SGR A* EMISSION PARAMETRIZATIONS FROM GRMHD SIMULATIONS

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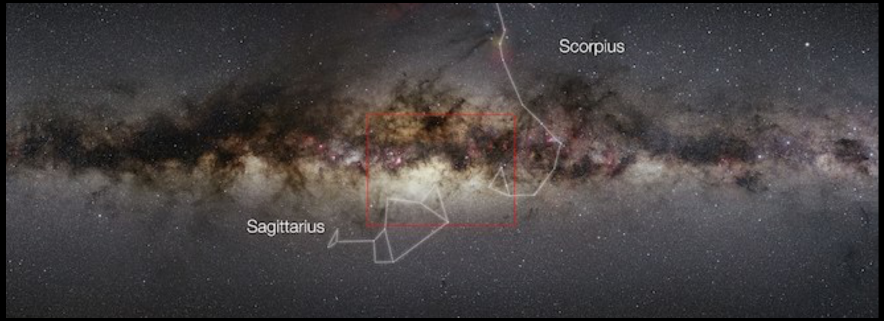
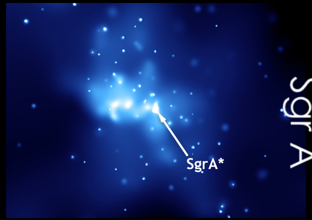
GALACTIC CENTER: HOME SWEET HOME

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



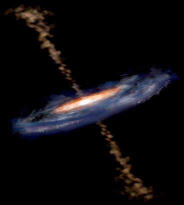
- The Galactic Center radio source Sgr A at d=7.86kpc (Boehle et al., 2016) has a relatively bright, non-thermal region, Sgr A*, surrounding a supermassive black hole

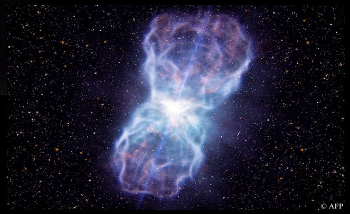


- Central black hole mass: $4\mathrm{x}10^6 M_\odot$ (Boehle et al. 2016)
- Sgr A* luminosity: $L_{SgrA*} = 10^{-9} L_{Edd} - 10^{-10} L_{Edd}$ (Sabha et al., 2018); $L_{SgrA*} \lesssim 10^{37}$ erg/s = 2600 $L_\odot$ (Narayan et al. 1998)

BLACK HOLES IN ASTRONOMY

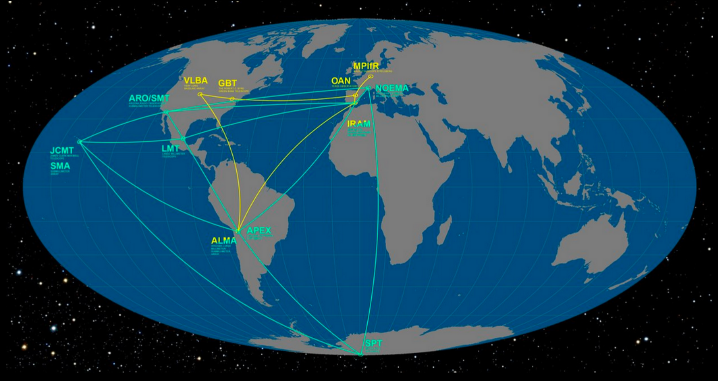
- Remnants of stars >4 $M_{\odot}$ produce black holes when the star runs out of nuclear fuel or degeneracy pressure counteracting gravitational collapse
- If a black hole is formed from a star that was in a binary system, it accretes the companion star, producing x-ray radiation
- Supermassive (10^6-10^{10} $M_{\odot}$) 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

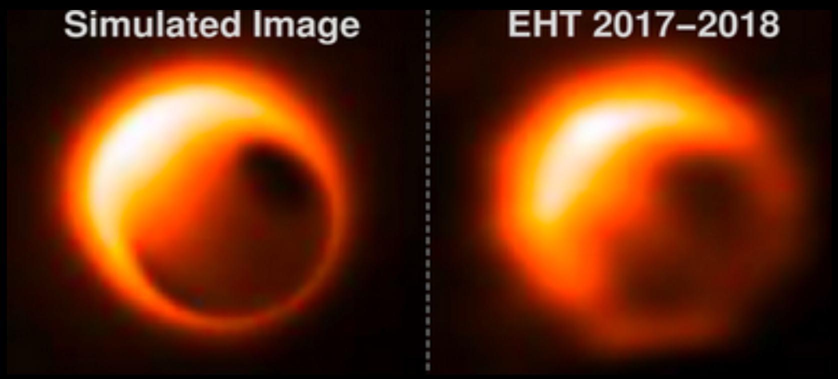




BLACK HOLES - OBSERVATIONS

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





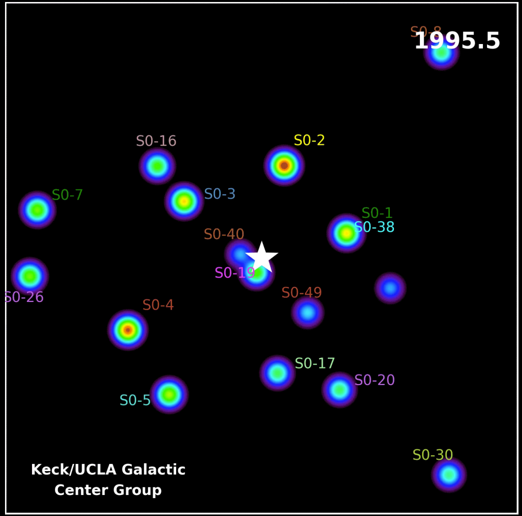
Confer: http://news.nationalgeographic.com/2017/04/black-hole-event-horizon-telescope-pictures-genius-science/

