Fitting AGN/galaxy X-ray-to-radio SEDs with CIGALE and improvement of the code

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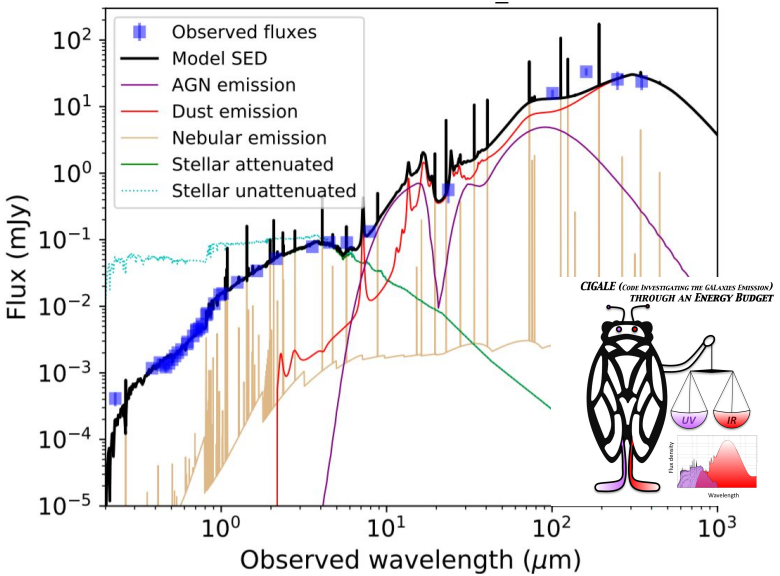
CIGALE: Code Investigating GALaxy Emission

Code Investigating GALaxy Emission (CIGALE; Boquien+2019) is open-source software for spectral energy distribution (SED) fitting.

Physical: CIGALE builds multi-component physical models that obeys energy conservation

Efficient: CIGALE supports parallel computing. A typical Intel i7/i9 desktop can construct 10^8 models within a few hours.

Easy to use: written in Python 3, pip/source installation, self-explanatory configuration files, plotting tools, and etc.



X-CIGALE: extending to X-ray wavelengths

However, CIGALE cannot deal with X-ray data, which are closed related to AGN activity.

We started the “X-CIGALE” project, developing a new **X-ray module** (Yang et al. 2020).

This new module accounts for **both AGN and galaxy** (hot gas & binaries) X-ray emission, although AGN is dominant in most cases.

Other improvements: a clumpy AGN torus model and polar-dust obscuration for type 1 AGN.

Major update: CIGALE v2022.0

X-CIGALE merged into CIGALE

Algorithm improved here and there -> **~50% faster**

More beautiful/organized/informative user interface

Science update (Yang et al. 2022):

1. AGN X-ray anisotropy
2. Adjustable AGN disk SED
3. Radio AGN component

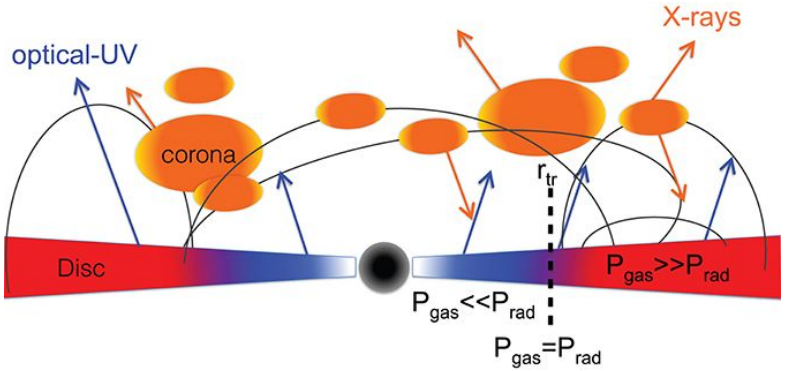
1. X-ray vs. viewing angle

AGN X-ray photons are generated by inverse Compton scattering of seed UV/optical photons from disk

Disk UV/optical emission depends on viewing angle ~ cosθ (1+2cosθ)

X-ray emission must inherit some anisotropy

There's some **observational evidence** for X-ray anisotropy, although most X-ray astronomers simply assume isotropy



