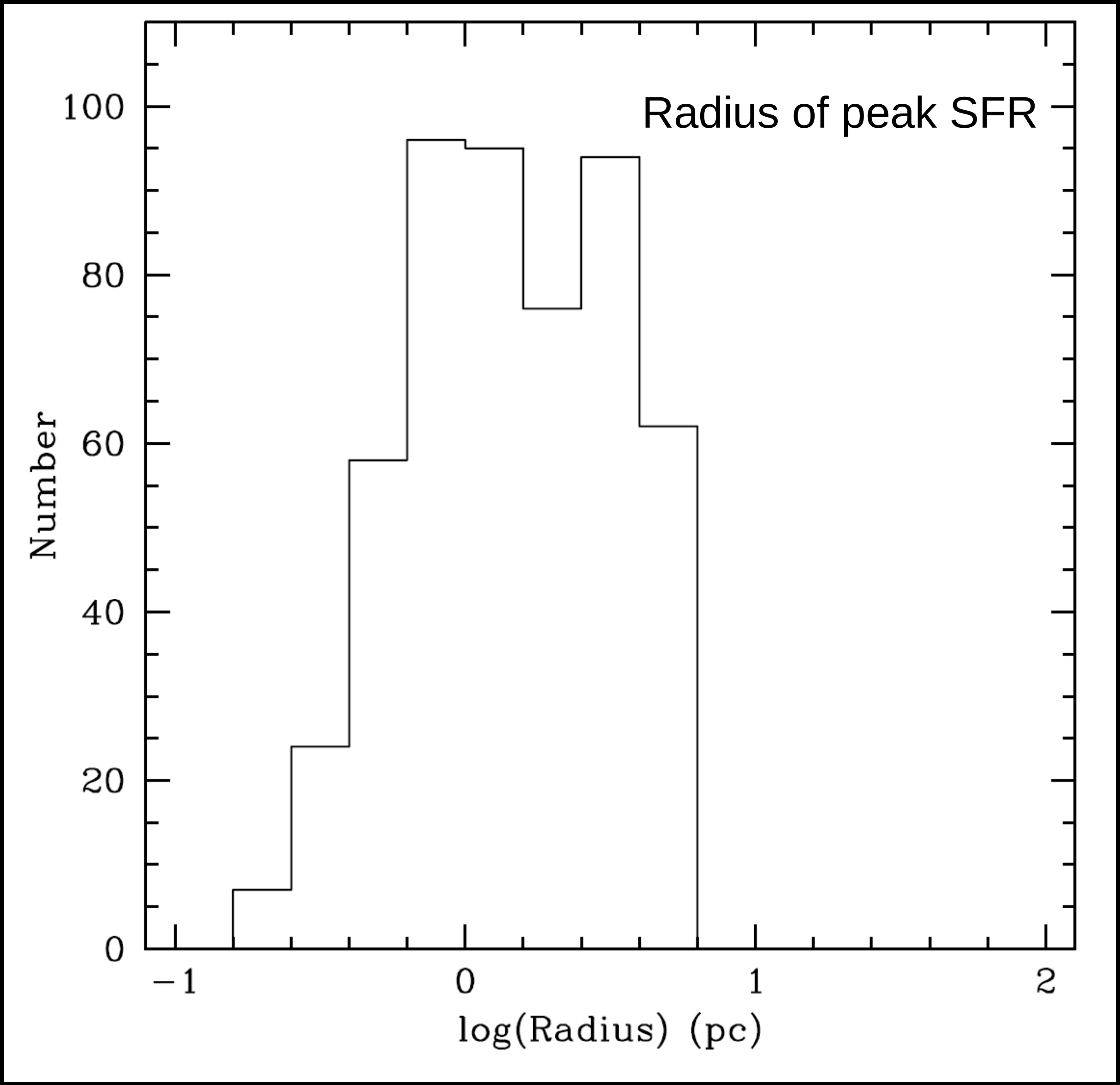
Toward a Physical Model

- Need to explore the physics of a starburst disk around a black hole.
  - What properties (star-formation rate, fueling rate, metallicity) are required in order for a disk to obscure an AGN?
  - How might this change with the host galaxy's evolution?
  - How does the AGN luminosity affect the disk structure?
- Begin with a 1D analytical model (Thompson et al. 2005).



Ballantyne (2008)