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

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

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

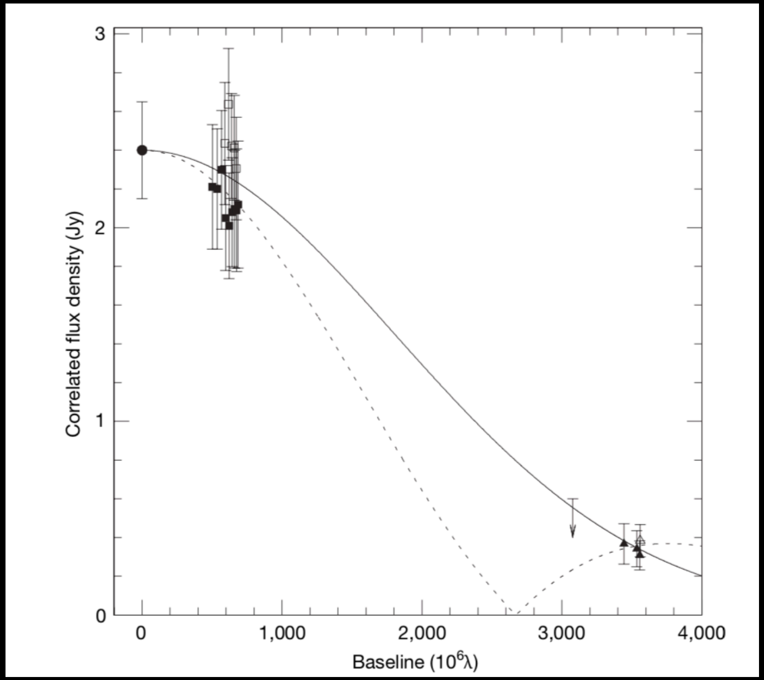


- Wolf-Rayet stars, which are hot w./ strong winds, accrete the most onto Sgr A*

WR 124 in Sagittarius

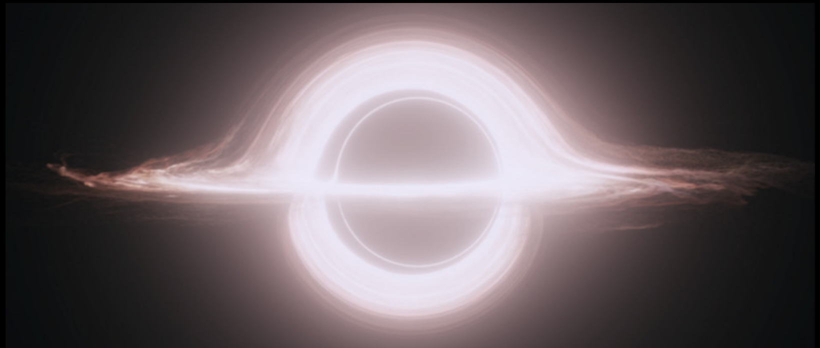
SGR A* IMAGE SIZE CONSTRAINTS

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



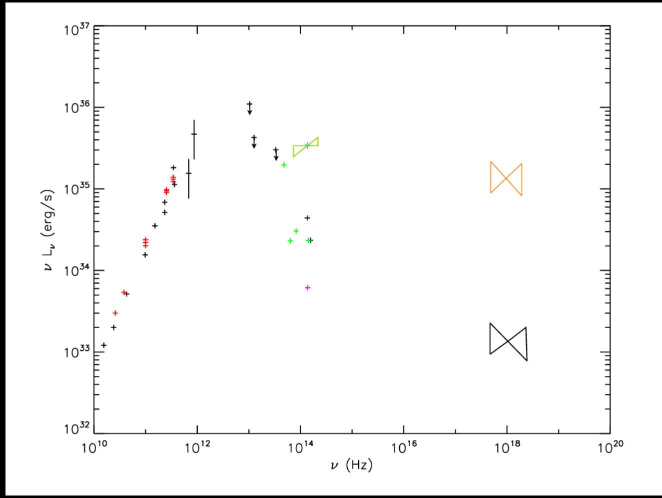
Doeleman et al., 2008

- Photon ring?



SGR A* OBSERVATIONS: SPECTRAL FLUX DENSITY

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

SGR A* OBSERVATIONS

- Low luminosity (L $\lesssim 10^{37}$ erg/s = 2600 $L_{\odot}$ (Narayan et al. 1998))
- Low mass accretion rate $\dot{M} \lesssim$ 2x10−7 $M_{\odot}$/yr (Marrone et al. 2007)
- EHT size constraints
  - Scattering size: $43^{+14}_{-8}\mu as$ (Doeleman et al. 2008)
- Spectral flux density observations
  - 1.3 Jy at 32 GH 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?*

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

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

- Scales
  - Black hole mass – $M = 4\text{x}10^6 M_\odot$ (Boehle et al. 2016)
  - Mass accretion rate – $\dot{M}$ determines normalization of spectral flux summed over intensity maps in various models at a chosen frequency
- Dynamical time for accretion shorter than timescale of Coulomb collisions between leptonic (e+e-) and hadronic plasma (p,ions) => Two-temperature plasma
- Electrons radiate heat more efficiently than protons: $T_e << T_p$

SIMULATION FLUID EQUATIONS

- Mass conservation

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

- Energy-momentum equation

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

  - Stress-energy-momentum tensor with electron 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 AND TEMPERATURE

- Entropy per particle

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

- Vlasov equation and 1st moment

$$\frac{\partial f}{\partial t} + \vec{\mathrm{v}} \cdot \vec{\nabla}_{\vec{\mathrm{x}}} f + \frac{q}{m}\left(\vec{E} + \frac{1}{c}\vec{\mathrm{v}}\times\vec{B}\right)\vec{\nabla}_{\vec{\mathrm{v}}} f = 0$$

$$\partial_\mu T_e^{\mu\nu} = -enu_e^\mu F_\mu^\nu, \qquad \partial_\mu T_p^{\mu\nu} = enu_p^\mu F_\mu^\nu$$

- Entropy equation

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

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

- Electron temperature model
  1) Constant Te/Tp at beta<<1
  2) Te suppressed at beta>>1

$$\frac{T_e}{T_{\text{sim}}} = f_e \operatorname{Exp}[-\beta/\beta_c]$$

- Constant β model

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

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: RADIATIVE TRANSFER

- IBOTHROS (Noble et al. 2007) solves general relativistic radiative transfer equations for photon geodesics $x^\mu(s)$ between source and "camera"

$$\frac{dN^\mu}{ds} = -\Gamma^\mu_{\alpha\beta} N^\alpha N^\beta, \qquad N^\mu = \frac{dx^\mu}{ds}$$

- Syncrotron emission and absorption are included in IBOTHROS ray tracing

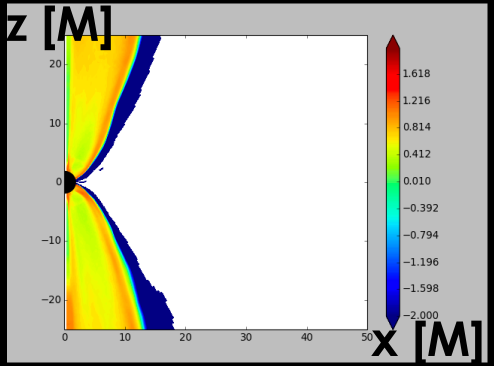
$$\frac{d\mathcal{I}}{ds} = \mathcal{J} - \mathcal{A}\mathcal{I}, \qquad \mathcal{J} = \frac{j_\nu}{\nu^2}, \mathcal{A} = \nu\alpha_\nu$$

POSTPROCESSING: SPECTRA

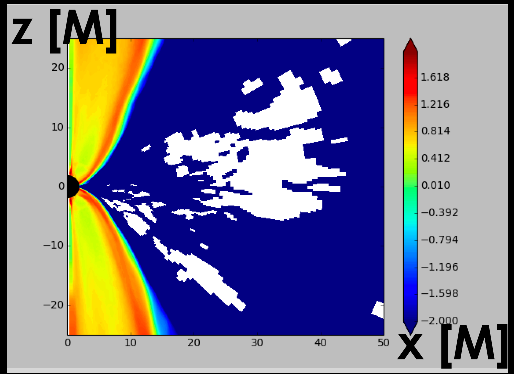
- GRMONTY (Dolence et al. 2009) computes spectra of hot accretion flows in the Kerr metric
- Synchrotron emission and absorption and Compton scattering included
- The code solves the trajectories of N Monte Carlo sample photons and weighs them by frequency to compute spectra
- GRMONTY converges with rate $N^{-1/2}$

SIMULATION ELECTRON TEMP PROFILES: ELECTRON TEMPERATURE MODEL

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



(f, β_c) =(0.1,0.01)



