Explaining the mm Excess in Radio-Quiet AGN

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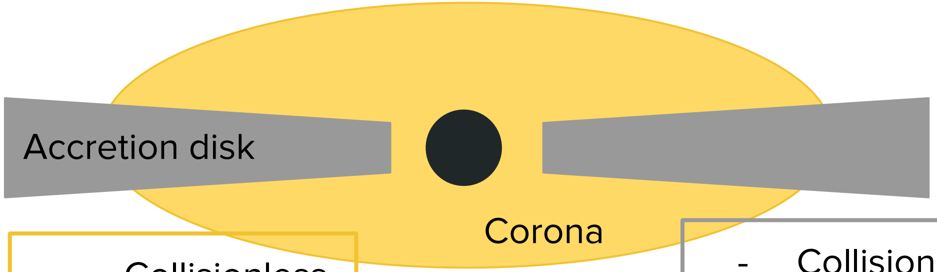
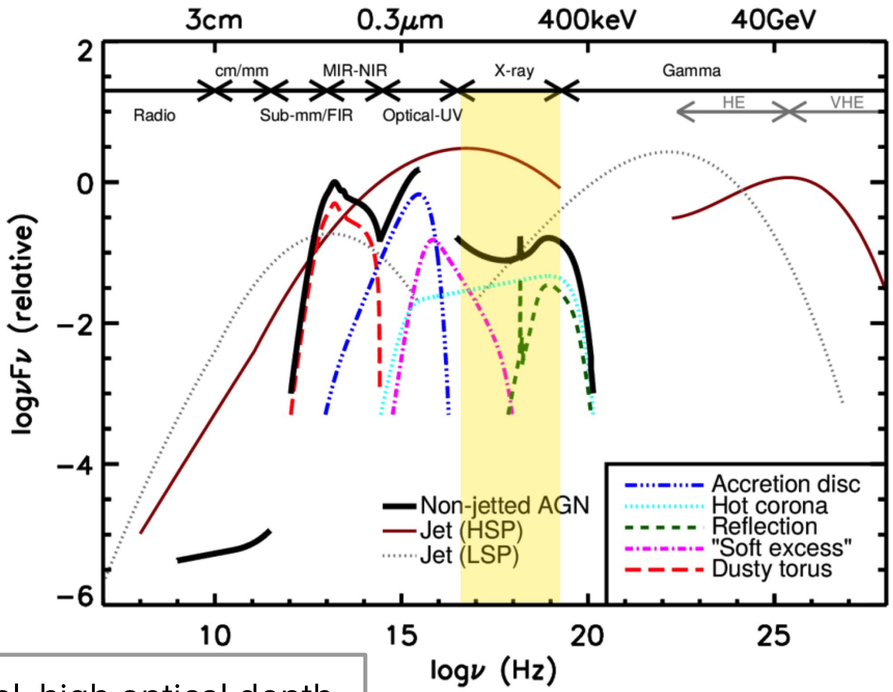
The X-ray Corona Probes Region Closest to Black Hole

- Present in XRBs and AGN
- Population of hot electrons (1e9 K), collisionless --> nonthermal particle acceleration possible
- Within 10 rg --> probes spacetime of the black hole



- Collisionless
- Hot (10^9 K)

- Collisional, high optical depth
- Cold (10^5 K for AGN)



Kim+ 2024

A Magnetically-powered X-ray corona

- Compact: R_c≂10 rg from timing, reverberation studies
- Hot: T_e≂10^9 K
- Dissipated magnetic energy = X-ray luminosity: $L_X \leq \frac{B_0^2}{8\pi} 4\pi R_c^2 c$

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Reconnection or turbulence accelerates nonthermal particles

→ Power-law of electrons

Where is the synchrotron emission?