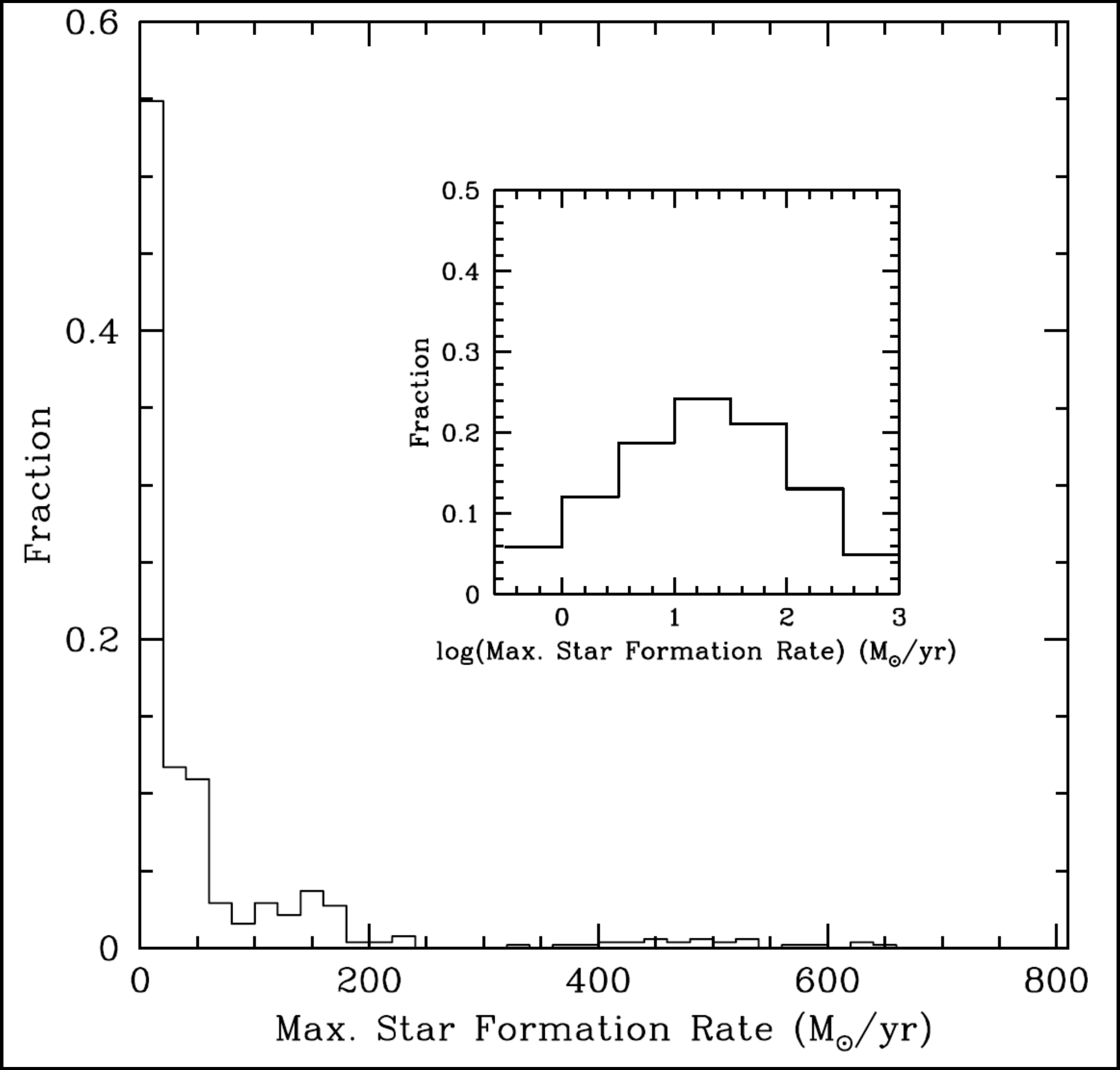
- Toomre's Q=1
- Eddington limited
- Global torque assumed to operate on disk
- Competition between star-formation and accretion



Ballantyne (2008)

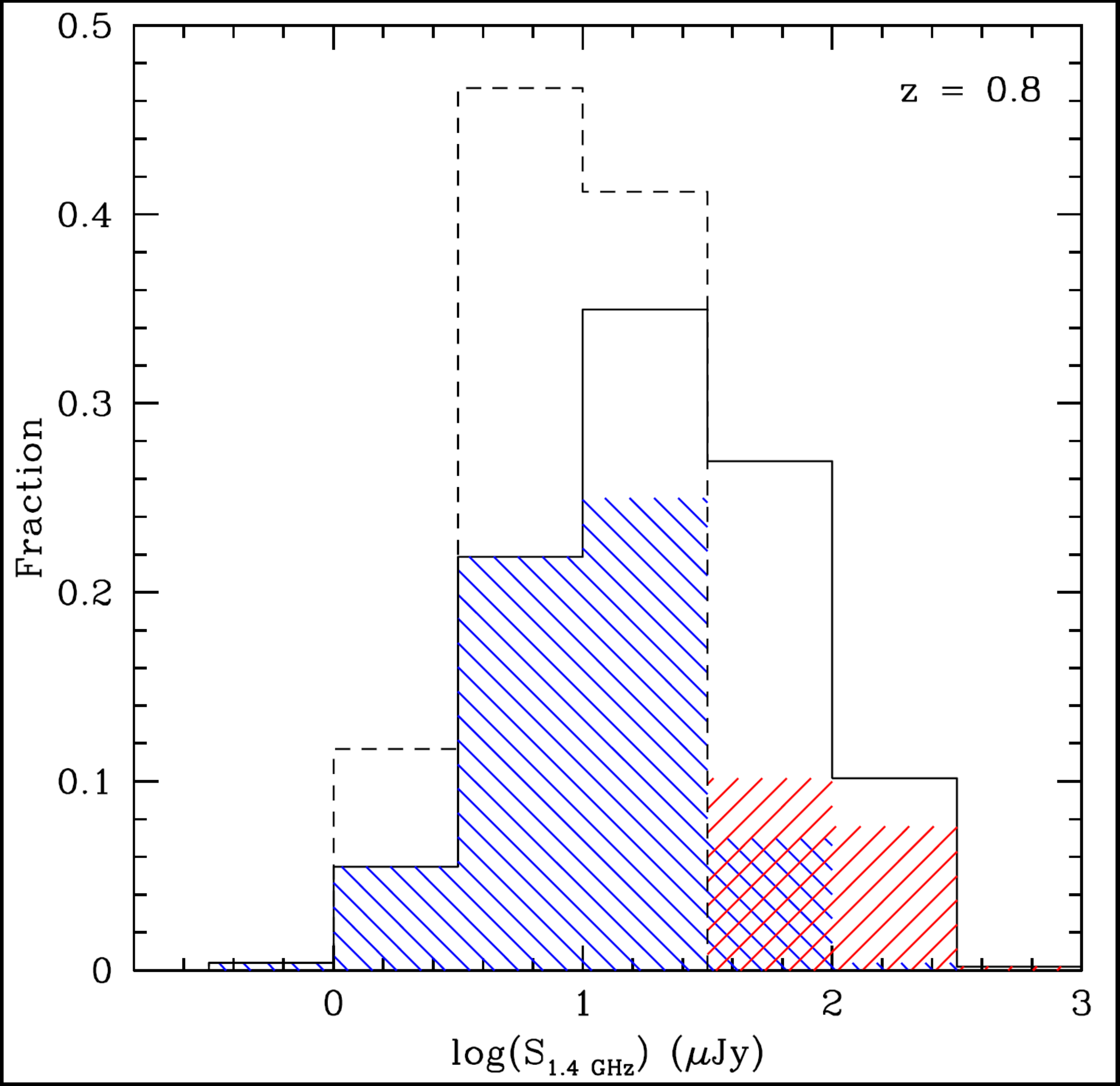
- 1260 starburst models
- Parameters:
  - M_{BH}
  - R_{out}
  - $f_{gas}(R_{out})$
  - Strength of angular momentum transport in disk
  - dust-to-gas ratio
- ~40% produce a pc-scale starburst