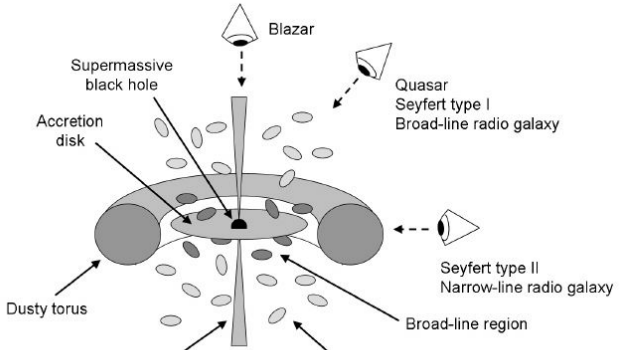
CIGALE v2022 allows X-ray anisotropy

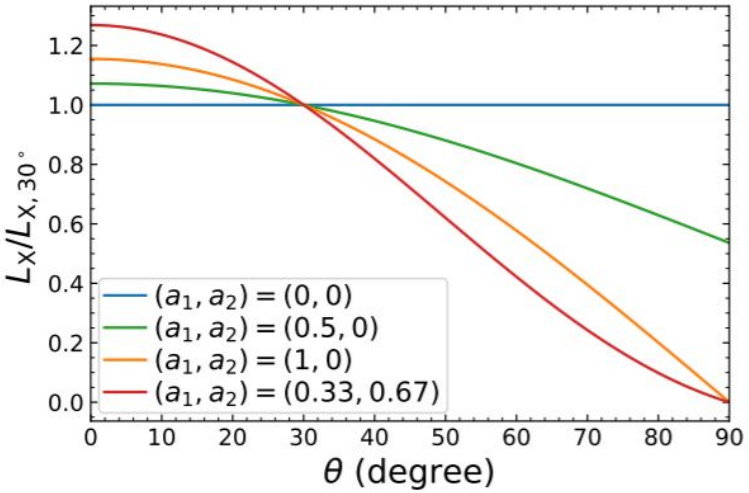
AGN viewing angle $\boldsymbol{\theta}$ is a free parameter in CIGALE

Now we allow L_X varies as **a function of $\boldsymbol{\theta}$**

$$\frac{L_X(\theta)}{L_X(0)} = a_1 \cos\theta + a_2 \cos^2\theta + 1 - a_1 - a_2$$

Three sets of **(a_1, a_2)** are tested in Yang+2022



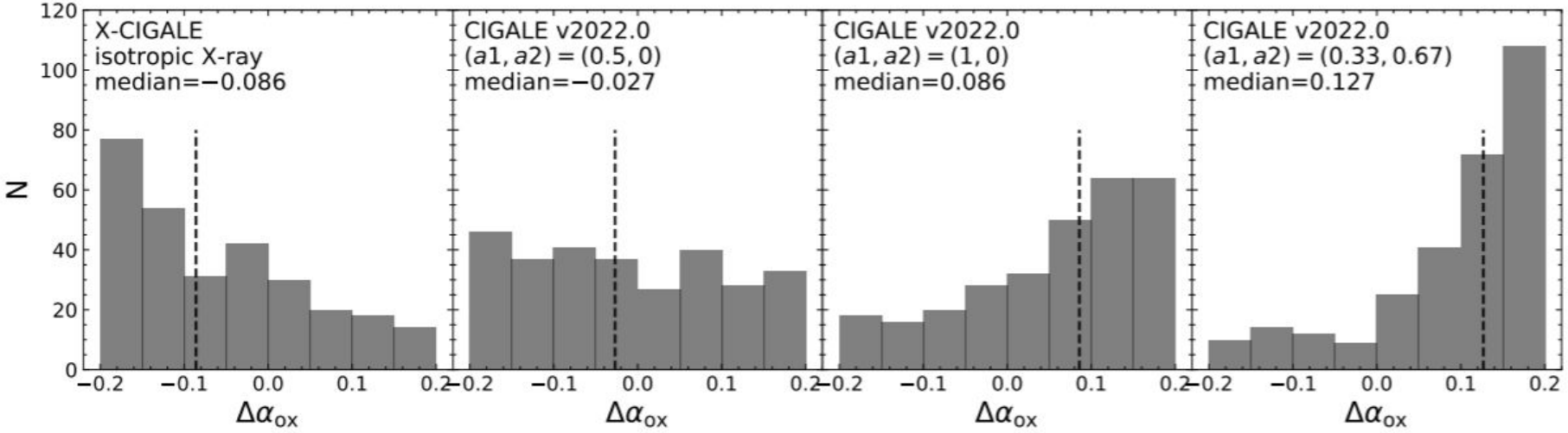


Moderately anisotropic model (a_1/a_2=0.5/0) is preferred

$\boldsymbol{\alpha}_{OX}$ is AGN UV/X-ray slope

$\Delta\boldsymbol{\alpha}_{OX}$ is the offset from the canonical $\boldsymbol{\alpha}_{OX}$-L_{UV} relation