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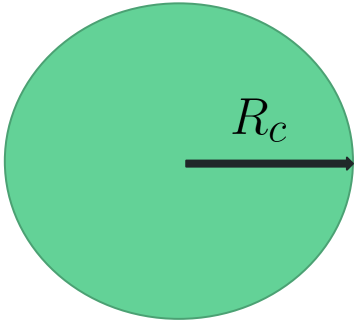
Radio, mm wavelengths

- Radio-quiet AGN: no jet contamination
- Compact -- close to 10 rg



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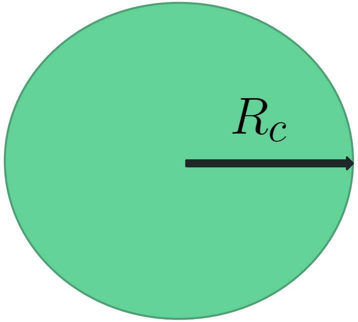
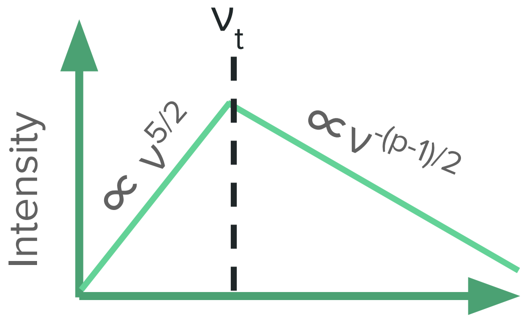


Synchrotron self-absorption



$$\nu_t = 10^{13}\ \mathrm{Hz} \left(\frac{R}{10 r_g}\right)^{1/3} \left(\frac{B}{10^3\ \mathrm{G}}\right)^{2/3}$$

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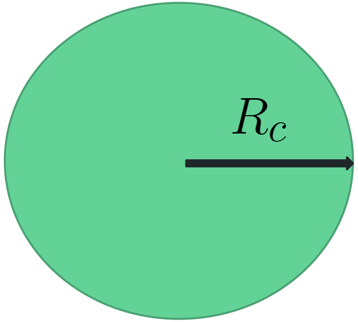

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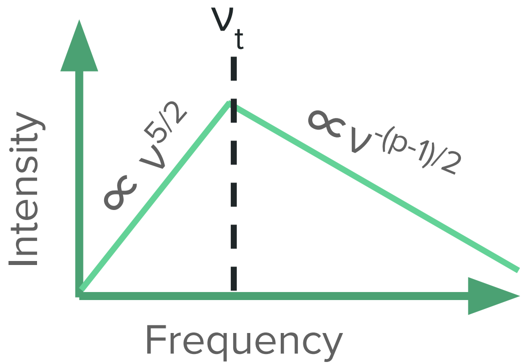

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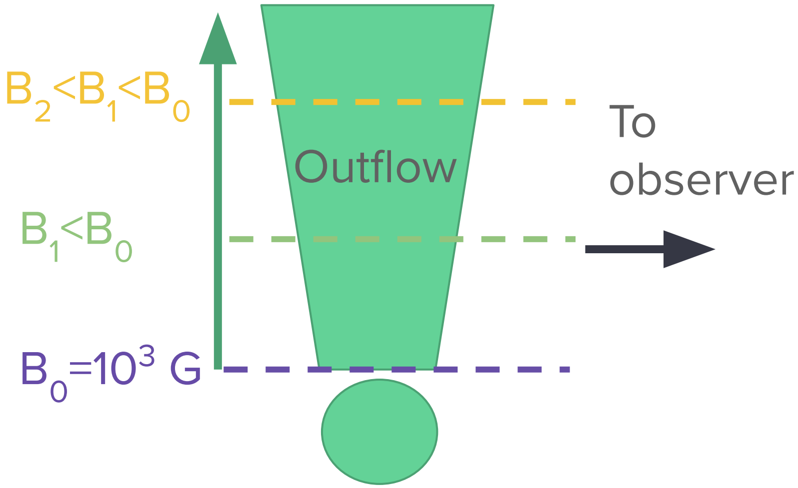
Wipes out synchrotron emission from coronal electrons! Unless...

Proposal: an extended (coronal) outflow

- Magnetic field gradient: higher frequencies from smaller radii (higher B)
- Mildly relativistic (no beaming), as in winds in GRMHD simulations