- Nearly 55% of pc-scale starbursts have max. SFRs < 20 $M_\odot$ yr^{-1}
- ~5% have SFRs > 300 $M_\odot$ yr^{-1}
- 10-30 $M_\odot$ yr^{-1} most common
- When gas extinguished, left with a nuclear star cluster?



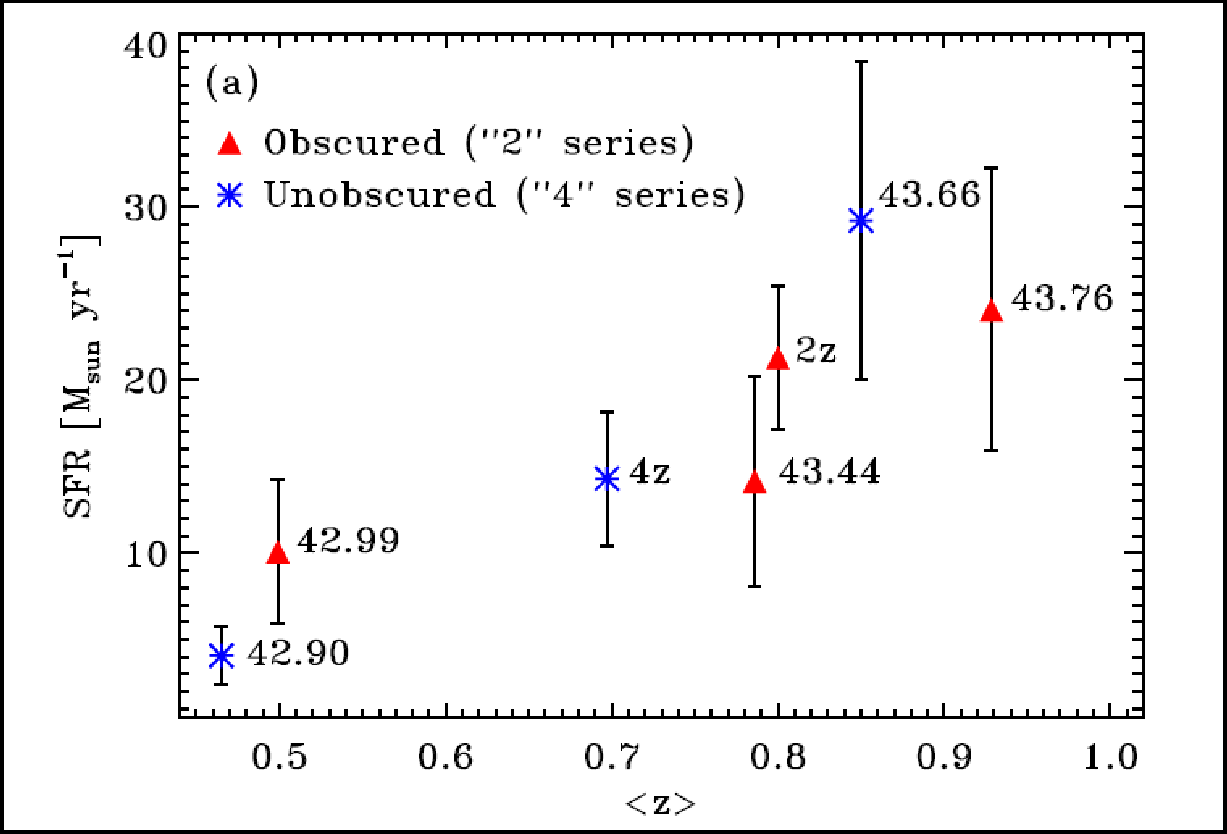
Ballantyne (2008)

- Estimate of radio flux at z=0.8 (using radio-far-IR correlation)
- Most common flux:
  ~10-30 μJy
- Red region
  SFR>100 M¤ yr-1
- Blue region
  SFR<30 M¤ yr-1
- Dashed histogram: estimated radio-quiet AGN flux



Ballantyne (2008)

