SGR A* EMISSION PARAMETRIZATIONS FROM GRMHD SIMULATIONS

Richard Anantua

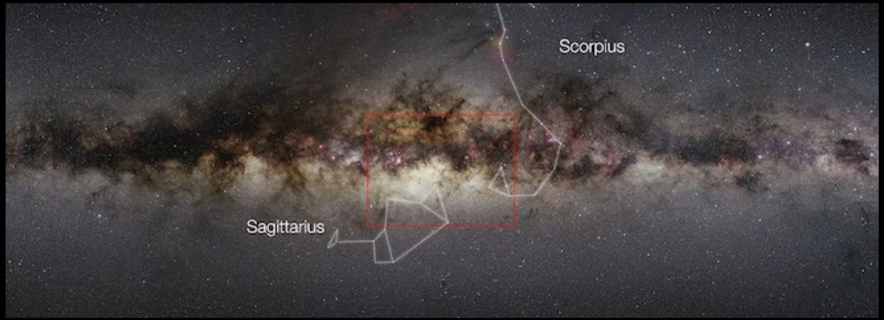
Collaborators: Sean Ressler and Eliot Quataert (UC Berkeley)

Invited Talk at City College of San Francisco

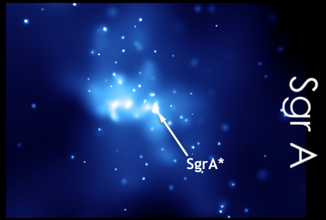
2-21-2018

GALACTIC CENTER: HOME SWEET HOME

- The Milky Way hosts a low luminosity active galactic nucleus (AGN) at its center



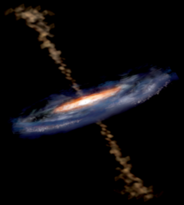
- The Galactic Center radio source Sgr A at d=7.86kpc (Boehle et al., 2016) has a relatively bright, non-thermal region, Sgr A*, surrounding a supermassive black hole

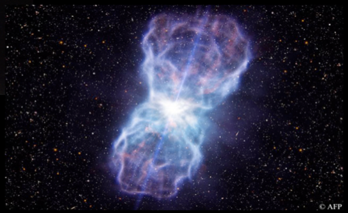


- Central black hole mass: $4\text{x}10^6 M_{\odot}$ (Boehle et al. 2016)
- Sgr A* luminosity: $L_{SgrA*} = 10^{-9} L_{Edd} - 10^{-10} L_{Edd}$ (Sabha et al., 2018); $L_{SgrA*} \lesssim 10^{37}$ erg/s = 2600 $L_{\odot}$ (Narayan et al. 1998)

BLACK HOLES IN ASTRONOMY

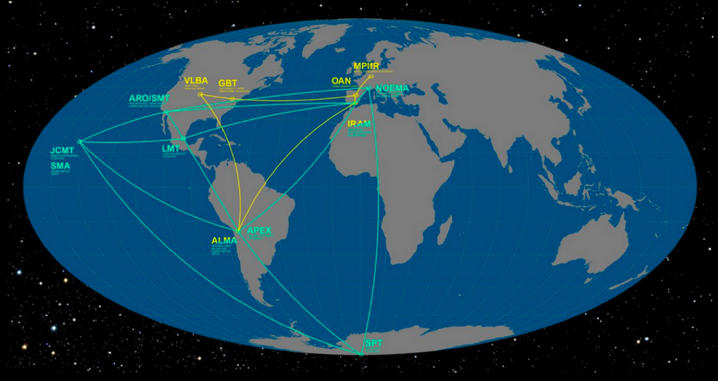
- Remnants of stars >4 $M_{\odot}$ produce black holes when the star runs out of nuclear fuel or degeneracy pressure counteracting gravitational collapse
- If a black hole is formed from a star that was in a binary system, it accretes the companion star, producing x-ray radiation
- Supermassive (10^6-10^{10} $M_{\odot}$) black holes form via mergers and accretion
- Relativistic jets of radiating cosmic rays can be ejected from the poles of black holes in:
    - AGN
    - BH/X-Ray binaries
    - Gamma ray bursts

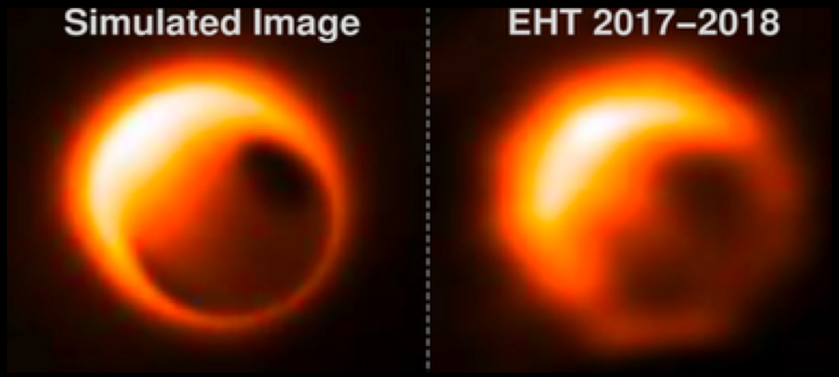




BLACK HOLES - OBSERVATIONS

- The Event Horizon Telescope is a collection of radio antennae forming a network of intercontinental baselines to form mm-images





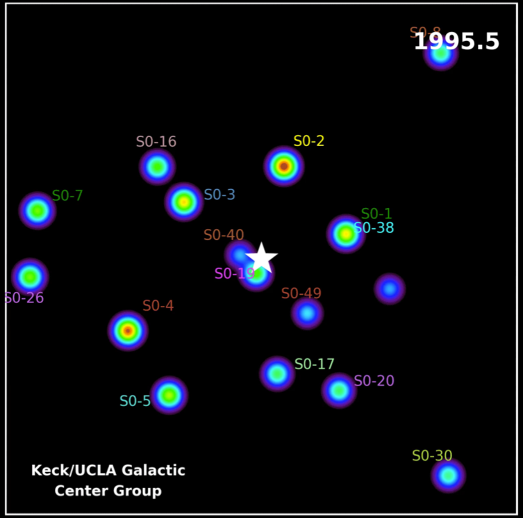
Confer: http://news.nationalgeographic.com/2017/04/black-hole-event-horizon-telescope-pictures-genius-science/

- Baselines of radio telescopes are very long in view of the angular resolution limit:

$$\Delta\theta_{\mathrm{min}} = 1.22 \frac{\lambda}{D_{\mathrm{aperture}}}$$

SGR A* OBSERVATIONS: MASS ACCRETION RATE

- $\dot{M} \lesssim 2\text{x}10^{-7} M_{\odot}$/yr (Marrone et al. 2007)
- Stars in the inner parsec of the Galactic Center Sgr A* (Courtesy of UCLA Galactic Center Group): http://www.galacticcenter.astro.ucla.edu/animations.html