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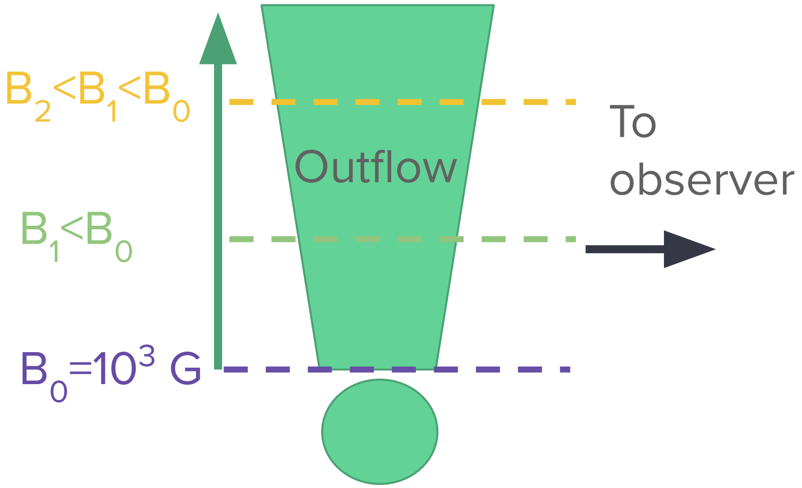
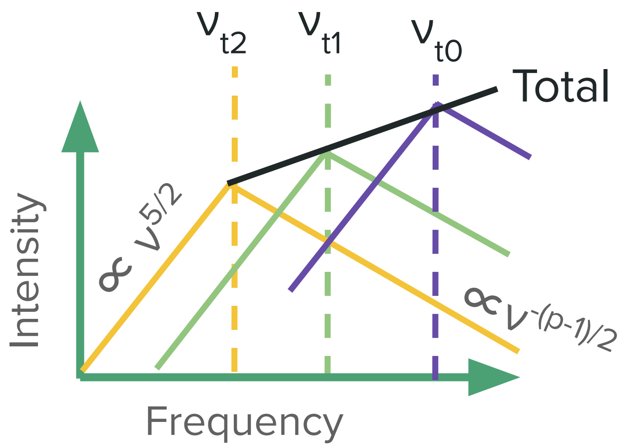
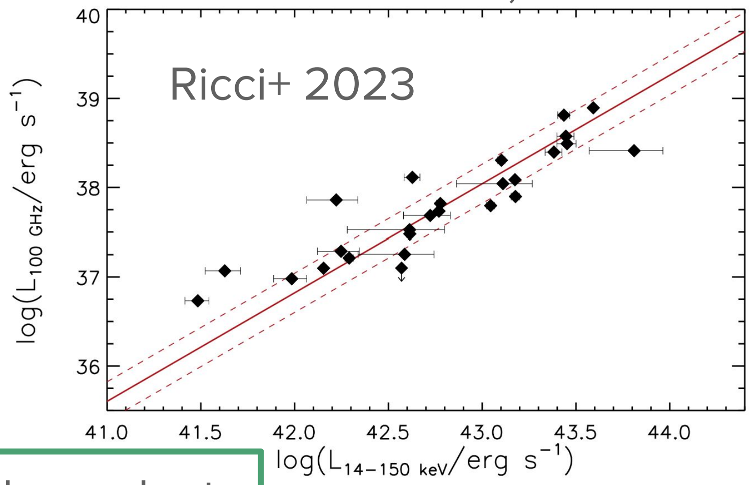