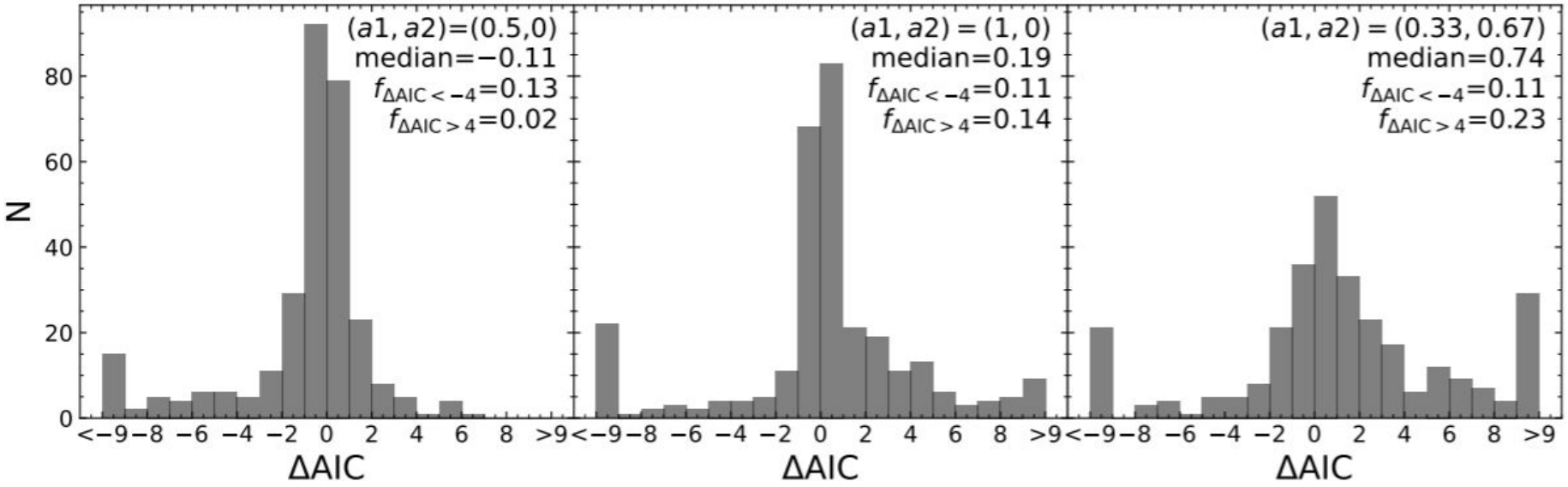
$\Delta\boldsymbol{\alpha}_{OX}$ distribution should **centers around 0**



Moderately anisotropic model (a_1/a_2=0.5/0) is preferred

Akaike information criterion (AIC) measures model quality (**lower -> better**)