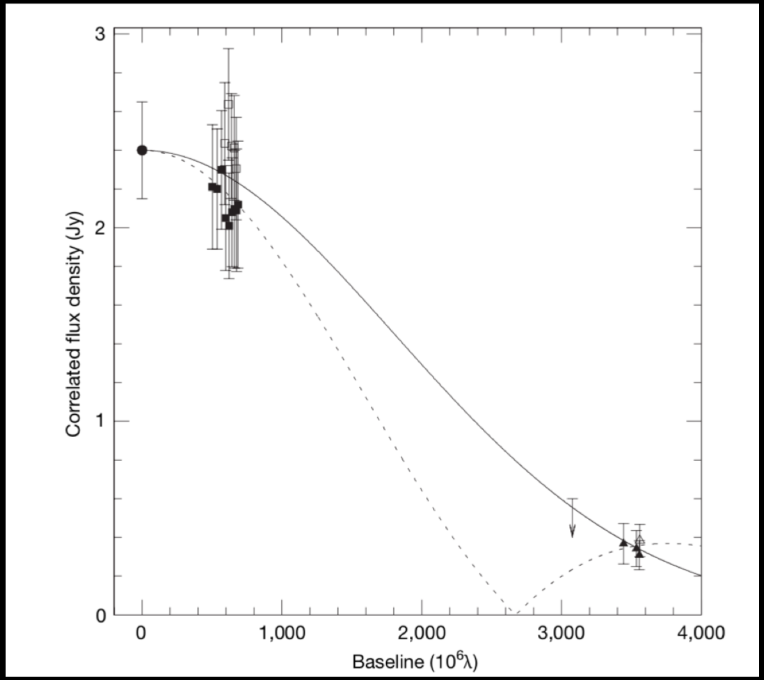


WR 124 in Sagittarius

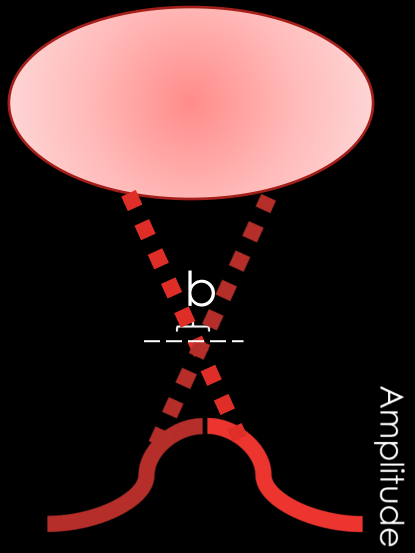
- Wolf-Rayet stars, which are hot w./ strong winds, accrete the most onto Sgr A*

SGR A* IMAGE SIZE CONSTRAINTS

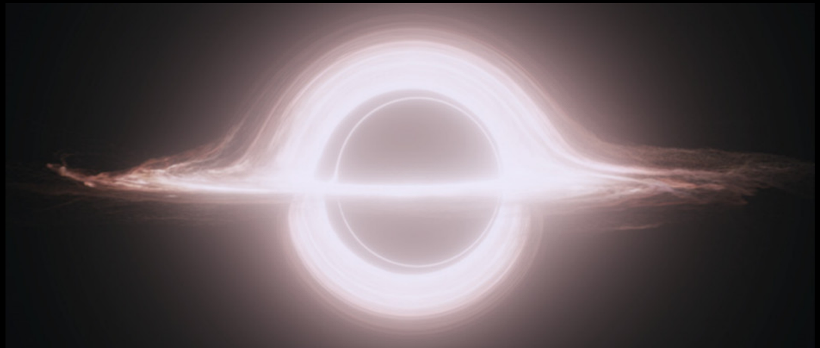
- EHT size constraints
  - Intrinsic size: $37^{+16}_{-10}\mu as$
  - Scattering size: $43^{+14}_{-8}\mu as$



Doeleman et al., 2008

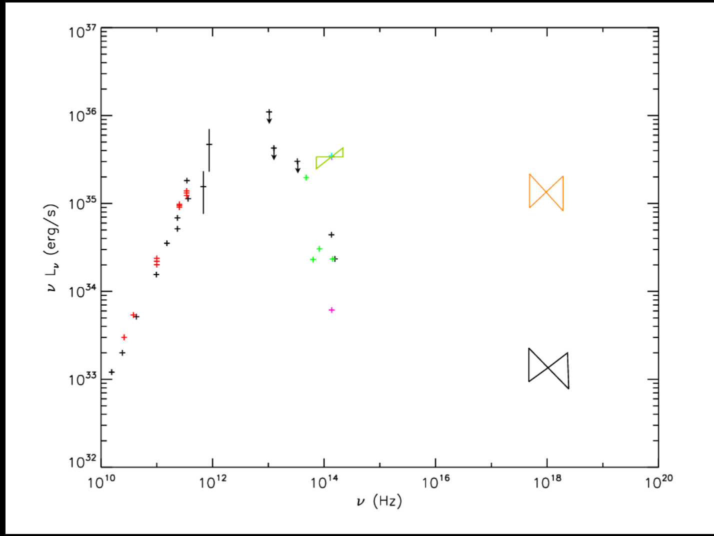


- Photon ring?



SGR A* OBSERVATIONS: SPECTRAL FLUX DENSITY

- Sgr A* spectrum from 10^{10}Hz microwaves to 10^{20}Hz X-rays
- Sub-mm ($\gtrsim 3\times10^{11}$Hz) bump in IR



(Falcke and Markoff 2013)

- Spectral flux density observations
  - 1.3 Jy at 32 GHz in ApJ (Bower et al. 2015)
  - 2.4 Jy at 230 GHz by EHT in Nature (Doeleman et al. 2008)

QUESTIONS

- *Can models of intuitive phenomenological emission mechanisms in general relativistic magnetohydrdynamic simulations reproduce Sgr A* observations?*

Some models reproduce some observational signatures better than others

- *Can a single parametric model describe Sgr A* emission over regions including disk, disk wind and outflow?*

Probably–
but not the obvious disk or jet emission models,
nor simple combinations thereof

SIMULATION: ASSUMPTIONS AND FLUID EQUATIONS

- Assumptions (Ressler et al. 2015, 2017)
  - Electrons radiate heat more efficiently than protons: $T_e << T_p$
  - Accretion dynamical time shorter than timescale of Coulomb collisions between leptonic (e+e-) and hadronic plasmas (p,ions) => Two-temperature model
  - Mass accretion rate – $\dot{M}$ determines normalization of spectral flux summed over intensity maps in various models at a chosen frequency
- GRMHD mass conservation and energy-momentum equations

$$\partial_\mu(\rho u^\mu) = 0$$

$$\partial_\mu T^{\mu\nu} = \nabla_\mu\left(T_g^{\mu\nu} + T_{EM}^{\mu\nu}\right) = -\tau^{\mu\nu}$$

  - Stress-energy-momentum tensor with viscous and heating terms

$$T_e^{\mu\nu} = (\rho_e + u_e + P_e)u_e^\mu u_e^\nu + P_e g^{\mu\nu} + \tau_e^{\mu\nu} + q_e^\mu u_e^\nu + q_e^\nu u_e^\mu$$
$$T_p^{\mu\nu} = \left(\rho_p + u_p + P_p\right)u_p^\mu u_p^\nu + P_p g^{\mu\nu} + \tau_p^{\mu\nu}$$