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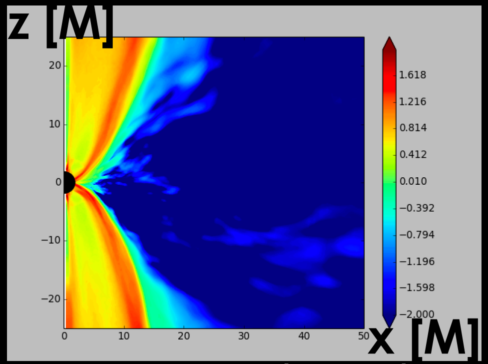
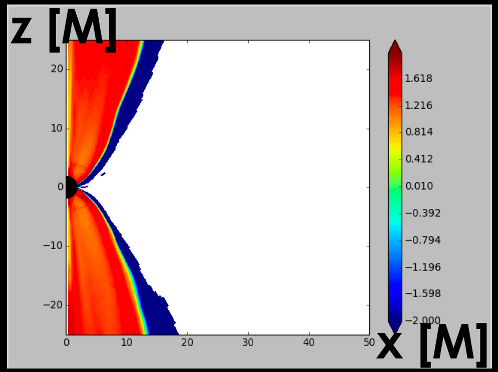
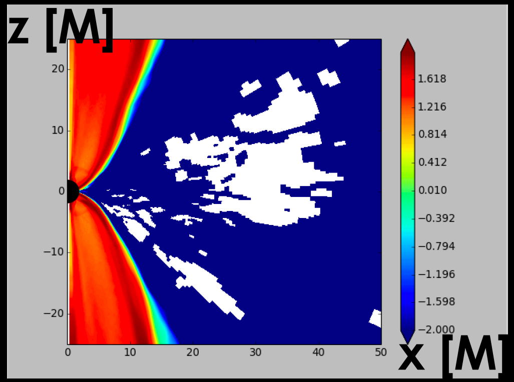


(f, β_c) =(0.1,1)

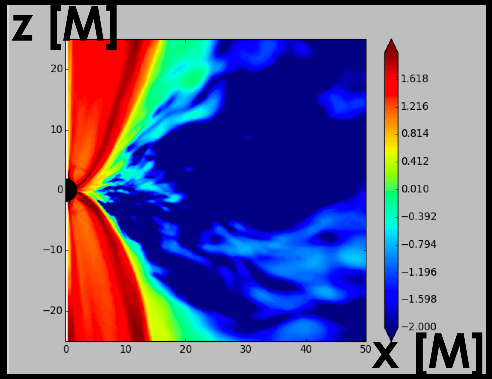
Log[T_e]



(f, β_c) =(0.5,0.01)



(f, β_c) =(0.5,0.1)



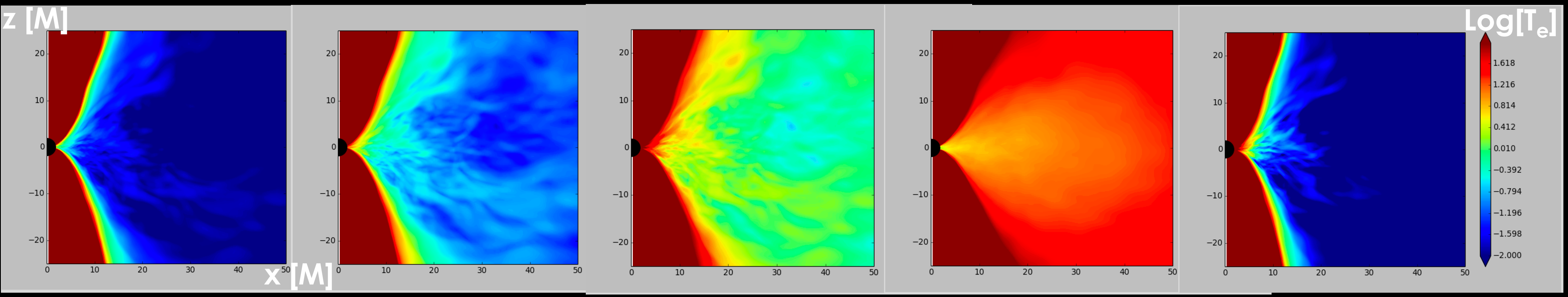
(f, β_c) =(0.5,1)

Log[T_e]

SIMULATION ELECTRON TEMP PROFILES: BETA AND BIAS MODELS

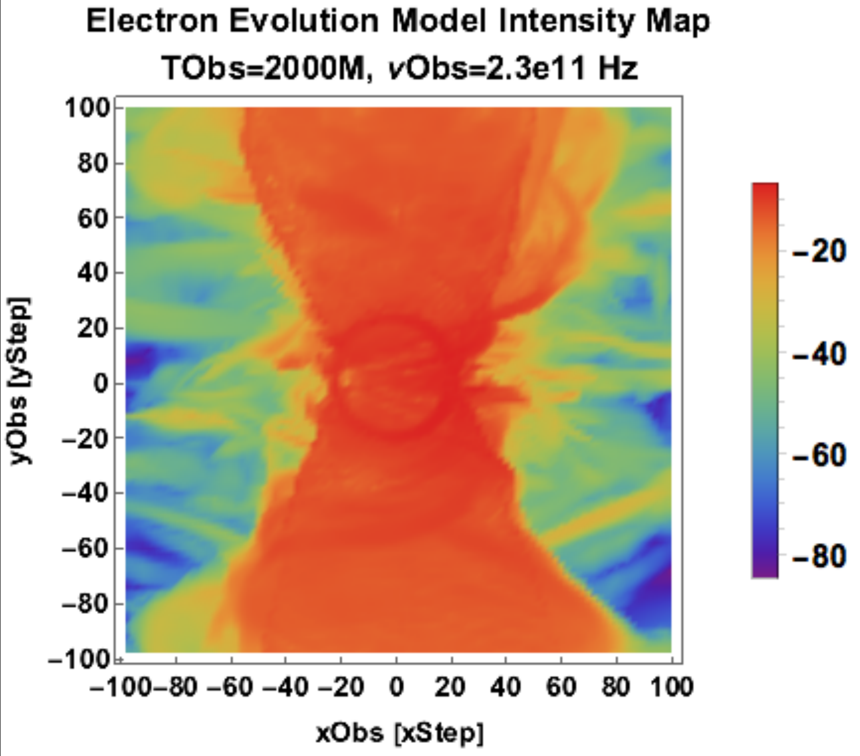
- Beta and bias model have highest electron temperature in the outflow interior

β =0.01 β =0.1 β =1 N=0 Bias N=4 Bias



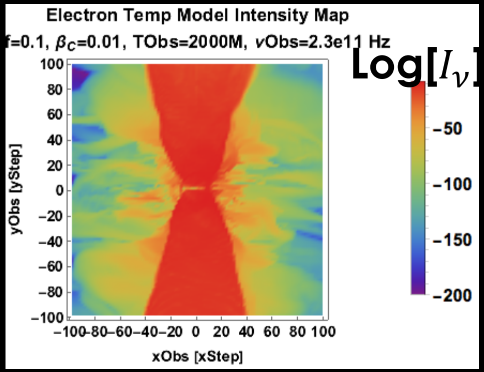
SYNTHETIC IMAGES

- Electron evolution model image (Log[I_ν]) plot for -100M<x,y<100M

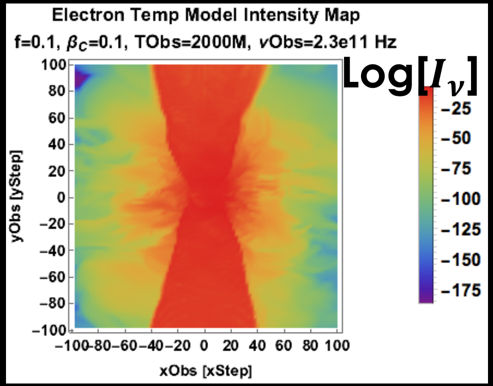


ELECTRON TEMPERATURE MODEL IMAGES

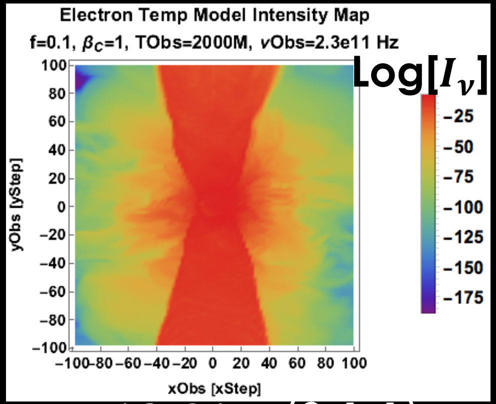
- Constant intensity throughout projected region enclosed by disk-jet corona