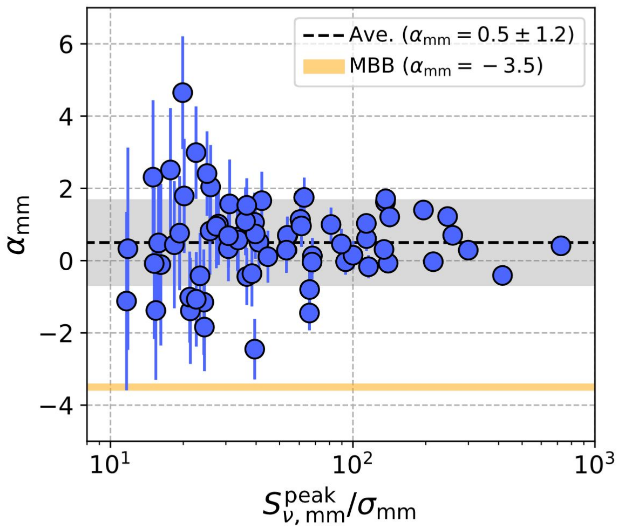


Characteristics of the mm excess

Lmm/LX: linear, 1e-5

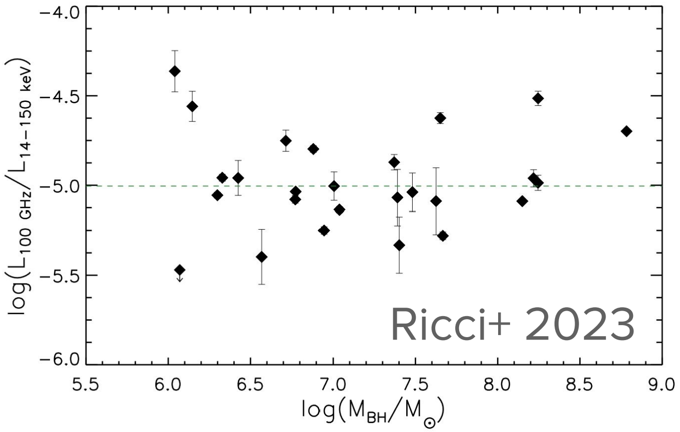


Flat Spectral Slope



Kawamuro+ 2022

Lmm/LX: mass-independent



Also: variability, time lags?

Analytic Prediction for Flux Spectral Index

Sum up contributions from different wind heights.

- Flatter spectrum than $\nu^{5/2}$

$$F_\nu \sim \nu^{\alpha_F}$$

Depends on density, B, nonthermal particle profiles

Observationally:
α_F= -0.5±1.2

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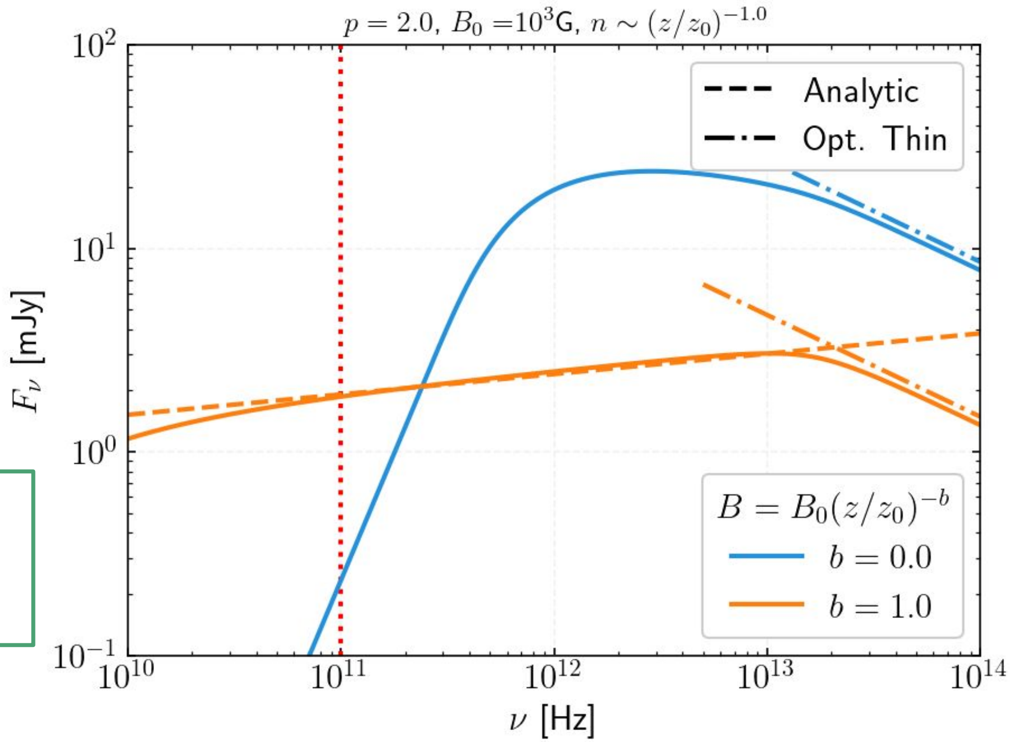


Analytic Prediction for Lmm/LX

- X-ray luminosity from magnetic reconnection or turbulence: $L_X \sim B_0^2$

B_0 probably not constant with M

$$\frac{L_{\rm mm}}{L_X} \sim \nu^{\alpha_F+1} B_0^{\beta_F-2}$$

Analytic Prediction for Lmm/LX

- X-ray luminosity from magnetic reconnection or turbulence: $L_X \sim B_0^2$
- Particle acceleration: depends on plasma magnetization σ_0 rather than B_0
  - Magnetic energy per particle --> needs to be greater than 1
  - Values of 10 - 100