SFR from COSMOS AGN

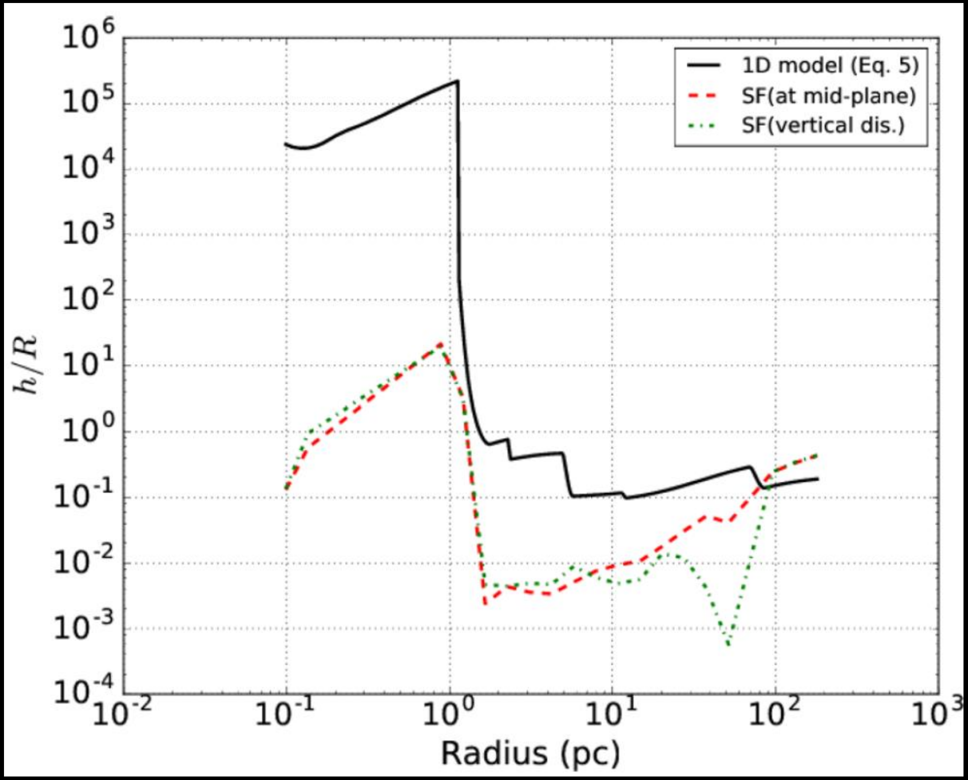


- z < 1 X-ray selected AGNs
- Radio stacks of undetected AGNs
- Corrected for AGN nuclear emission
- Residual flux interpreted as SF

Pierce et al. (2011)

Same Results in 2D

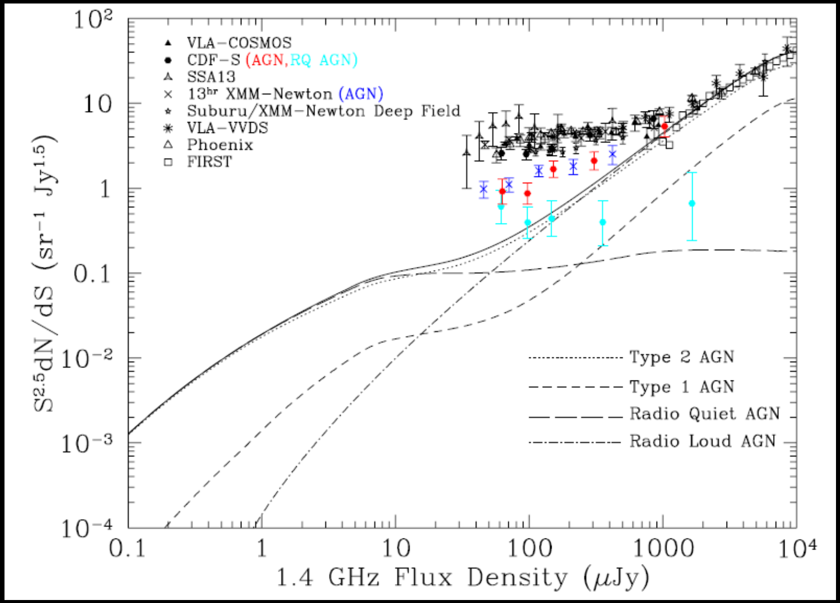
- Calculate the hydrostatic balance at every radius for a midplane SFR given by the 1D model.
- As before, obtain expanded atmospheres at pc scales
- Therefore, pc-scale starbursts are a viable method to obscure AGNs at z~1.

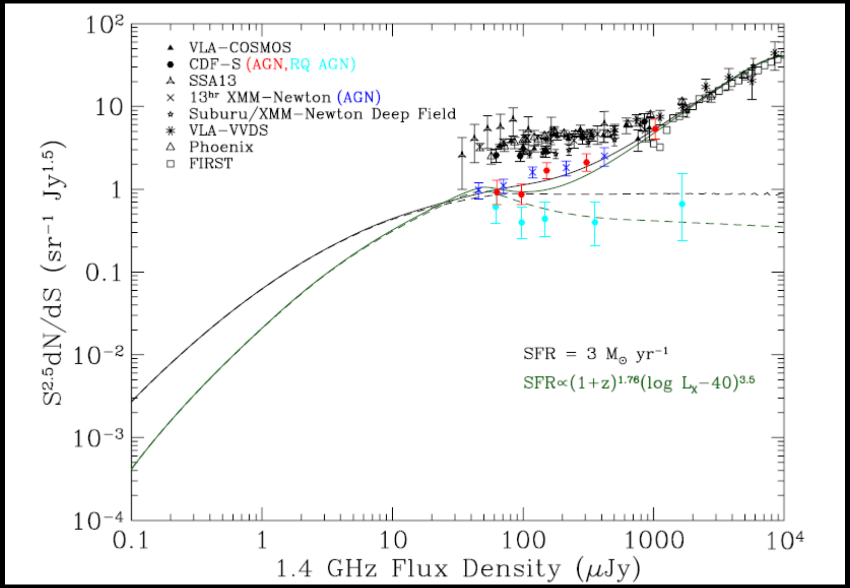


Gohil & Ballantyne (2017)

Evidence of SF in AGN Host Galaxies from 1.4 GHz Number Counts

- Ballantyne (2009) computed the expected 1.4 GHz AGN radio counts from a X-ray Background model
- Depending on the details of the core X-ray -> radio luminosity conversion, SF in the host galaxy was needed to fit the observed number counts





- Draper et al. (2011) used these calculations to investigate the contribution of AGNs and their host SF to the CRB at 1.4 GHz