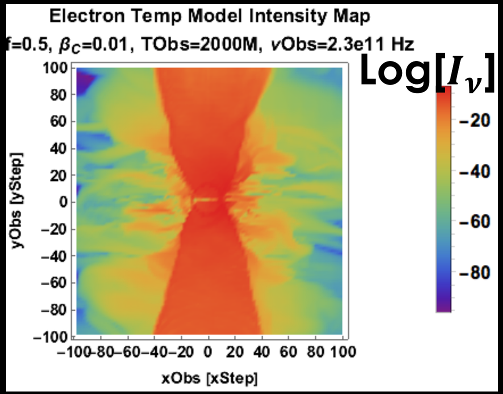
(f, β_c) =(0.1,0.01)



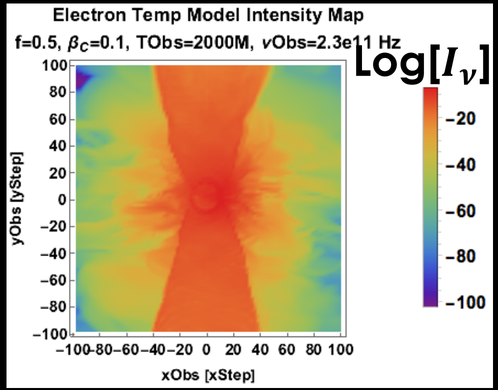
(f, β_c) =(0.1,0.1)



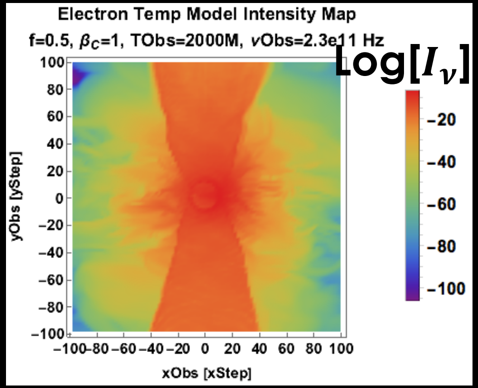
(f, β_c) =(0.1,1)



(f, β_c) =(0.5,0.01)



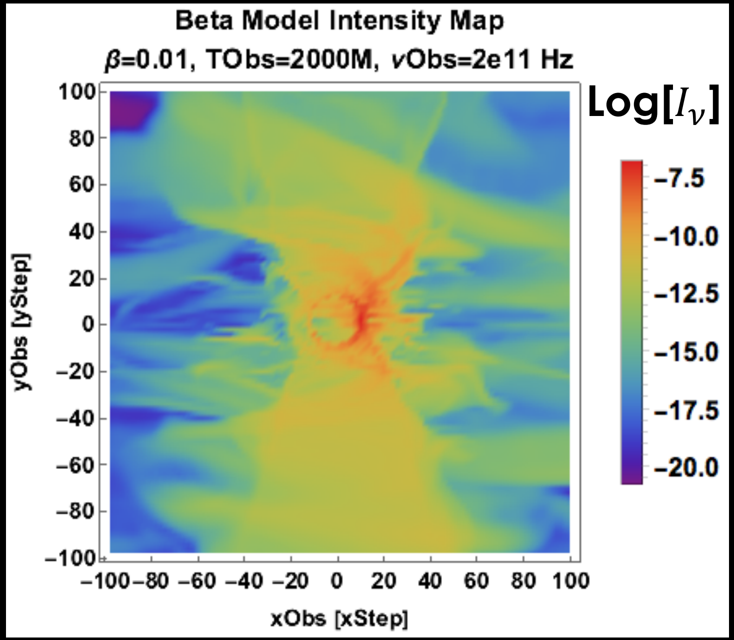
(f, β_c) =(0.5,0.1)

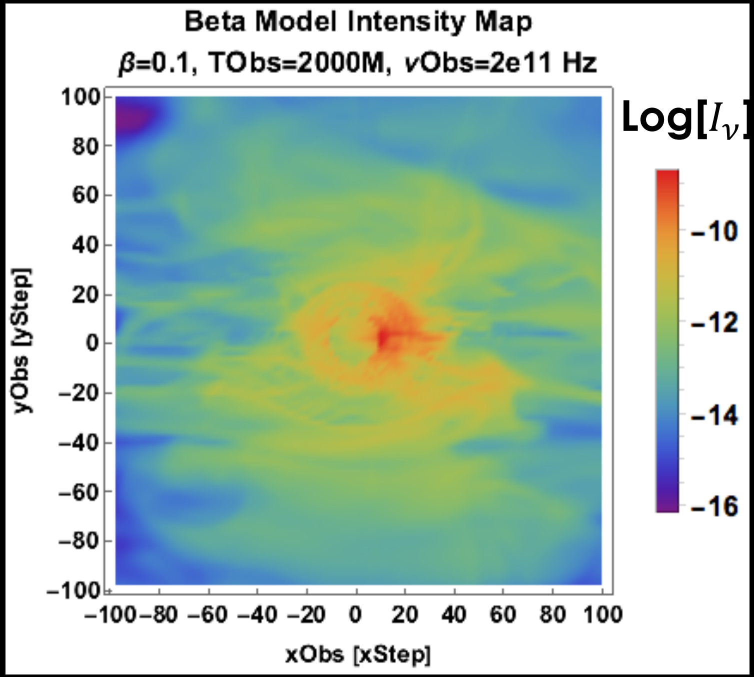


(f, β_c) =(0.5,1)