B_0 probably not constant with M

$$\frac{L_{\rm mm}}{L_X} \sim \nu^{\alpha_F+1} B_0^{\beta_F-2}$$

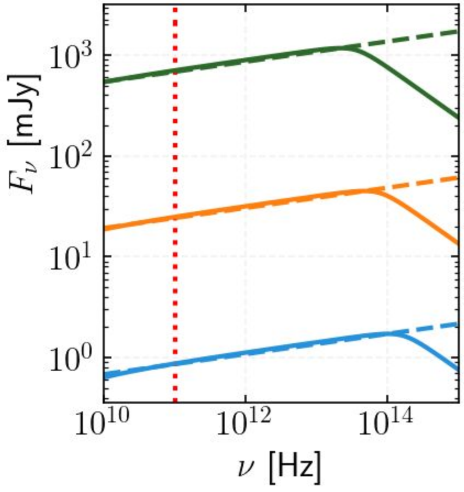
$$\sim \nu^{\alpha_F+1} \sigma_0^{\beta_F/2-1} M^{1-\beta_F/2}$$

σ_0 probably **is** constant with M

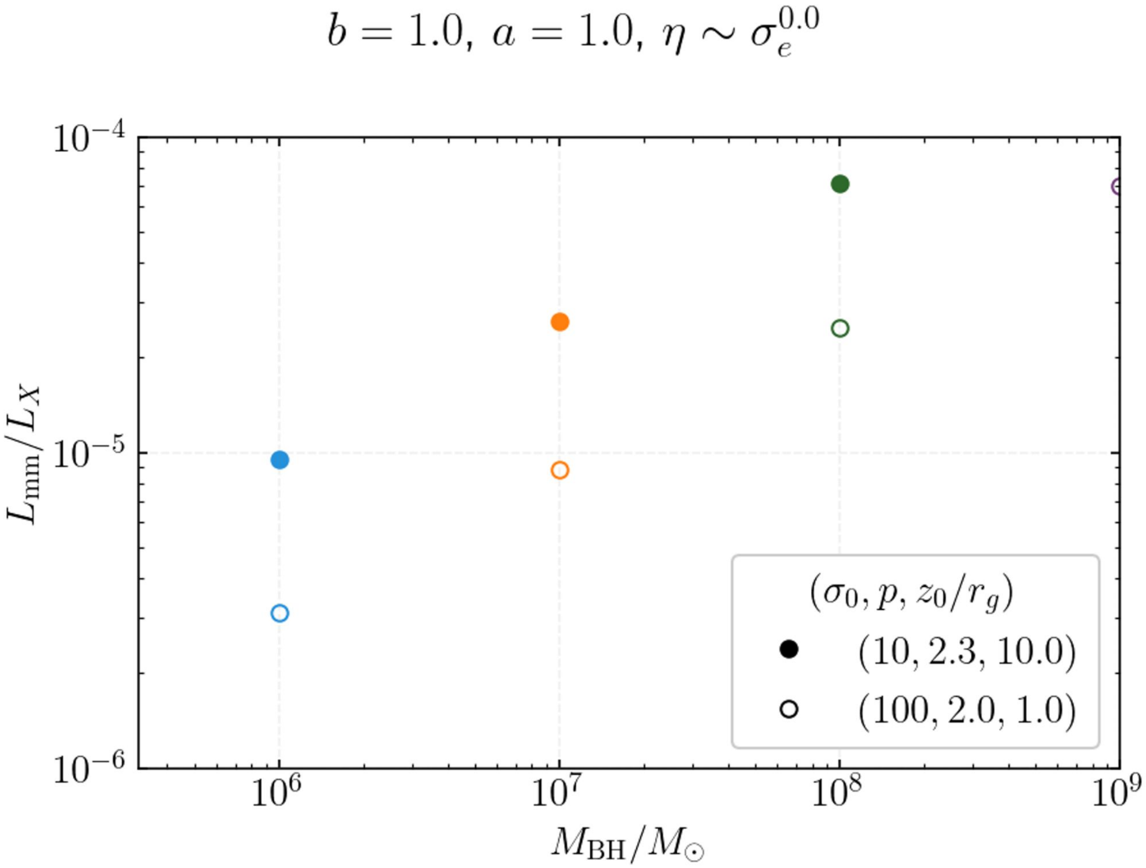
This exponent should be ≈0

Case Study

- Fix magnetic field, density profile



Close to mass-independent



Hankla+ in prep

Implications for variability, simultaneous X-ray/mm

- Observations of mm variability on 1e4 s time-scales constrain source size to be <~ 1000 rg (Petrucci+ 2023, Michiyama+ 2024, Shablovinskaya+ 2024)
  - Expected in extended source: 100 GHz emission comes from 100 rg

$$t_{\rm sync} = 5\times 10^3\ {\rm s} \left(\frac{\gamma}{10}\right)^{-1} \left(\frac{B}{100\ {\rm G}}\right)^{-2}$$