ΔAIC = AIC_anisotropic − AIC_isotropic

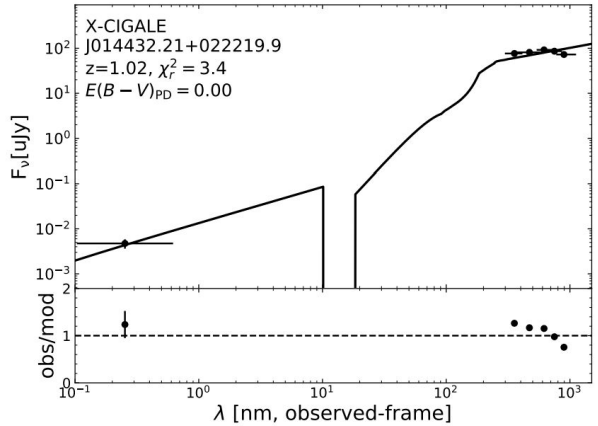


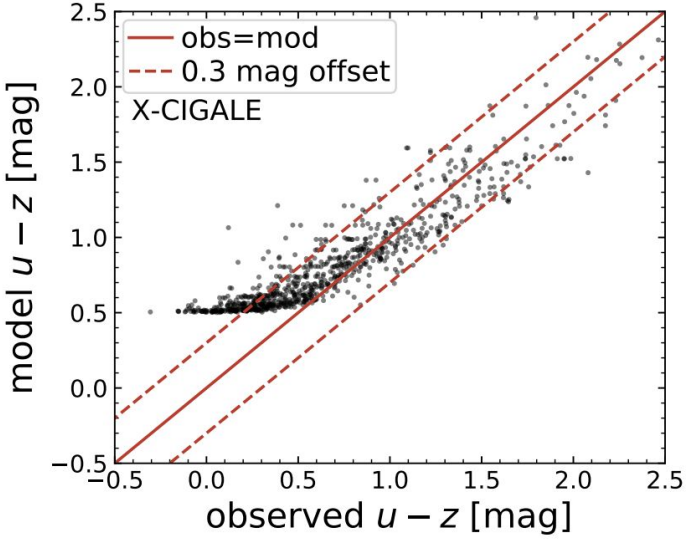
2. AGN disk SED

Previous CIGALE adopts a **single intrinsic SED shape** for AGN UV/optical disk emission (Schartmann et al. 2005)

But observations show AGN have **diversified UV/optical slope**

One way to see this is the observed u-z color is sometimes bluer than the model, which **can't be explained by dust extinction**



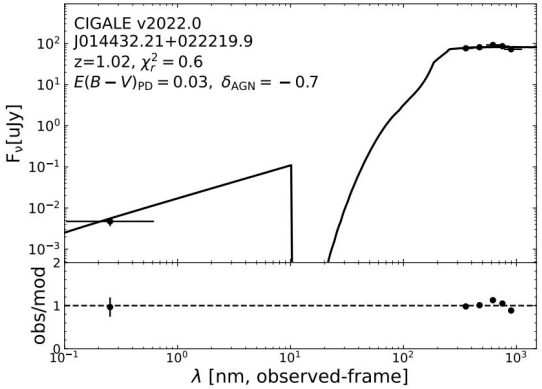


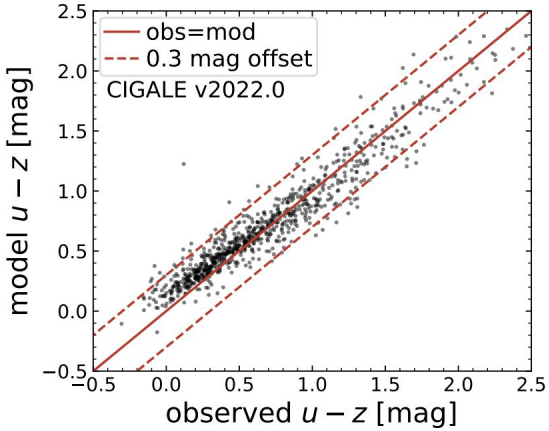
CIGALE v2022 allows adjustable disk slope

CIGALE v2022 introduces a new parameter $\square_{\mathrm{AGN}}$, the **deviation from the original slope**

$$\lambda L_\lambda \propto \begin{cases} \lambda^2 & 0.008 \leq \lambda \leq 0.05\ [\mu\mathrm{m}] \\ \lambda^{0.8} & 0.05 < \lambda \leq 0.125\ [\mu\mathrm{m}] \\ \lambda^{-0.5+\delta_{\mathrm{AGN}}} & 0.125 < \lambda \leq 10\ [\mu\mathrm{m}] \\ \lambda^{-3} & 10 < \lambda \leq 1000\ [\mu\mathrm{m}] \end{cases}$$

By allowing $\square_{\mathrm{AGN}}$ from -1 to +1, the **fit quality is improved**