BETA MODEL IMAGES

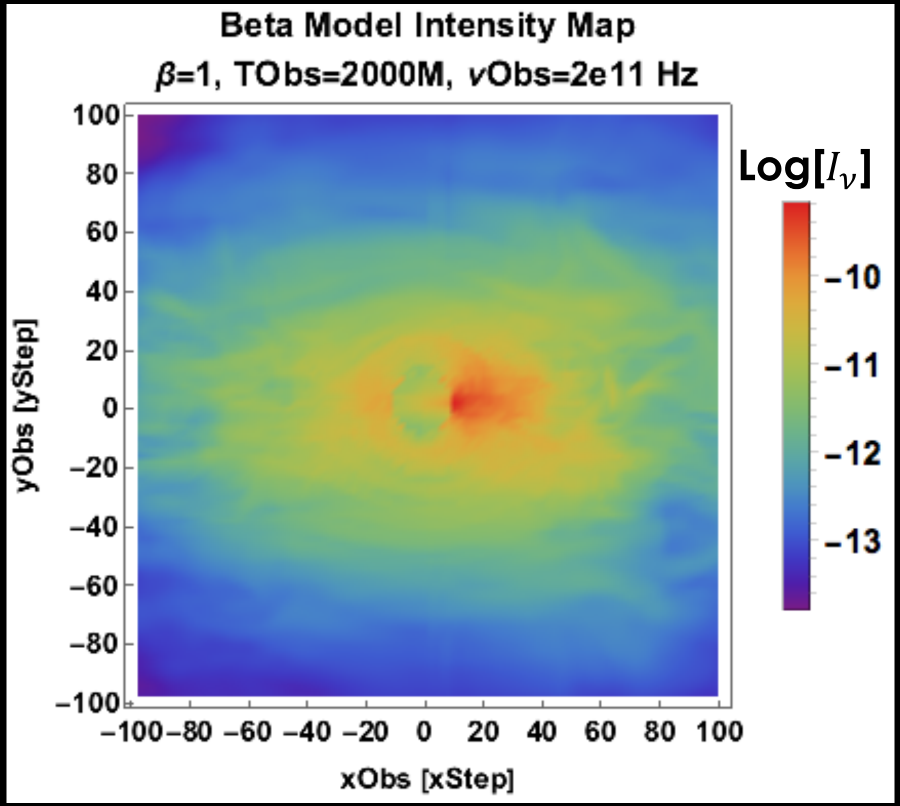
- Beta models light up the extended outflow at low β and small radii (photon ring) at high β
  - β = 0.01, β = 0.1





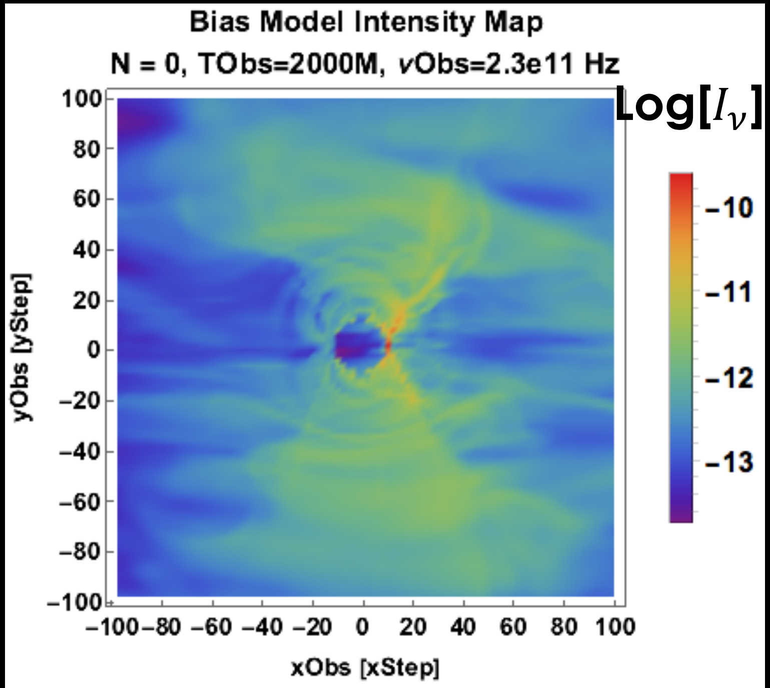
EQUIPARTITION MODEL IMAGE

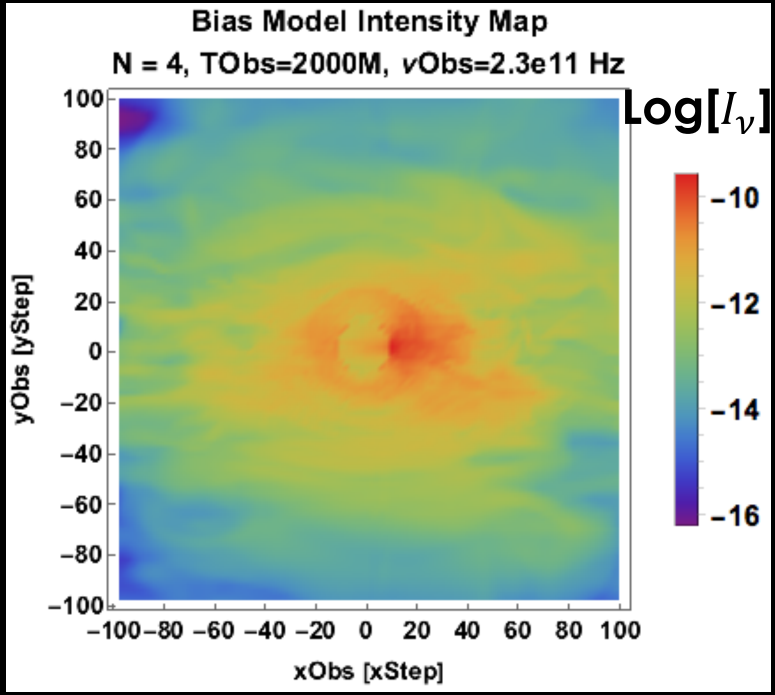
- The equipartition model ($\beta = 1$) lights up a spherical region tens of r_g from the hole



BIAS MODEL IMAGES

- Bias models light up near the horizon where photon trajectories form rings
  - N=0, N=4