Table 2
Contributions of Various Sources to the 1.4 GHz CRB

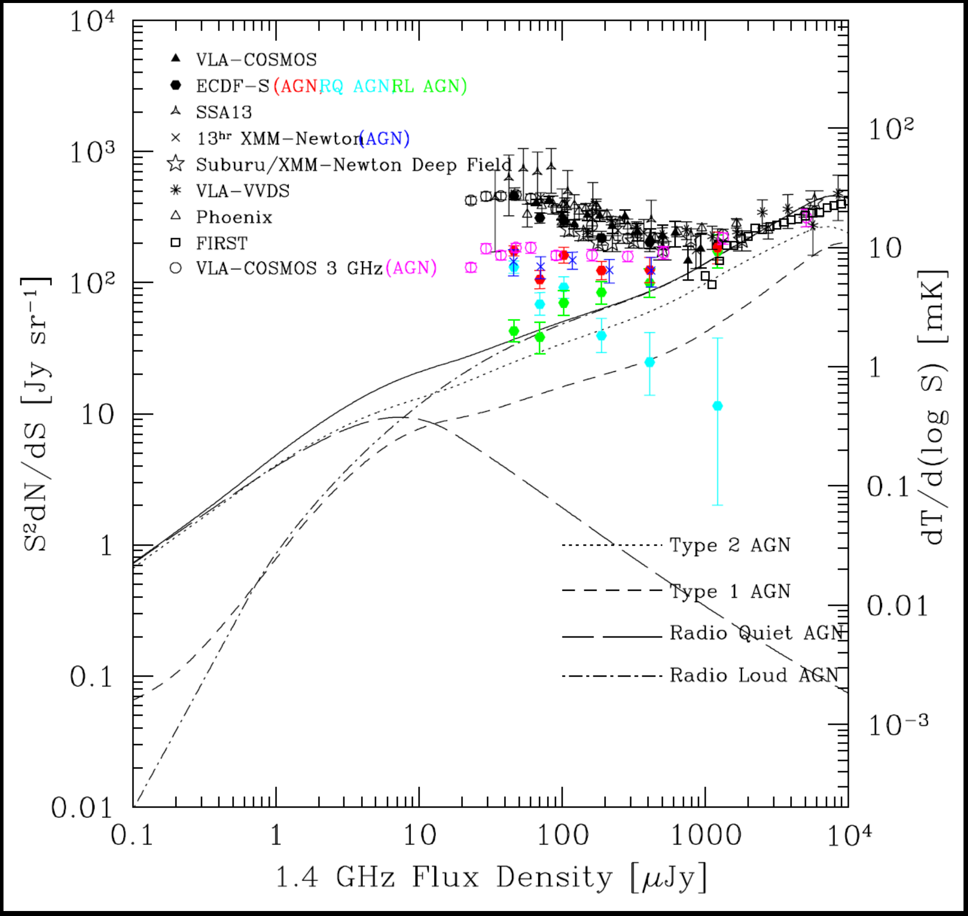
		Brightness Temperature (K)	Reference
	Total Measured CRB	0.48 ± 0.07	Fixsen et al. (2011)
	AGN	0.018	This work
	AGN+SF	0.025	This work
(1)	Max AGN+SF	0.042	This work

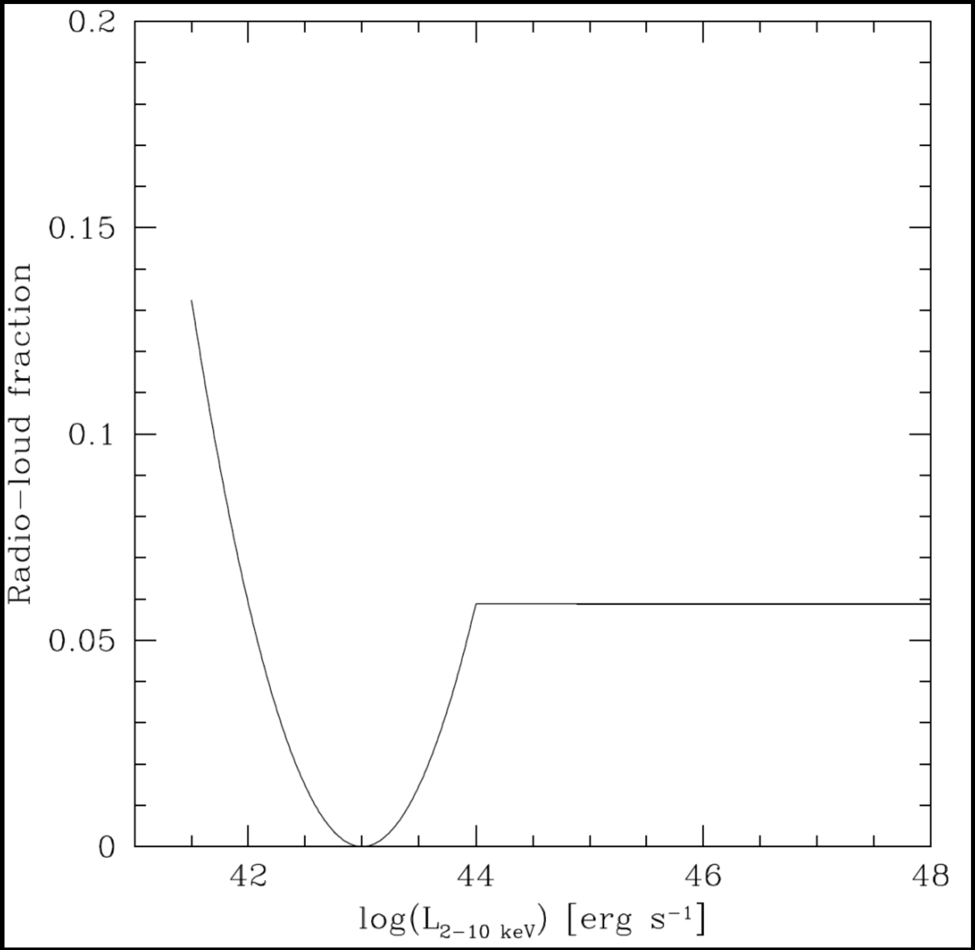
- AGN+SF could at most explain 9% of the CRB, leaving about ~40% unexplained.