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- Correlation between X-ray/mm could be tricky
  - Not the same electrons radiating X-ray and mm. Need to be re-accelerated!
  - Contributions from multiple heights

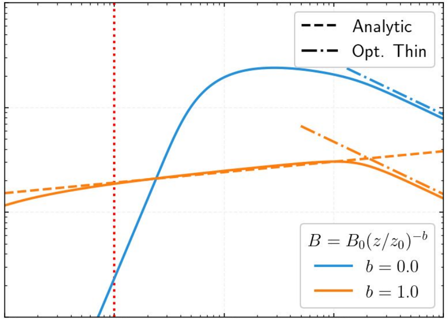
Conclusions

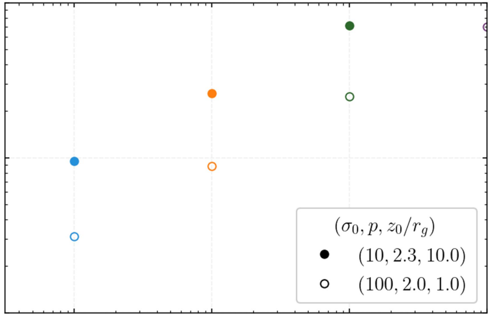
Importance: mm emission could probe dissipation in the corona. Continual reacceleration mechanism?

Strong magnetic fields in a compact region --> synchrotron self-absorbed --> mm must come from **extended region** --> inhomogeneous coronal outflow.

Reproduces observations:

- Flat spectral slope at 100 GHz
- Lmm/LX approx. 1e-5, close to mass-independent





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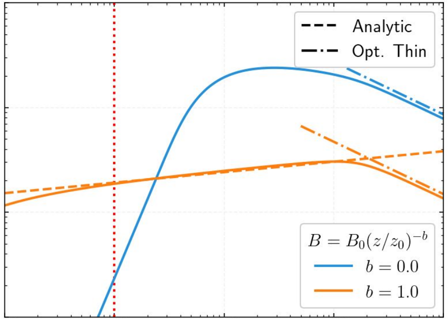
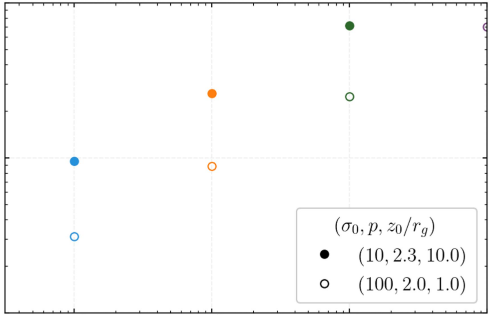
Questions?





Back-up slides

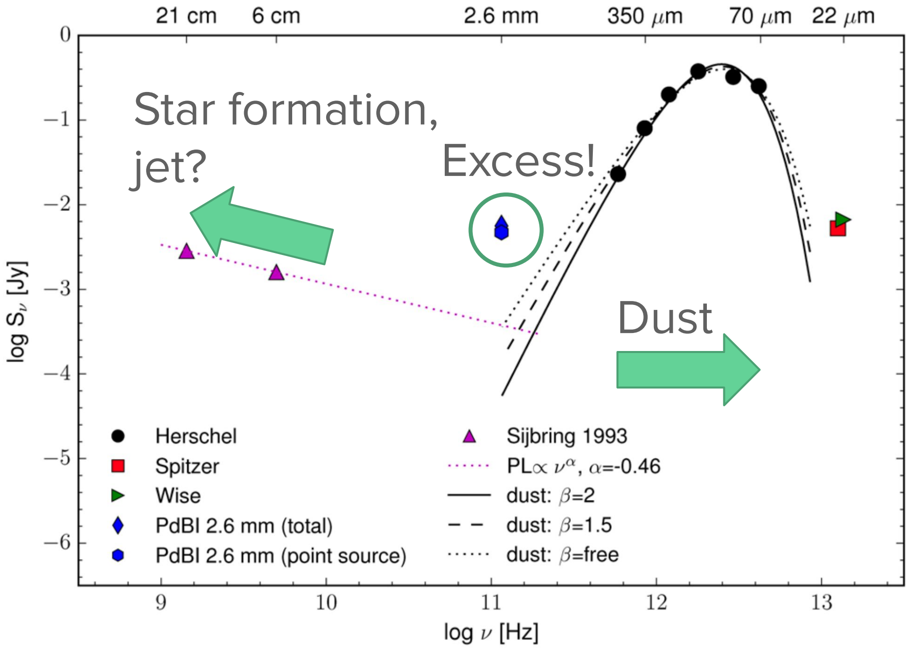
Observed excess in mm emission from RQ AGN