- Entropy governed by Vlasov eq. and 1st moment, and entropy eq.

$$s = \frac{\ln P\rho^{-\gamma}}{\gamma - 1}$$

$$\frac{\partial f}{\partial t} + \vec{\mathrm{v}}\cdot\vec{\nabla}_{\vec{\mathrm{x}}} f + \frac{q}{m}\left(\vec{E} + \frac{1}{c}\vec{\mathrm{v}}\times\vec{B}\right)\vec{\nabla}_{\vec{\mathrm{v}}} f = 0$$
$$\partial_\mu T_e^{\mu\nu} = -enu_e^\mu F_\mu^\nu, \qquad \partial_\mu T_p^{\mu\nu} = enu_p^\mu F_\mu^\nu$$

$$\rho T_e u^\mu \partial_\mu s_e = Q_e - \partial_\mu q_e^\mu - a_\mu q_e^\mu$$

KEY PARAMETERS

- Plasma beta

$$\beta = \frac{P_g}{P_b} = \frac{(\gamma - 1)u_g}{b^2/2}$$

- Bias, or magnetic dominance, N=2n

$$P_g \sim b^{2n}$$

- Electron heating fraction f_e

$$Q_e = f_e Q$$

EMISSION MODELS AND RADIATIVE TRANSFER

- Electron temperature model
  1) Constant T_e/T_p at beta<<1
  2) T_e suppressed at beta>>1

$$\frac{T_e}{T_{\rm sim}} = f_e \,\mathrm{Exp}[-\beta/\beta_c]$$

- Constant β model

$$\beta = \frac{P_g}{P_b} = \frac{(\gamma-1)u_g}{b^2/2} \Longrightarrow u_g = \frac{1}{(\gamma-1)}\beta\frac{b^2}{2}$$

Equipartition for $P_g \sim P_b$

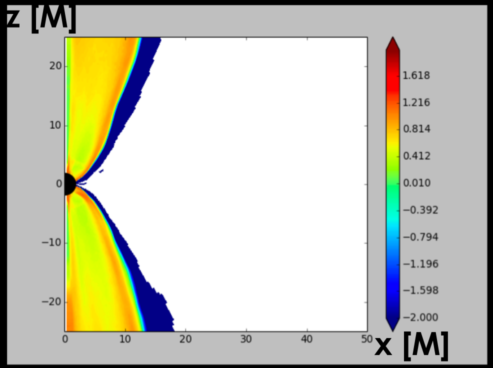
- Bias model

$$P_e = K_N\left(\frac{b}{\sqrt{2}}\right)^N, \qquad K_N = K_2\frac{\langle\frac{b^2}{2}\rangle}{\langle\left(\frac{b}{\sqrt{2}}\right)^N\rangle}, K_2 = \beta$$

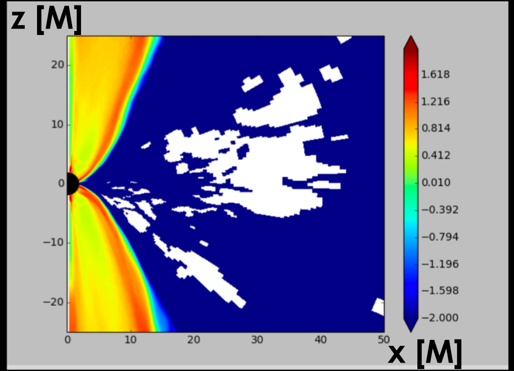
- Postprocessing
  - Intensity maps computed using IBOTHROS (Noble et al. 2007) for radiative transfer
  - Spectra computed using GRMONTY (Dolence et al. 2009) Monte Carlo ray tracing

SIMULATION ELECTRON TEMP PROFILES: ELECTRON TEMPERATURE MODEL

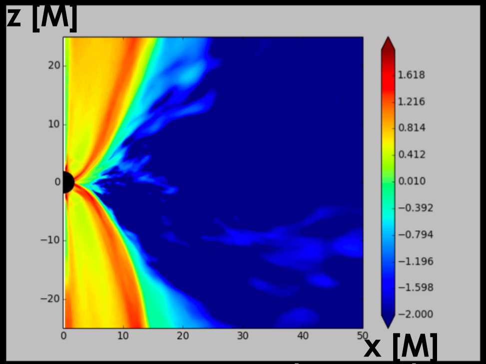
- Boundary layer on disk-jet corona have highest T_e in electron temp models.



(f_e, β_c) =(0.1,0.01)

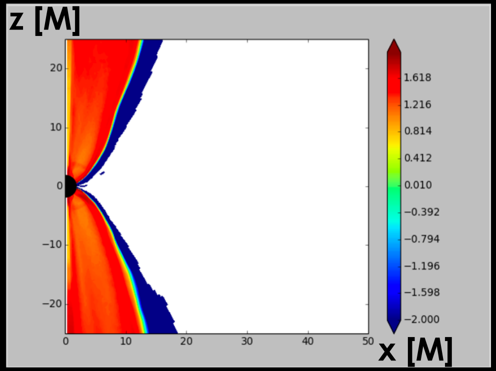


(f_e, β_c) =(0.1,0.1)

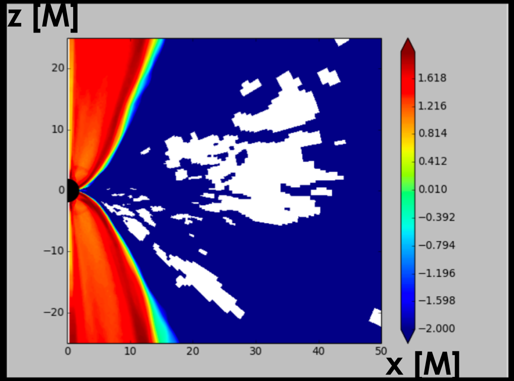


(f_e, β_c) =(0.1,1)

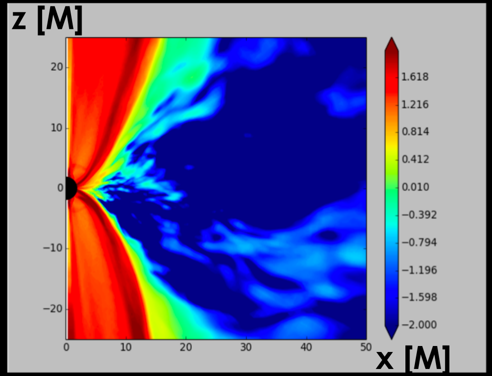
Log[T_e]



(f_e, β_c) =(0.5,0.01)



(f_e, β_c) =(0.5,0.1)