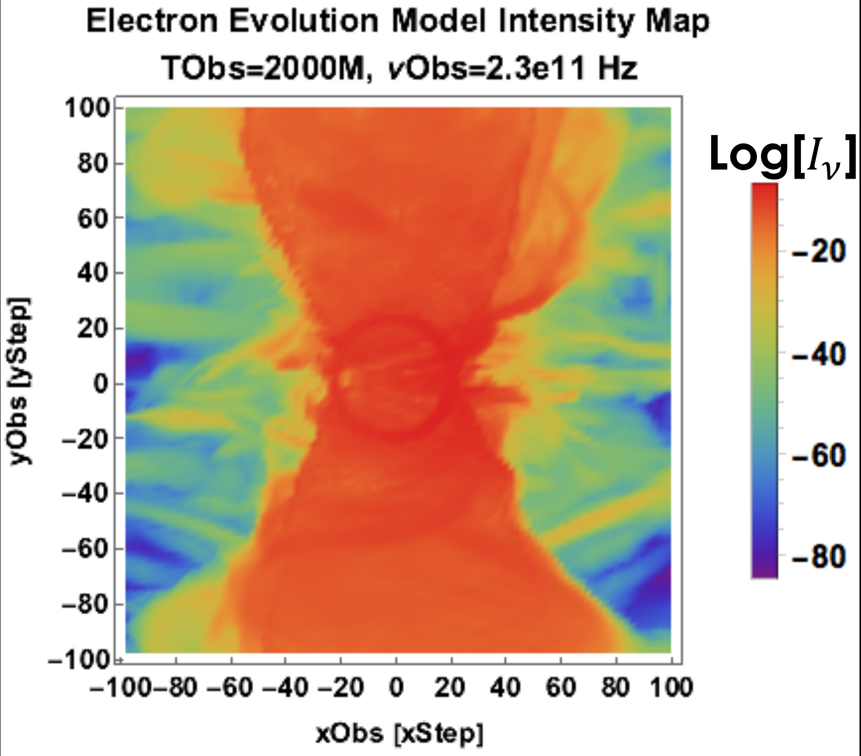
IMAGES SUMMARY

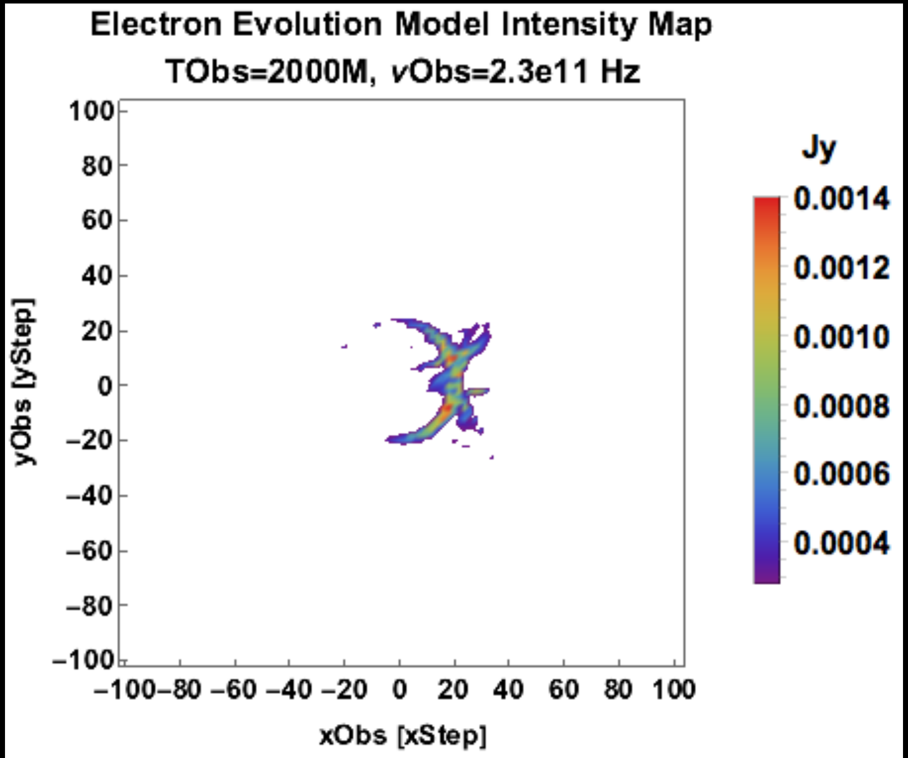
- Electron evolution model emission is seen throughout the outflow, especially near the photon ring
- Electron temperature model emission is uniform throughout the projected coronal region
- Beta model images incorporate outflow and photon ring emission at low beta (high magnetic pressure), but mostly emission near the photon ring at higher beta
- Bias models images incorporate outflow and photon ring at low N (constant electron gas pressure), and favor photon ring emission from small radii at high N

COMPARING IMAGES WITH EHT SIZE CONSTRAINT

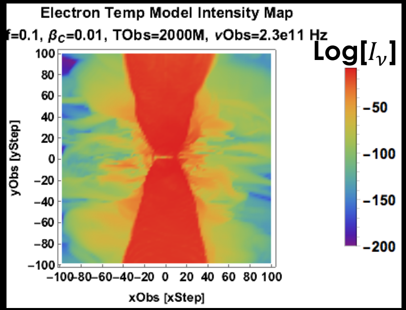
- Observational EHT size constraints for circular Gaussian emitting region FWHM
  - $5.4M < D < 10.6M$ intrinsic size
  - $7M < D < 11.4M$ scattering size
- Define "emitting region" to be portions of an image plane with intensity at least $I_{Floor} = f_{Floor} \times I_{max}$
- Take as characteristic length D of the emitting region the diameter of a circular region with area $A_{Emitting}$
- Take $f_{Floor} = 0.2$, as this was the value required to get emitting regions compact enough to satisfy EHT size constraint in some models

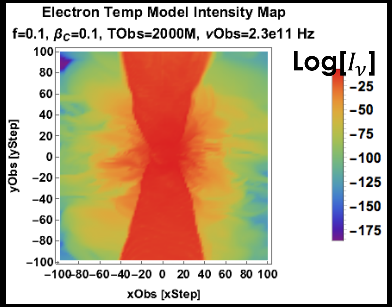
EMITTING REGION IN ELECTRON EVOLUTION MODEL

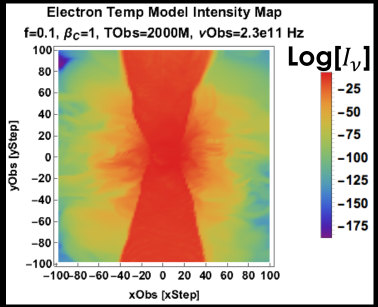


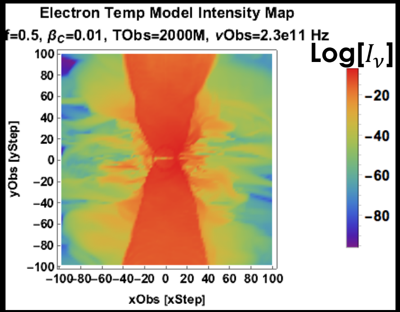


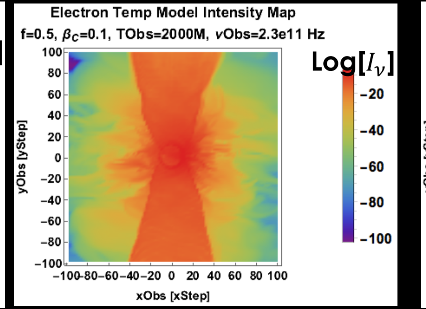
EMITTING REGIONS IN ELECTRON TEMPERATURE MODELS