- Updates to the calculation:
  - Up-to-date X-ray background model, calibrated to fit the latest *NuSTAR* results (Harrison et al. 2016)
    - Ueda et al. (2014) HXLF, Burlon et al. (2011) N_H distribution, Ballantyne (2014) f_2-L_X relationship
  - Included recent radio counts to constrain model
    - E-CDFS (Padovani et al. 2015), VLA-COSMOS 3 GHz (Smolčić et al. 2017)
  - Use α=0.2 ($S_\nu \propto \nu^{-\alpha}$) for AGN core emission (Massardi et al. 2011)
  - Panessa et al. (2015) $L_{1.4\ GHz}$ -L_X relationship
  - Murphy et al. (2011) SFR-$L_{1.4\ GHz}$ relationship

Contribution to 1.4 GHz T_B – AGNs (no SF)

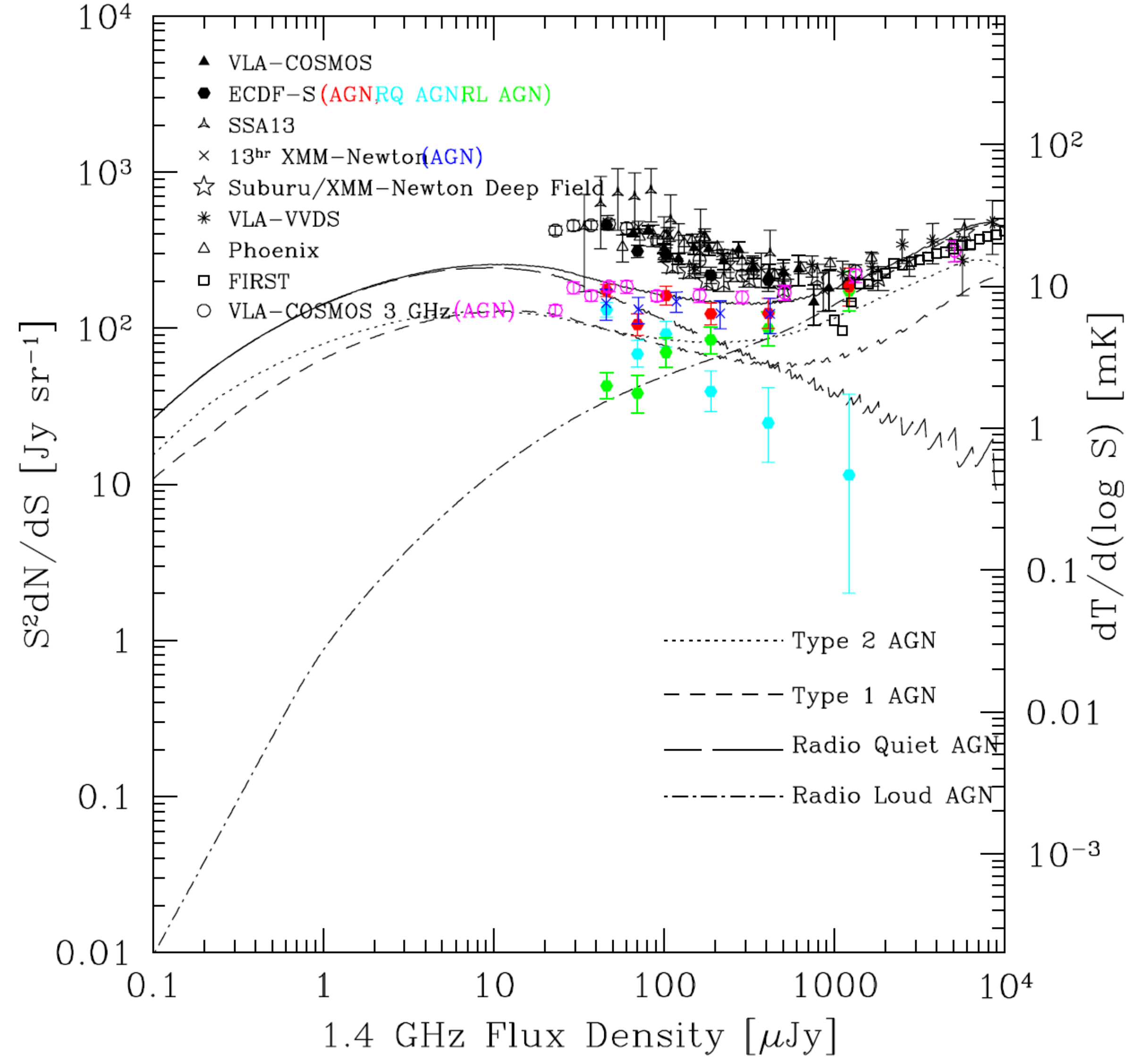
- $$\frac{dT_B}{d\log S} = \left(\frac{\ln(10)c^2}{2k_B\nu^2}\right) S^2 \frac{dN}{dS}$$
- The RL counts from ECDF-S are used to set the L_X-dependent radio-loud fraction
- Total brightness temperature of AGNs: 0.016 K





- No physics here – just a simple paramaterization
- But, shape is inspired by observations of jetted AGNs being more common at low accretion rates (roughly lower luminosities)