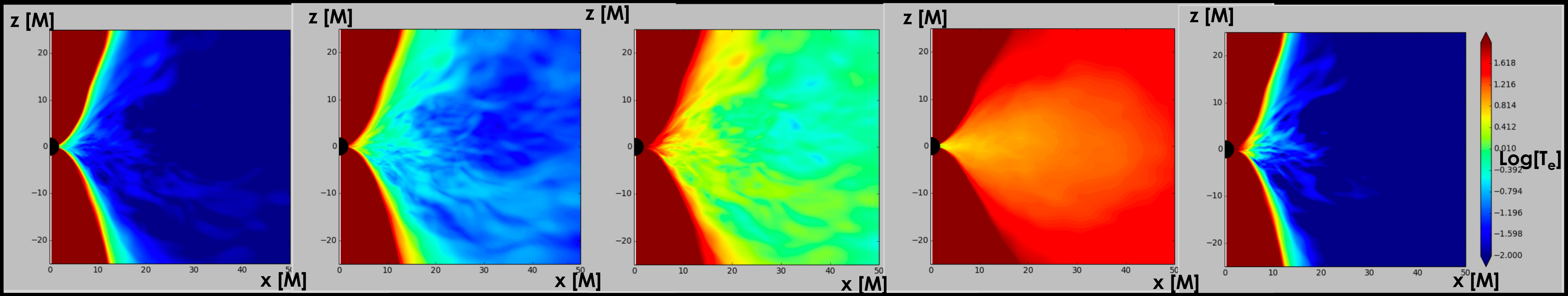
(f_e, β_c) =(0.5,1)

Log[T_e]

SIMULATION ELECTRON TEMP PROFILES: BETA AND BIAS MODELS

- Beta and bias model have highest electron temperature in the outflow interior

β =0.01 β =0.1 β =1 N=0 N=4

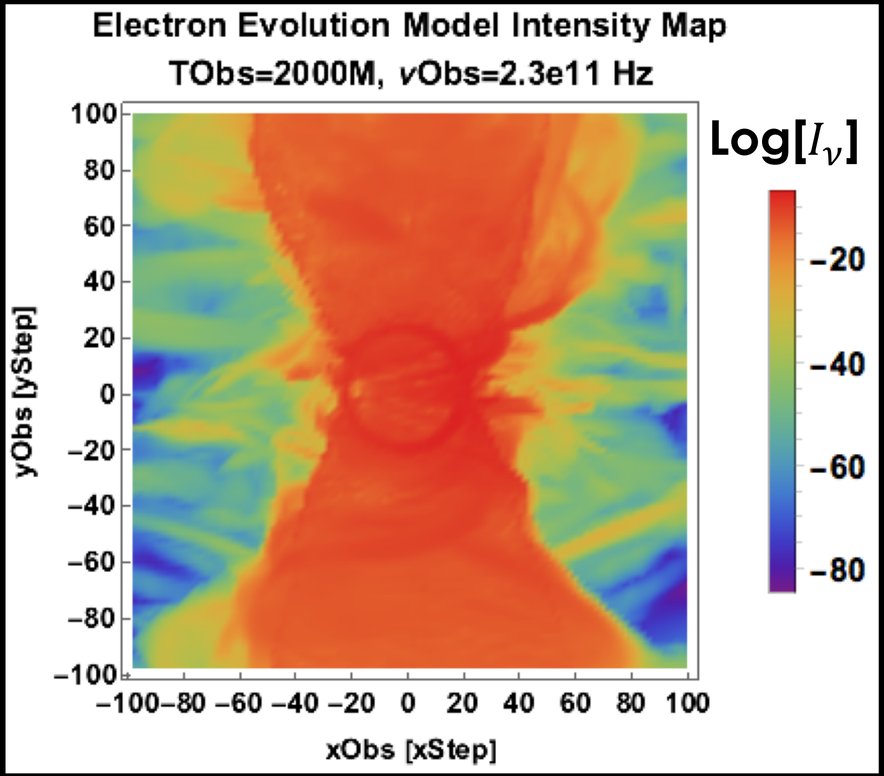


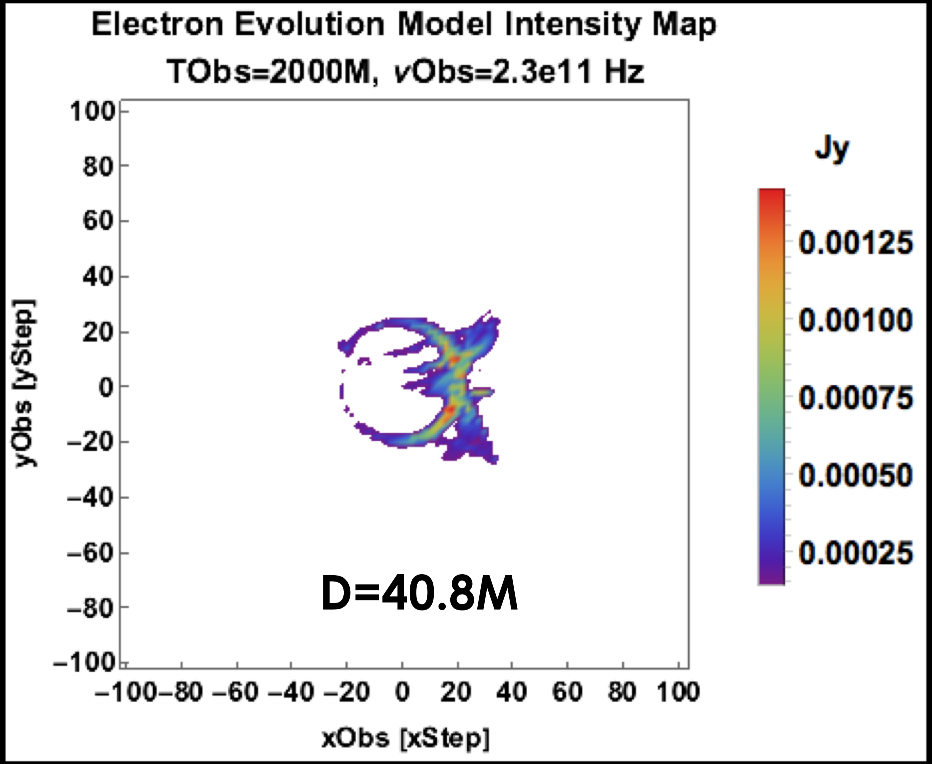
COMPARING IMAGES WITH EHT SIZE CONSTRAINT

- Define "emitting region" to be portions of an image plane with intensity at least $I_{Floor} = f_{Floor} \times I_{max}$
- Take as characteristic length D of the emitting region the diameter of a circular region with area $A_{Emitting}$
- EHT intrinsic size constraints for circular Gaussian emitting region
  - $9.8M < D_{Int,fFloor=0.1} < 19.3M$
  - $8.2M < D_{Int,fFloor=0.2} < 16.2M$
  - $5.4M < D_{Int,FWHM} < 10.6M$
- EHT scattering size constraints for circular Gaussian emitting region
  - $12.8M < D_{fFloor=0.1} < 20.8M$
  - $10.7M < D_{fFloor=0.2} < 17.4M$
  - $7M < D_{FWHM} < 11.4M$