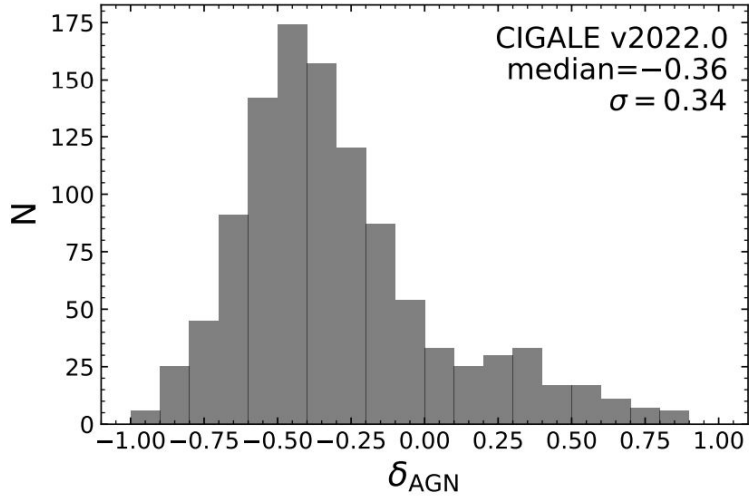


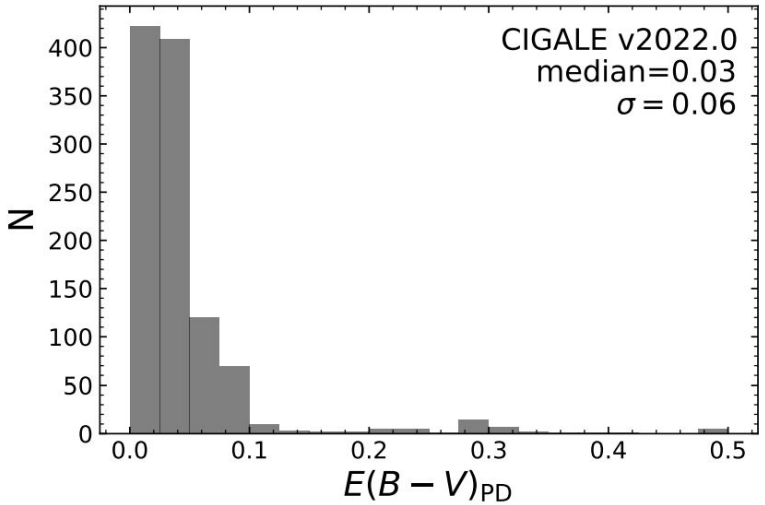
Fitting result

The median δ_{AGN} is negative (-0.36), suggesting typical AGN SED is **bluer than Schartmann template**

A reason might be Schartmann+2005 **doesn't consider dust**

From our fits, the dust extinction is low but non-negligible (median EBV=0.03)



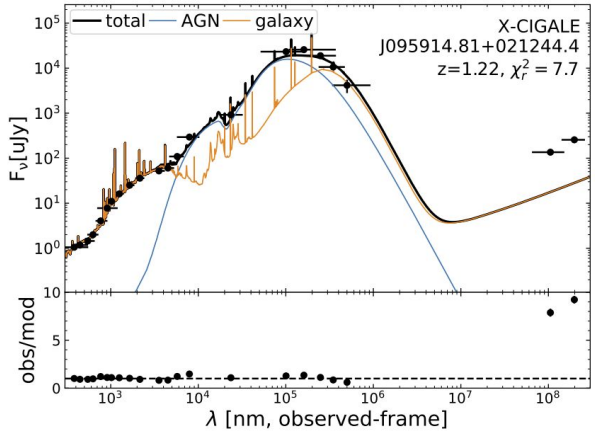


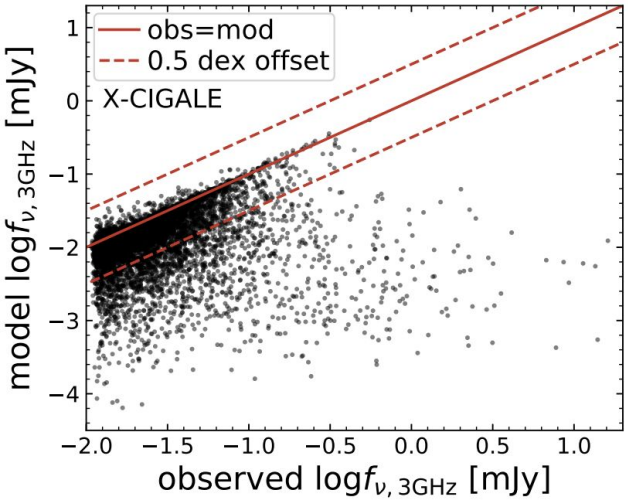
3. AGN radio emission

Previous CIGALE has a radio module, but it only has a SF component (**no AGN**)

In our COSMOS test sample, many sources have observed 3 GHz fluxes beyond the expectation from SF (lead to over-estimated SFR)