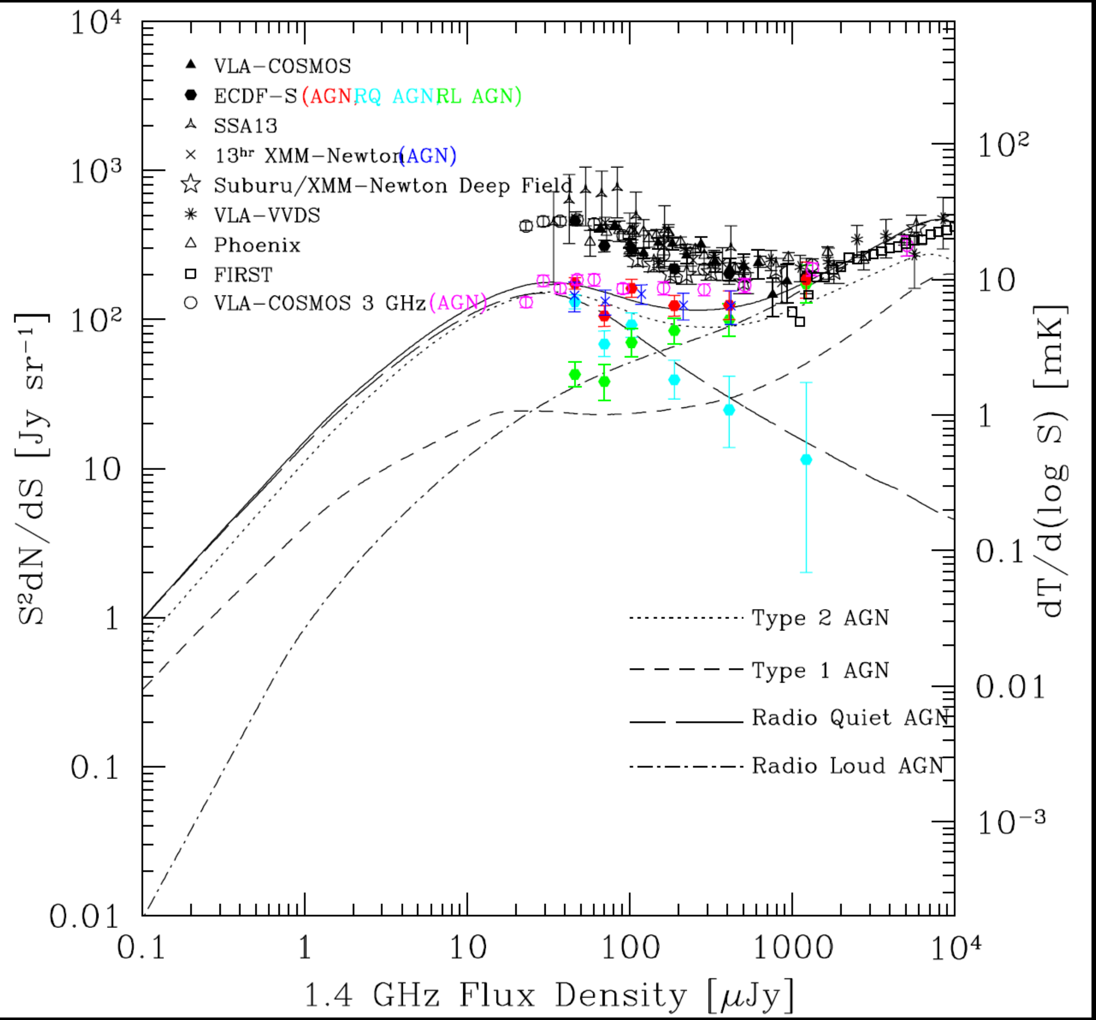
1.4 GHz T_B – AGNs (const. SF)