EMITTING REGION IN ELECTRON EVOLUTION MODEL

f_{Floor}=0.1, 12.8M<$D_{fFloor=0.1}$<20.8M

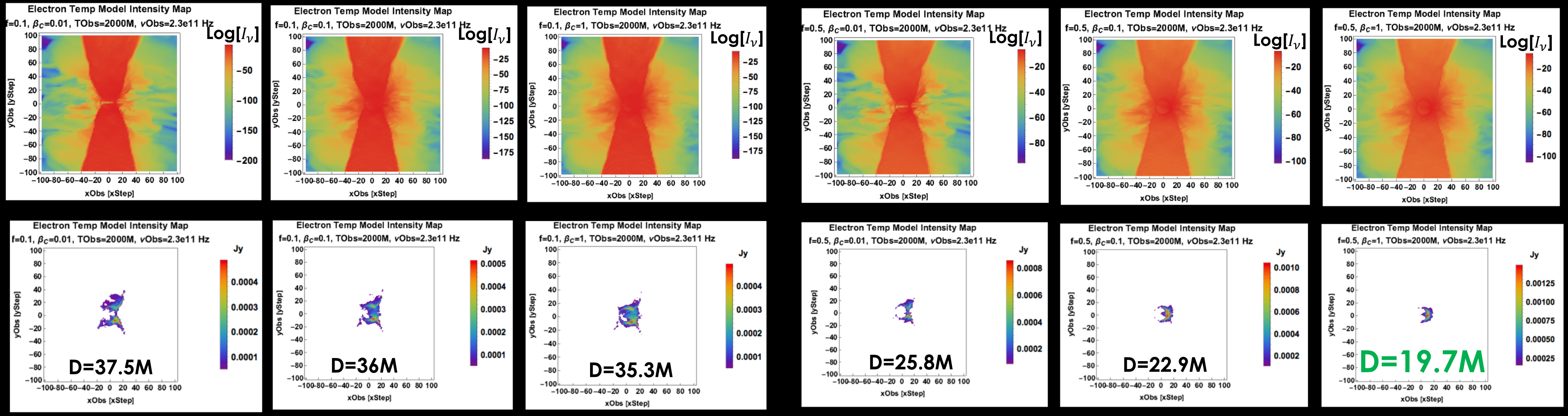




EMITTING REGIONS IN ELECTRON TEMPERATURE MODELS

f_{Floor}=0.1, 12.8M<$D_{fFloor=0.1}$<20.8M

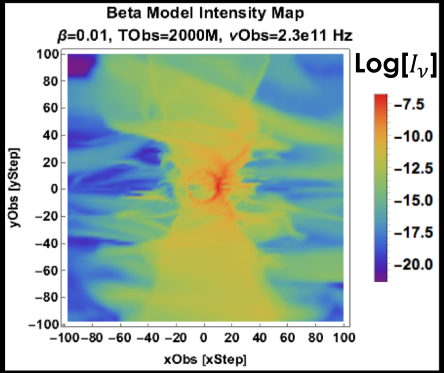
$(f_e\ ,\ \beta_c)$=(0.1,0.01) $(f_e\ ,\ \beta_c)$=(0.1,0.1) $(f_e\ ,\ \beta_c)$=(0.1,1) $(f_e\ ,\ \beta_c)$=(0.5,0.01) $(f_e\ ,\ \beta_c)$=(0.5,0.1) $(f_e\ ,\ \beta_c)$=(0.5,1)

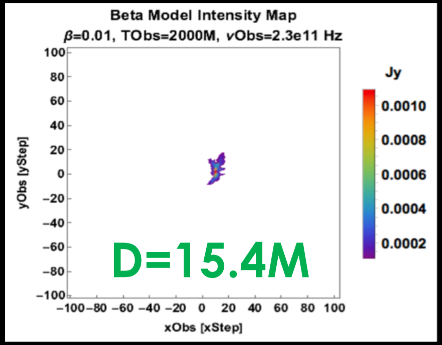


EMITTING REGIONS IN BETA AND BIAS MODELS

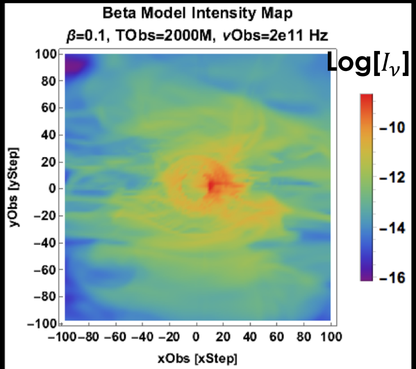
$f_{Floor}=0.1$, $12.8M<D_{fFloor=0.1}<20.8M$