- Dust dominates above ~300 GHz
- Star formation important <~10 GHz

--> Excess in mm

- Observed in tens of radio-quiet AGN (e.g. Kawamuro+ 2022, Ricci+ 2023)

Scharwaechter+ 2016



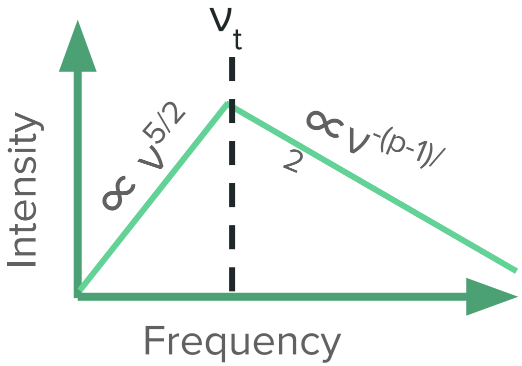
One-zone Model for the mm Excess

Emission from the "corona": a compact (<100 rg), uniform, magnetized sphere.

Problems:

- Radio spectra don't show $I_\nu \propto \nu^{5/2}$ (expected if opt. thick)
- Magnetic field of ~10 G not high enough to be magnetically heated

Synchrotron self-absorption



Solve system of two equations

Unknown

From spectrum

$$1 = \tau_{\nu_t} = \alpha_\nu R \approx B^{(p+2)/2} \nu_t^{-(p+4)/2} R$$

$$F_{\nu_t} = j_\nu \frac{V}{4\pi d^2} \approx B^{(p+1)/2} \nu_t^{-(p-1)/2} R^3$$

Cooling and Compactness

$$\sigma_e = \frac{B^2}{4\pi n_e m_e c^2} = \frac{B^2}{4\pi n_e m_e c^2}\frac{\sigma_T r_c}{\sigma_T r_c} = 2\frac{\ell_B}{\tau}$$

$$\ell_B \sim U_B \sim \frac{\ell_{\mathrm{rad}}(U_X)}{\beta_{\mathrm{rec}}}$$

- Radiative compactness: 1 - 100; Reconnection rate: ~0.1 --> magnetic compactness 10 - 1e3. With tau=1, also has sigma of 10 - 1e3

Wind Assumptions

- Mass and flux conservation
- Wind magnetization decreases with height
- Wind velocity increases/constant with height
- Number density from Thomson optical depth = 1
- Rc = 10 rg, Rw0 = 10 rg
- Dissipation happens when wind is sub-Alfvenic

Inoue & Doi 2018

Assumptions:

- SSA peak flux = 10 mJy, turnover frequency = 100 GHz
- Energy fraction in nonthermal electrons = 4%