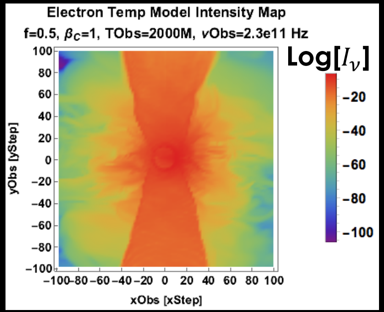


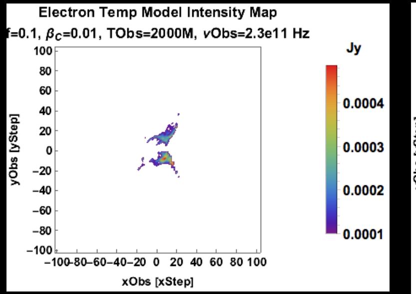


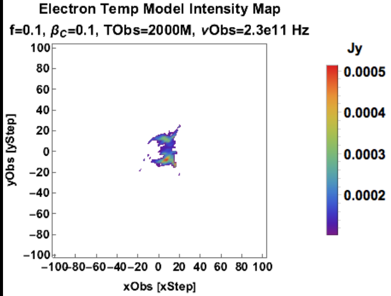


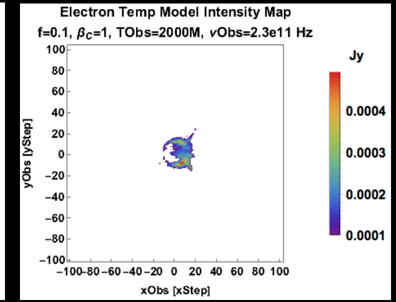


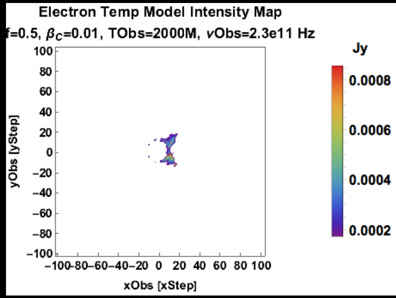


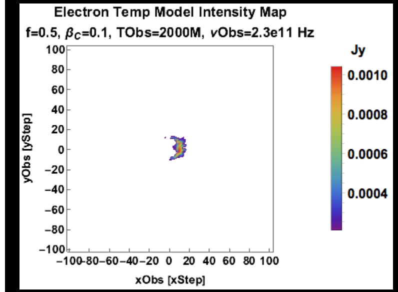


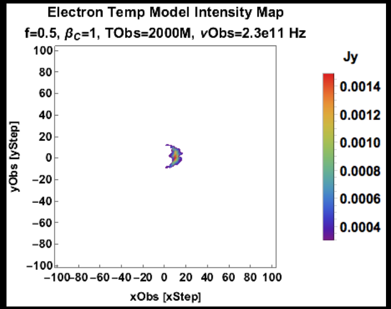




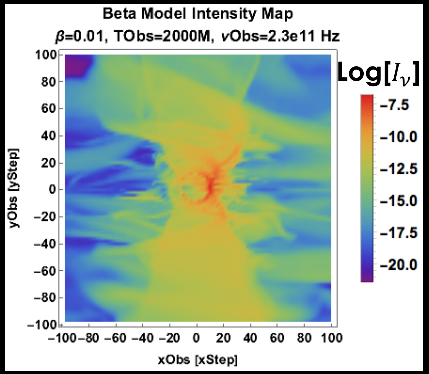


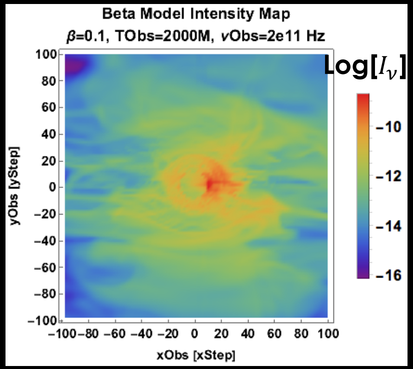


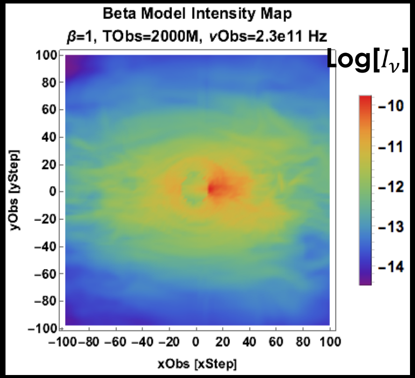


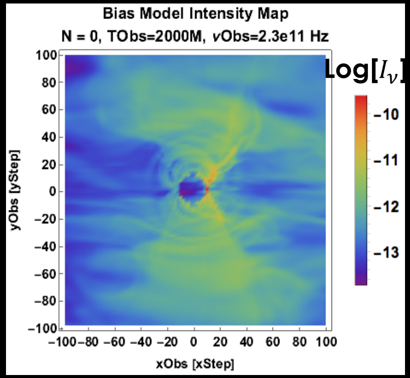


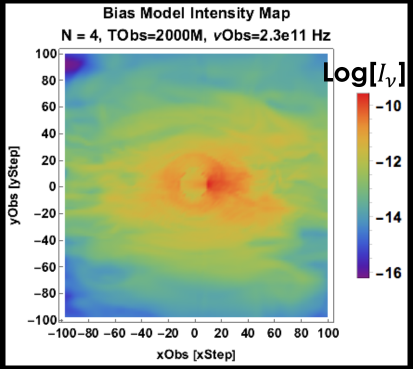
EMITTING REGIONS IN BETA AND BIAS MODELS