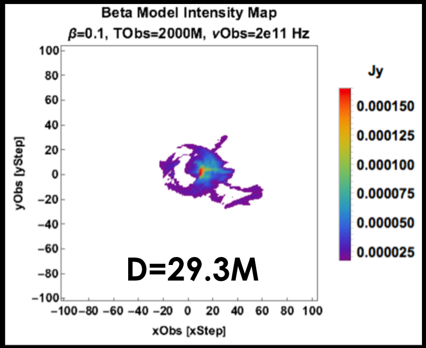
β = 0.01



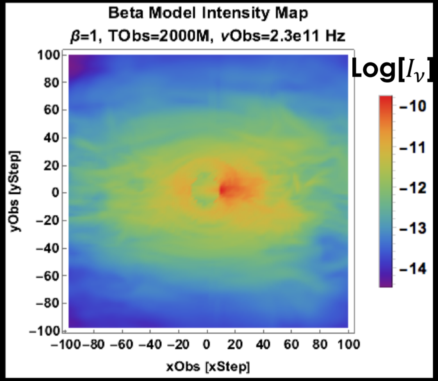


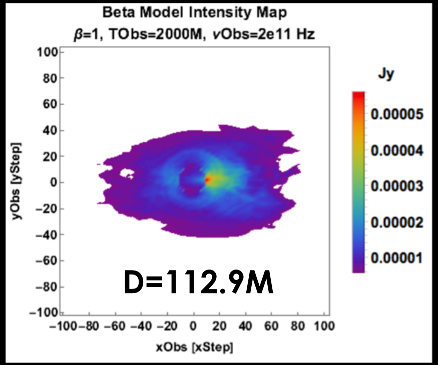
β = 0.1



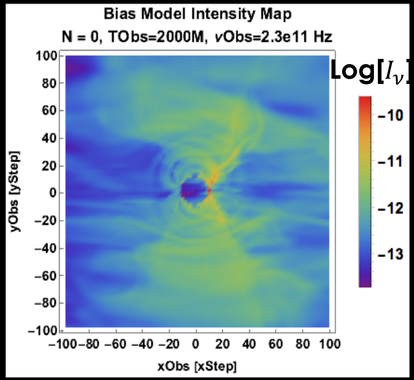


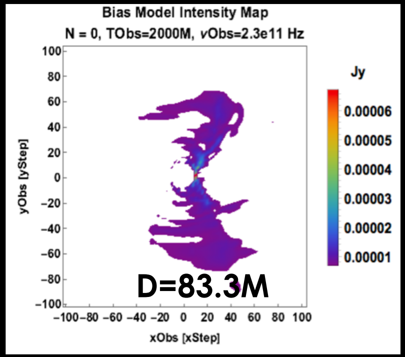
β = 1



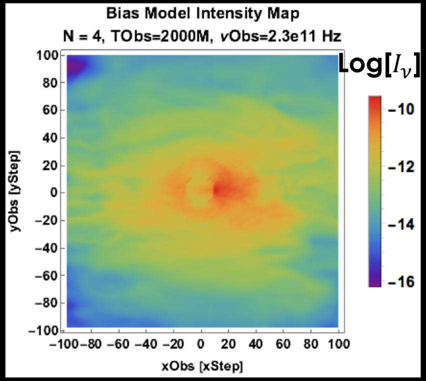


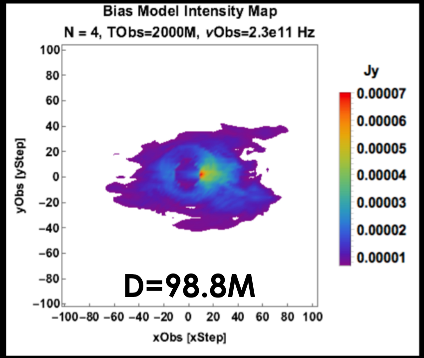
N=0





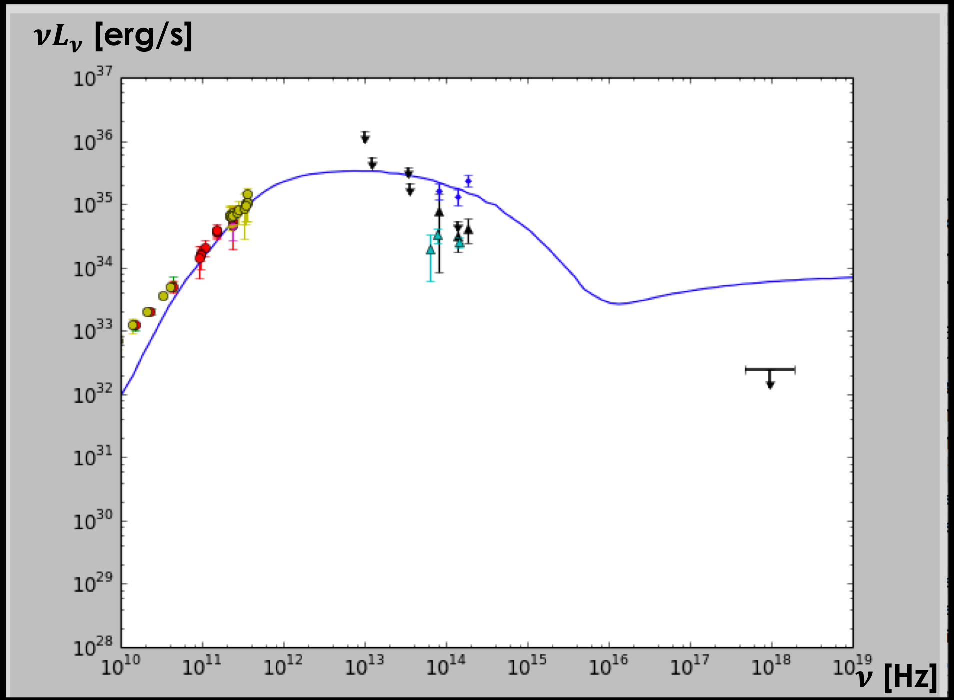
N=4





SYNTHETIC SPECTRA

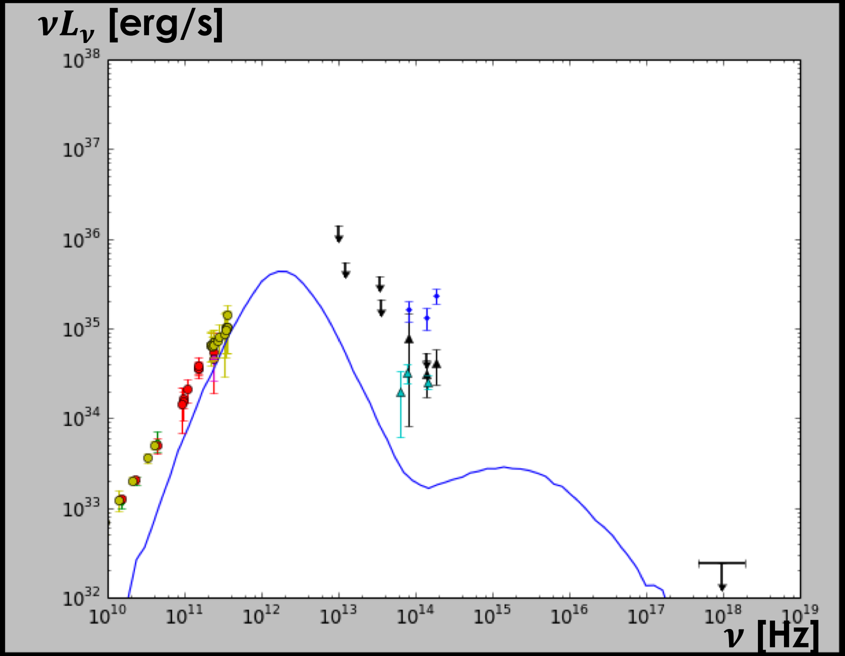
- Electron evolution model is a detailed calculation fitting a good deal of the data

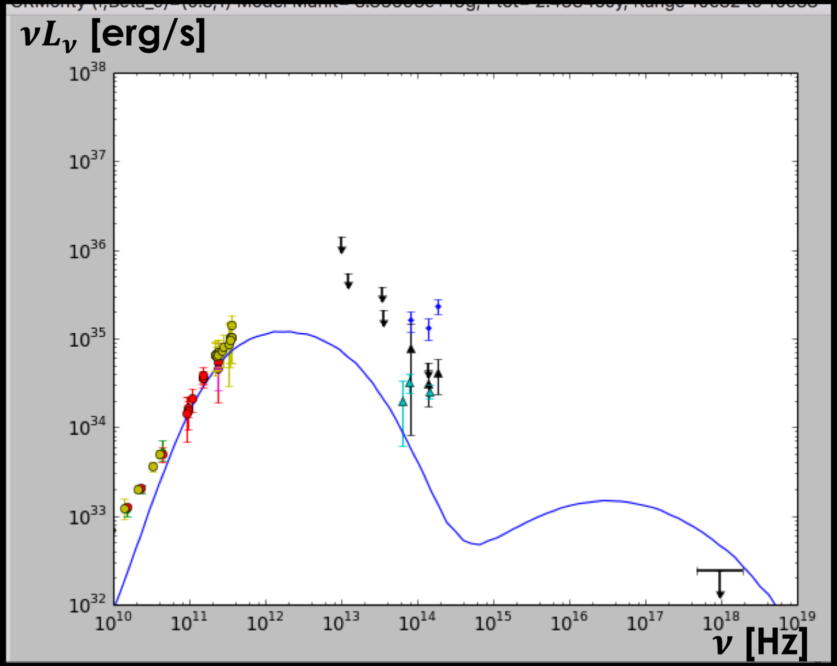


SPECTRA IN ELECTRON TEMPERATURE MODEL

- Electron temperature (f_e , β_c) models have steeper-than-observed spectrum likely corona-dominated
  - (f_e , β_c)=(0.1,1)