2.7 $M_\odot$ yr^{-1} for both Type 1 and 2 AGNs

T_B=0.038 K

1.4 GHz T_B – AGNs (z and L dependent SF)

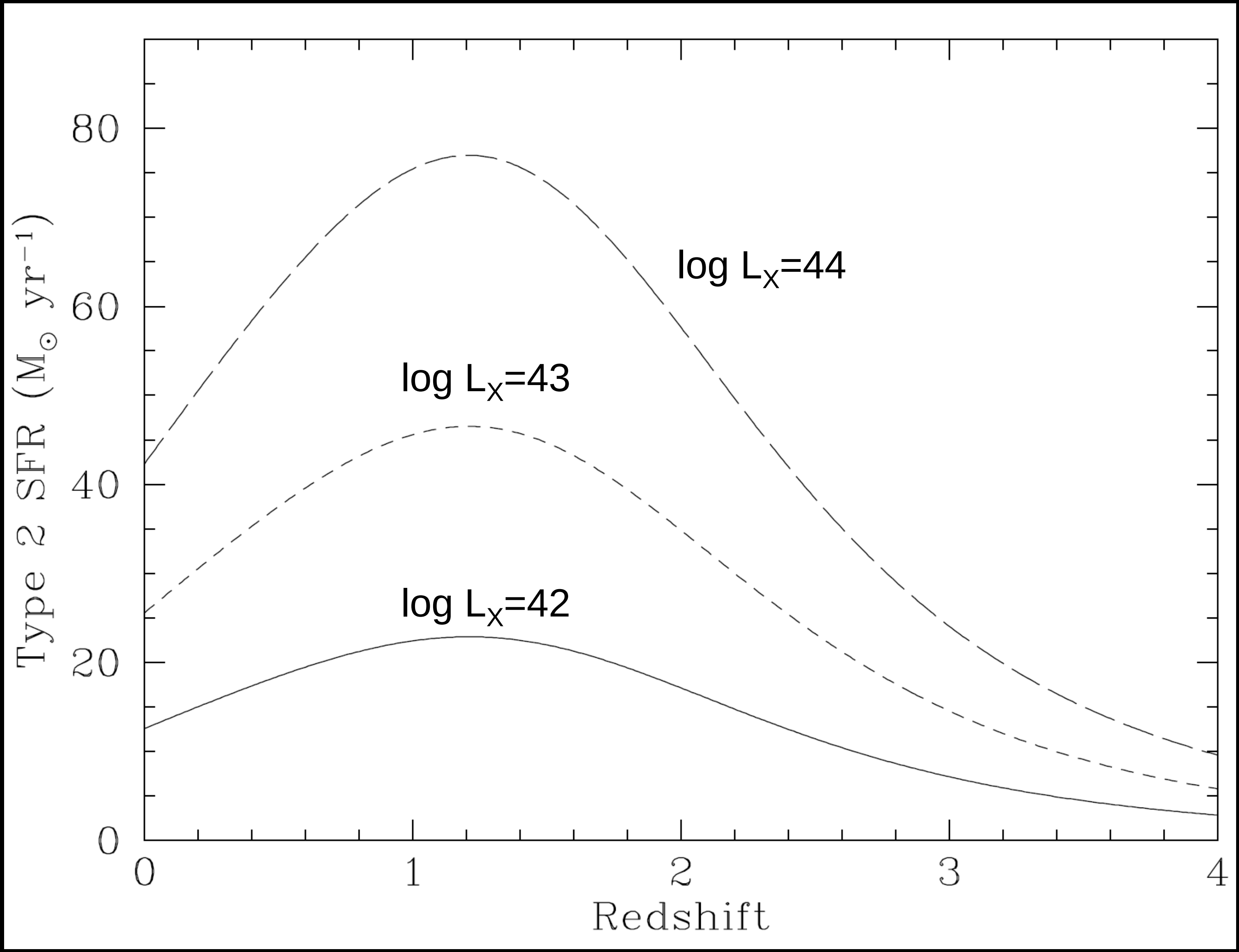


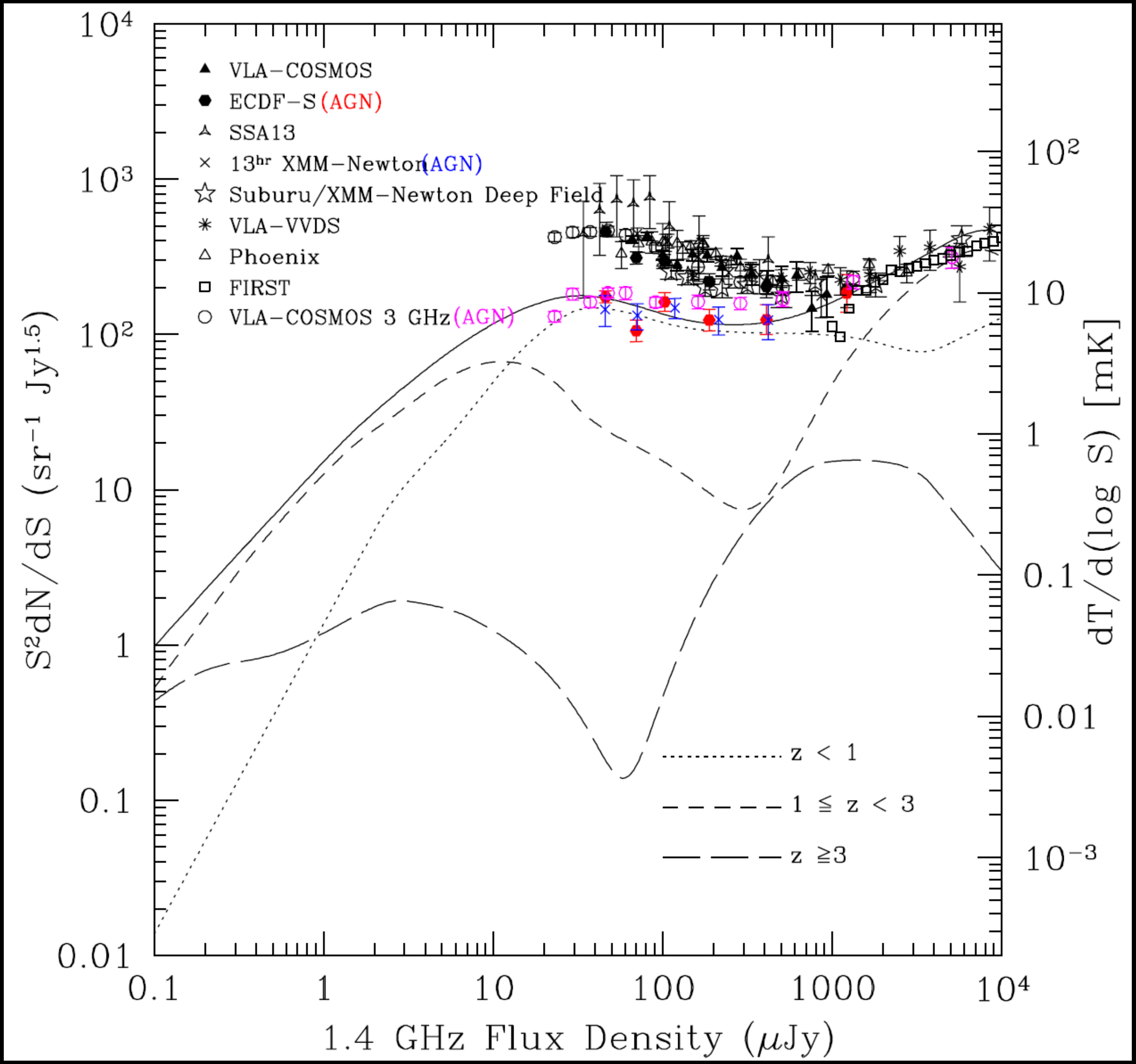
SF law follows the SFRD evolution from Madau & Dickinson (2014) except for a shallower rise with z: $(1+z)^{1.0}$ instead of $(1+z)^{2.7}$

Luminosity evolution goes as $(\log L_x\text{-}40)^{1.75}$

Stronger SF in Type 2s than Type 1s

T_B=0.025 K


log L_X=44
log L_X=43
log L_X=42
Type 2 SFR (M_⊙ yr⁻¹)
Redshift
0
20
40
60
80
0
1
2
3
4



VLA−COSMOS
ECDF−S (AGN)
SSA13
13hr XMM−Newton (AGN)
Suburu/XMM−Newton Deep Field
VLA−VVDS
Phoenix
FIRST
VLA−COSMOS 3 GHz (AGN)
z < 1
1 ≦ z < 3
z ≧3
S²dN/dS (sr⁻¹ Jy^1.5)
dT/d(log S) [mK]
1.4 GHz Flux Density (μJy)

Conclusions

- The AGN radio counts at the μJy level will be dominated by SF in obscured AGNs.
  - Tracking how this SF changes with z and L_X will determine if this is related to the obscuration and AGN fueling properties.
- After updates to the XRB model, and including the latest radio number counts and X-ray->radio conversions, the AGN contribution to the 1.4 GHz radio background remains at most 8%