This "**radio excess**" strongly suggests AGN radio emission





CIGALE v2022 introduces AGN radio emission

The new AGN component is a simple **power law** with two free parameters

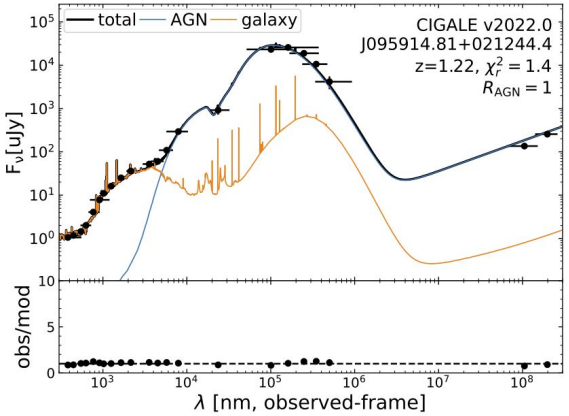
$$L_{\nu,\mathrm{AGN}} \propto \nu^{-\alpha_{\mathrm{AGN}}}, \quad R_{\mathrm{AGN}} = \frac{L_{\nu,5\mathrm{GHz}}}{L_{\nu,2500\text{Å}}},$$

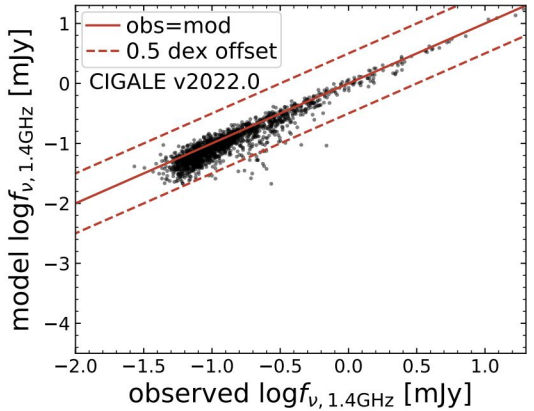
α_{AGN} controls the **shape**

R_{AGN} controls the **normalization**

In our fits, α_{AGN} is fixed to 0.7 (typical value for radio AGN)

R_{AGN} is allow to vary in a wide range from 0.01 to 10000



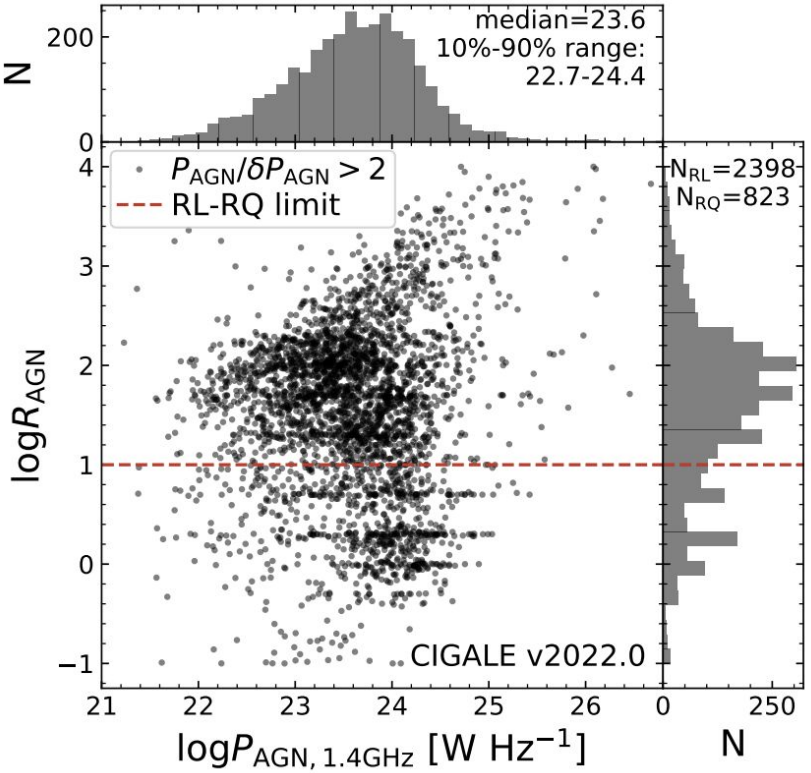


Fitting result

~50% radio selected sources have a statistically significant (>2**σ**) AGN component

These AGNs have a **wide R_{AGN} range**, from 0.1 to 10000, so that AGN radio emission is not well correlated with disk