(f_e , β_c)=(0.5,1)

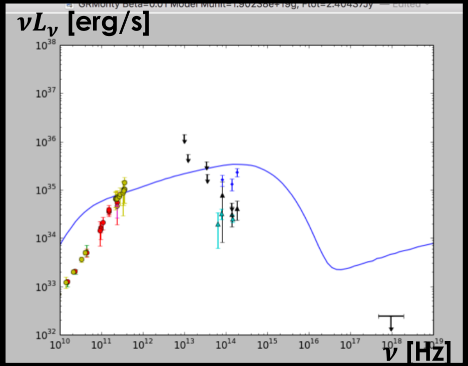




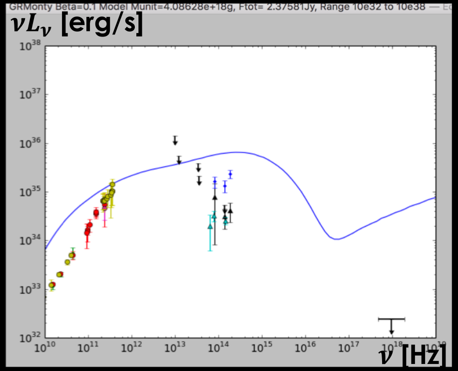
SPECTRA IN BETA AND BIAS MODELS

- Beta models have flatter-than-observed spectra near sub mm-bump, but similar slopes to observed spectrum after
- Bias model spectra are slightly flatter than observed and overproduce high frequency end
- Analytic model of jet outflow with $B \sim B_\phi \sim 1/r$ and equipartition assumption yields flat spectrum, isothermal jet (Blandford and Konigl 1979)
- GRMHD simulations (Moscibrodska and Falcke, 2013) confirm flat spectrum due to optically thick regions

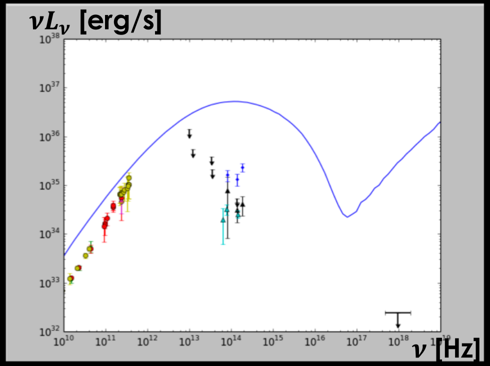
$\beta = 0.01$



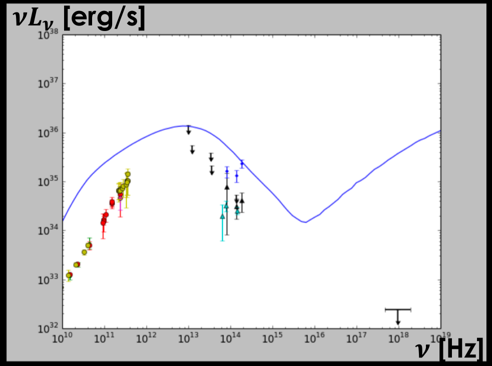
$\beta = 0.1$



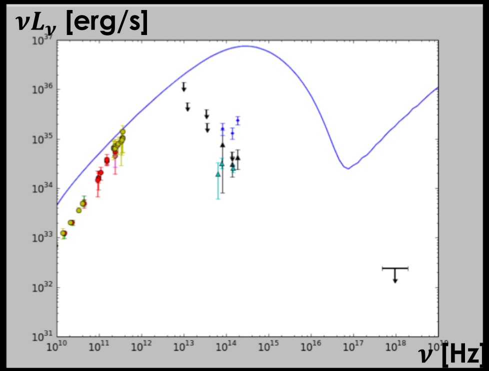
$\beta = 1$



$N = 0$



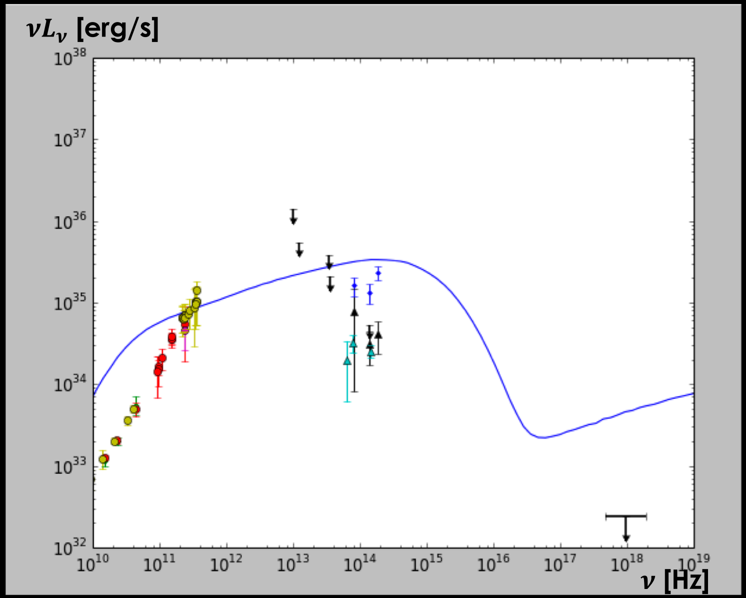
$N = 4$



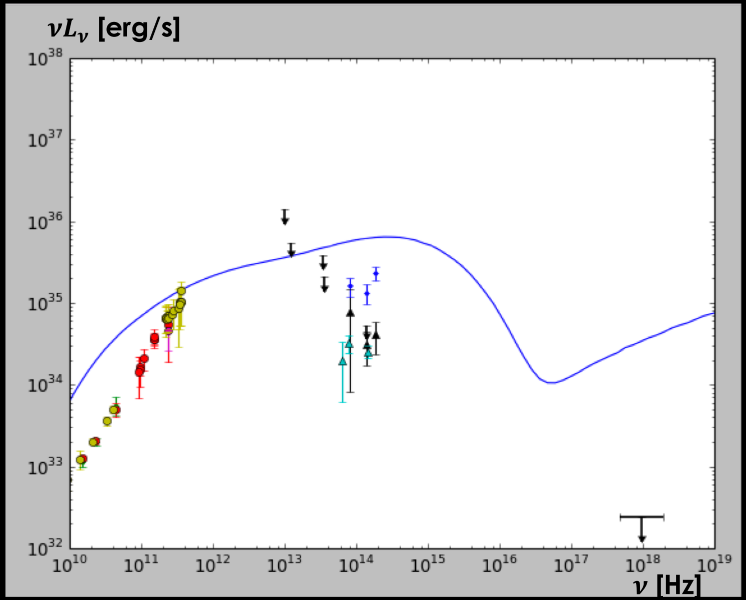
FLATTER SPECTRUM FOR LOWER BETA IN BETA MODELS

- Low β (magnetic pressure dominance) may lead to near-horizon outflow regions dominating emission