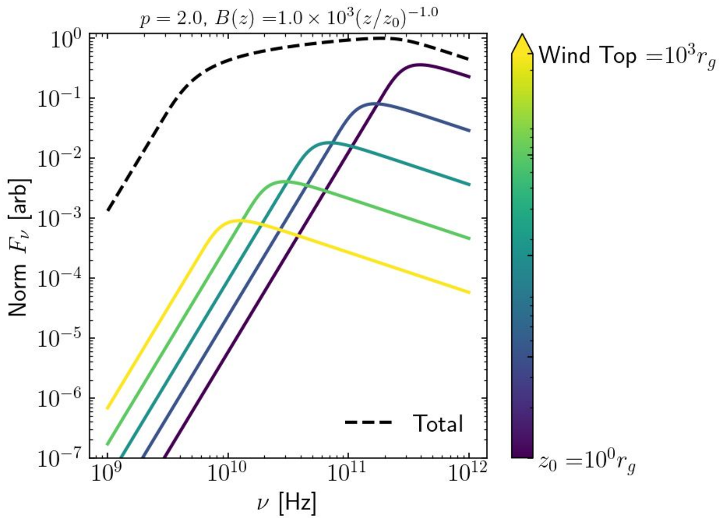
Findings

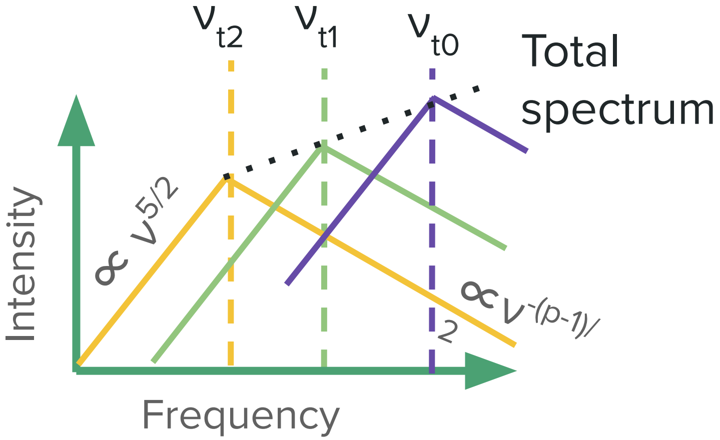
- R≂40 rg, B≂10 G, p=2-3

$$\alpha_F = \frac{5}{2} + \frac{(p+4)(r+b/2+1)}{2(r-a-d)-b(p+2)} = \frac{5}{2} - \frac{\gamma_F}{2}(p+4)$$

$$\beta_F = -\frac{1}{2} - \frac{(p+2)(r+b/2+1)}{2(r-a-d)-b(p+2)} = -\frac{1}{2} + \frac{\gamma_F}{2}(p+2)$$

$$\gamma_F = \frac{-2(r+b/2+1)}{2(r-a-d)-b(p+2)}.$$


$p = 2.0,\ B(z) = 1.0 \times 10^3 (z/z_0)^{-1.0}$
Norm F_ν [arb]
ν [Hz]
Total
Wind Top $= 10^3 r_g$
$z_0 = 10^0 r_g$


ν_{t2}
ν_{t1}
ν_{t0}
Total spectrum
Intensity
Frequency
$\propto \nu^{5/2}$
$\propto \nu^{-(p-1)/2}$

Dust

From Scharwaechter+ 2016: assume dust grains have a single temperature Td, it's optically-thin, neglect power-law component at shorter wavelengths. Fit gives Td/(1+z) ~ 24 K

- What is the beta parameter?
- T of 15 - 25K: stars (young or old) heat interstellar dust
- T of 30 - 40 K: young O and B stars heat dust in star-forming regions (they cite Cog, Kruegel, Mezger 1986)

Radio Slope Extrapolation

- Two sources: star-formation and jet.
  - Jet has synchrotron power-law, so can extrapolate to higher frequencies assuming spectral slope is constant
  - Star formation is tricky. Relies on different methods; seems to predict lower than observed.
- Outstanding question for me: if the 1.4, 5 GHz emission comes from a synchrotron-emitting jet, why is it so quiet? Is it not observed in extended emission? That should be separate from the coronal emission?
  - Is the low radio emission extended or compact?

Scharwaechter+ 2016 Detail

Mostly from Sec. 4.3

- Get expectation for 2.6 mm flux from two data points (one at 1.4 GHz, one at 5 GHz), which have Snu ~ nu^-0.46. Extrapolate to 2.6 mm and find the observed value exceeds the prediction by a factor of 10.
- Free-free emission from HII regions have Snu ~ nu^-0.1 in the 1.4 - 10 GHz range. The flat SED from radio to mm (indicated by the high value of 2.6 mm flux) can't be explained by Snu ~ nu^-0.1 --> AGN contribution
- SFR rate suggests something else (AGN? jet?) contributing to radio
    - Get SFR rate from CO; Get independent SFR from correlation of IR and radio --> suggests SFR 10 times higher than CO rate --> contribution from non starforming mechanism.