Adopting a traditional radio-loud vs. quiet classification (R_{AGN}=10), most (74%) of the radio-selected AGNs are **radio loud** (likely powered by jet)



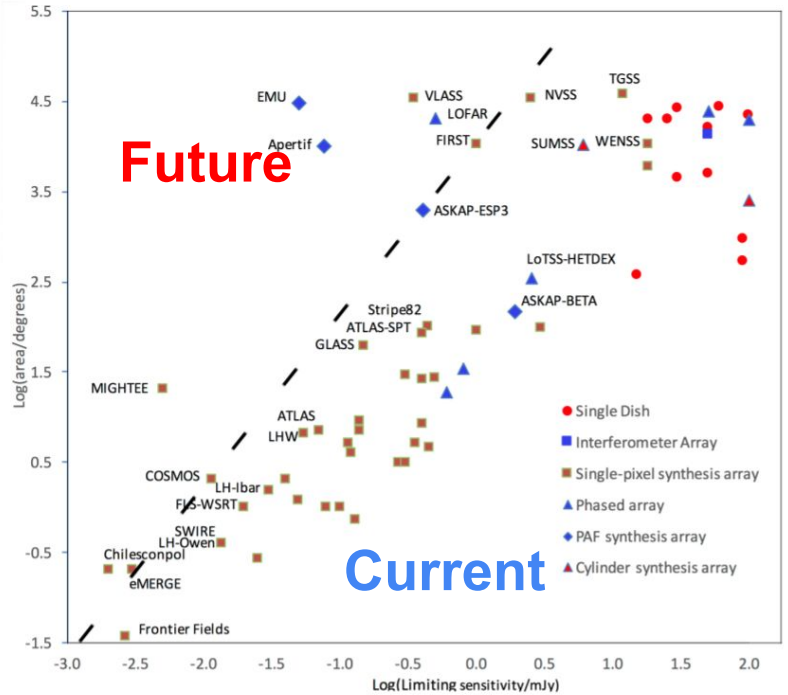
Future: BIG radio data are coming

Current radio surveys are either wide/shallow or narrow/deep. But future radio surveys will be both wide and deep.

LOFAR two-metre Sky Survey (LoTSS, ongoing): low-frequency (120-168MHz), entire northern sky (Shimwell+2017).

LOFAR+multiwavelength SED modeling is on the way (Małek in perp.)

DSA-2000 (2026, 0.7-2 GHz), **SKA** (2027, 70 MHz-10 GHz), and **ngVLA** (2028, 1.2-116 GHz)



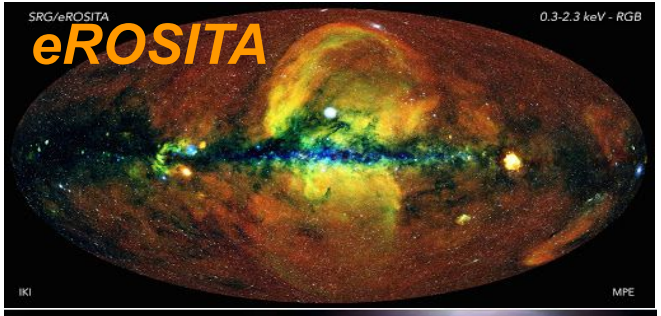
Norris et al. 2017

Other multiwavelength data will be available too

Other multiwavelength data are also needed for SED modelling of radio-selected sources.

Wide/all-sky multiwavelength surveys from X-ray to IR will be available in the near future, e.g.,

- ***eROSITA*** (ongoing) all-sky X-ray
- ***巡天/CSST*** (2024) UV/optical 17500 deg^2
- ***Euclid*** (2022) NIR survey 15000 deg^2
- Others: **Rubin** (LSST, 2022), ***Roman*** (WFIRST, 2025), ***JWST*** (2021 Nov.), ***Athena*** (2031)



Summary

CIGALE is a powerful SED-fitting software that can model **radio-to-X-ray** data with AGN+galaxy components.

We have improved CIGALE in three aspects: **X-ray anisotropy, adjustable UV/optical slope, and radio AGN emission**.

In the future, CIGALE can be applied to the **big survey data** from radio telescopes such as LOFAR, SKA, and ngVLA and other multiwavelength telescopes such as *eROSITA*, *巡天/CSST*, and *Euclid*.

Check our our website for the latest release (v2022.0) and the developing versions of CIGALE: https://cigale.lam.fr/