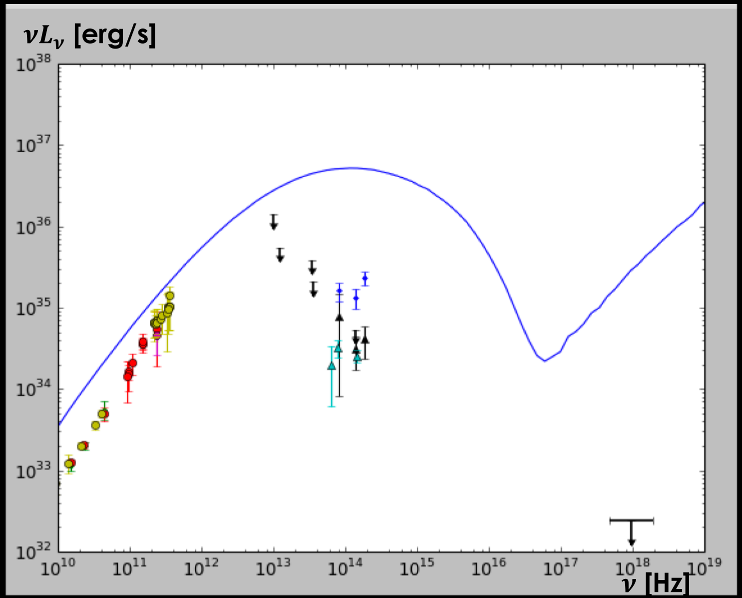
β=0.01



β=0.1



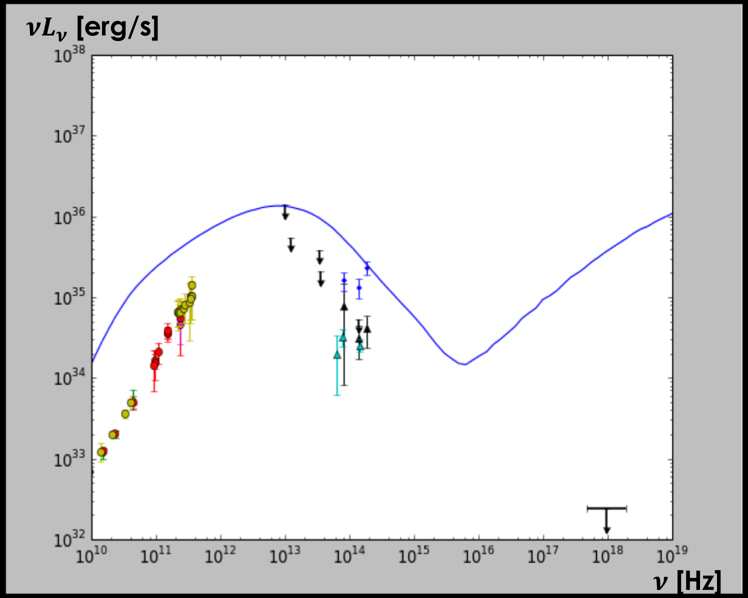
β=1



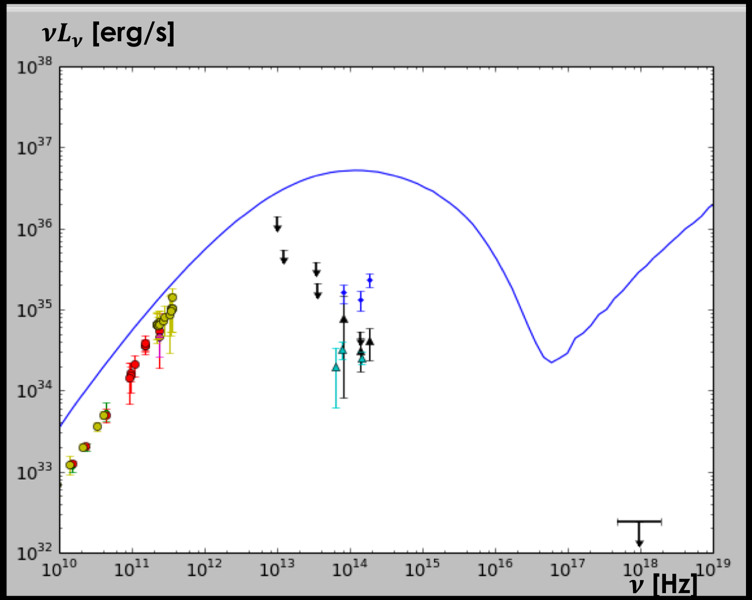
FLATTER SPECTRUM FOR LOWER N BIAS MODELS

- Lower N reduces the falloff of u_e with radius, possibly resulting in flatter spectra

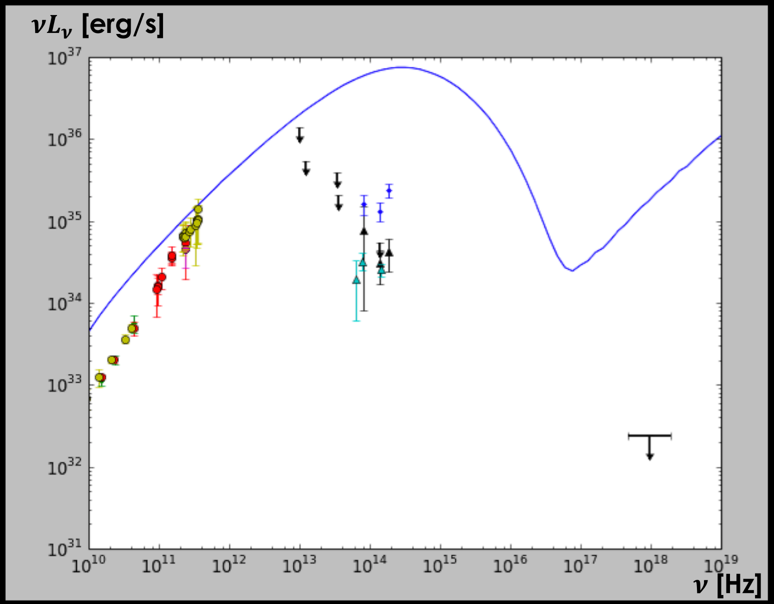
$N = 0$



$N = 2$



$N = 4$



FLATTER SPECTRUM FOR BETA AND BIAS VS $(f_e\ ,\ \beta_c)$ MODELS

- Spectra in models inspired by equipartition (beta and bias) may be dominated by near-horizon outflow emission
- Spectra in electron temperature models may be dominated by corona emission

CONCLUSIONS

- Our parameterized models reproduce some aspects of Sgr A* observed/expected morphology (e.g., asymmetry, photon ring) and spectrum (e.g., slope and/or amplitude at lower or higher frequencies than $\nu \sim 10^{12}$Hz bump)
- 230 GHz intensity maps on the scale of tens of gravitational radii appear:
  - Mostly uniform for electron temperature models
  - Mixed outflow/near horizon for equipartition-inspired (beta and bias) models
    - More concentrated around horizon photon ring for increasing β and increasing N
- Synthetic spectra are:
  - Flatter spectra in beta and bias models than electron temperature models
  - More peaked spectra for increasing β and increasing N
- Most compact emitting regions for β=0.01 and (f_e , β_c)=(0.5,1), satisfying EHT size constraint