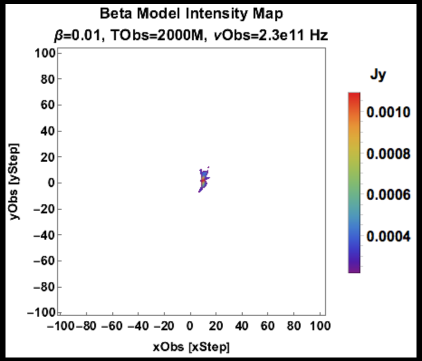


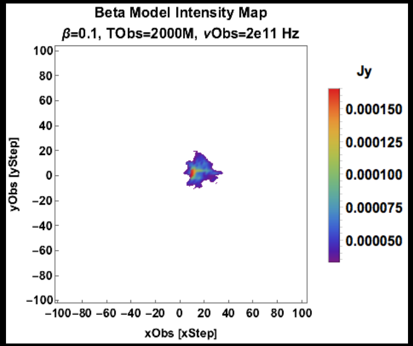


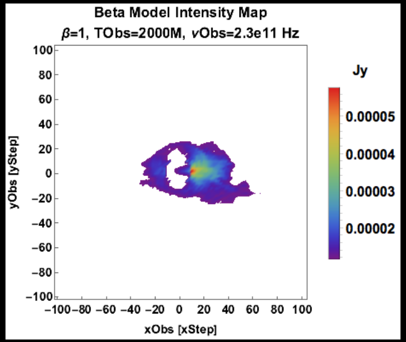


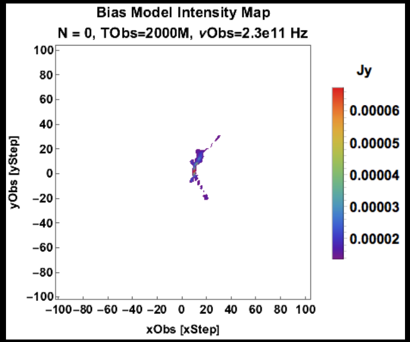


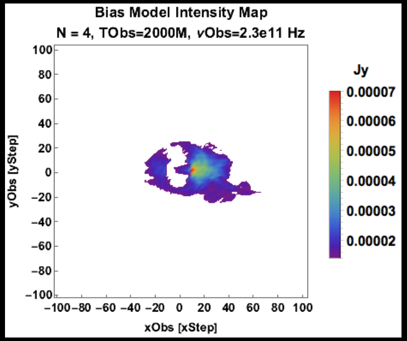






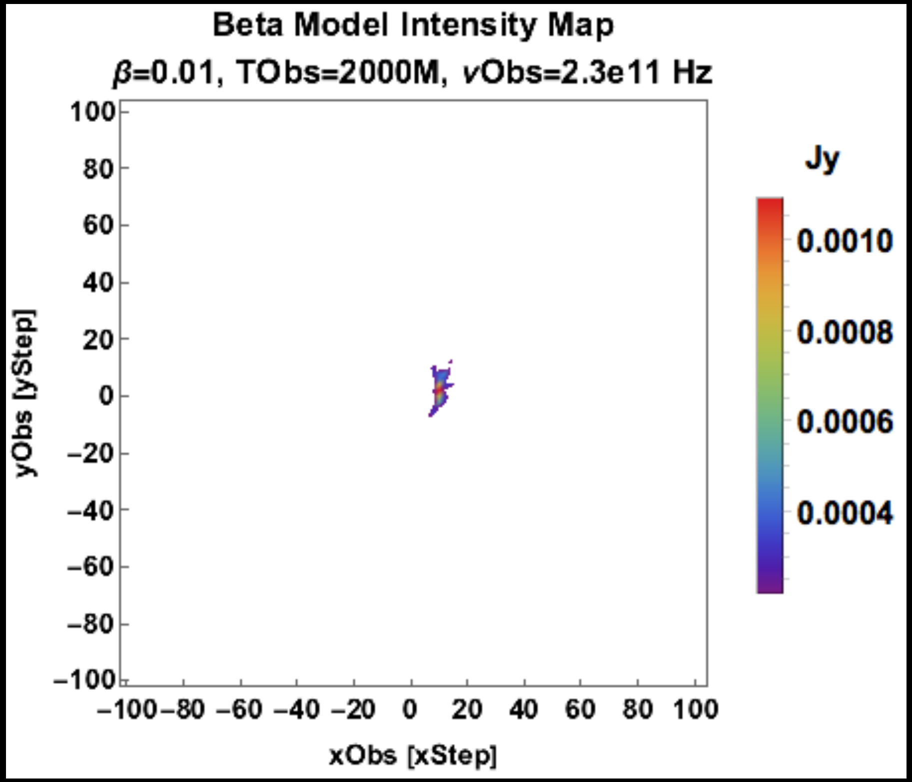






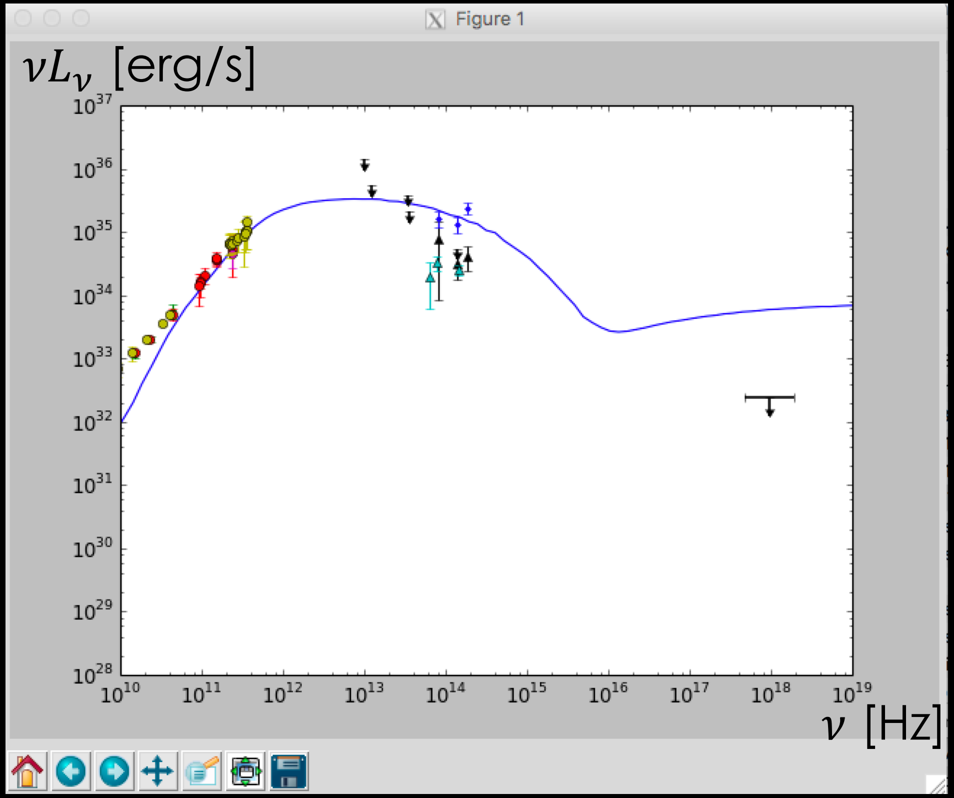
EHT SIZE CONSTRAINTS

- The model with the most compact emitting region is



RESULTS: SYNTHETIC SPECTRA

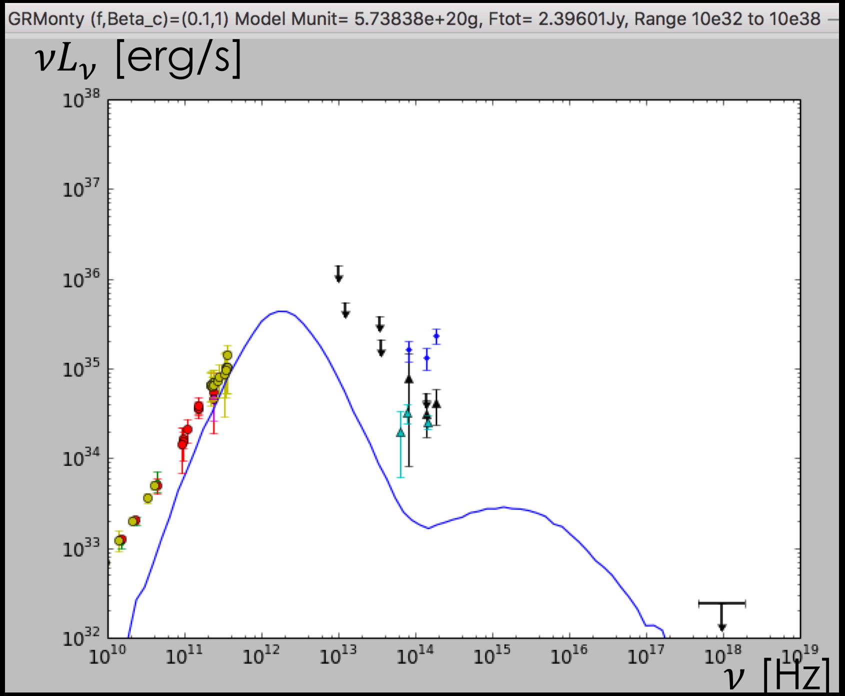
- Electron evolution model is a detailed calculation fitting most of data

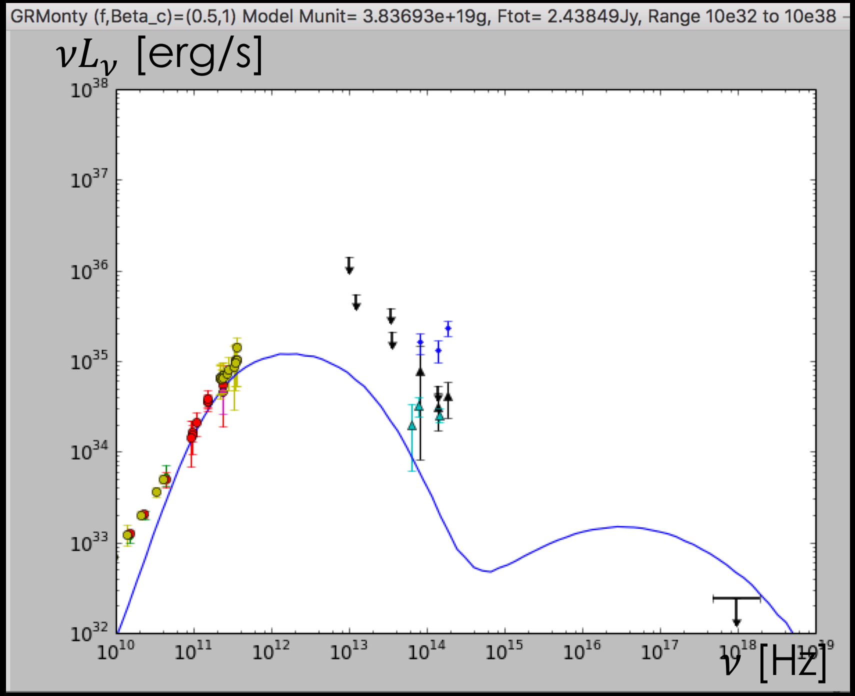


RESULTS: SYNTHETIC SPECTRA

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

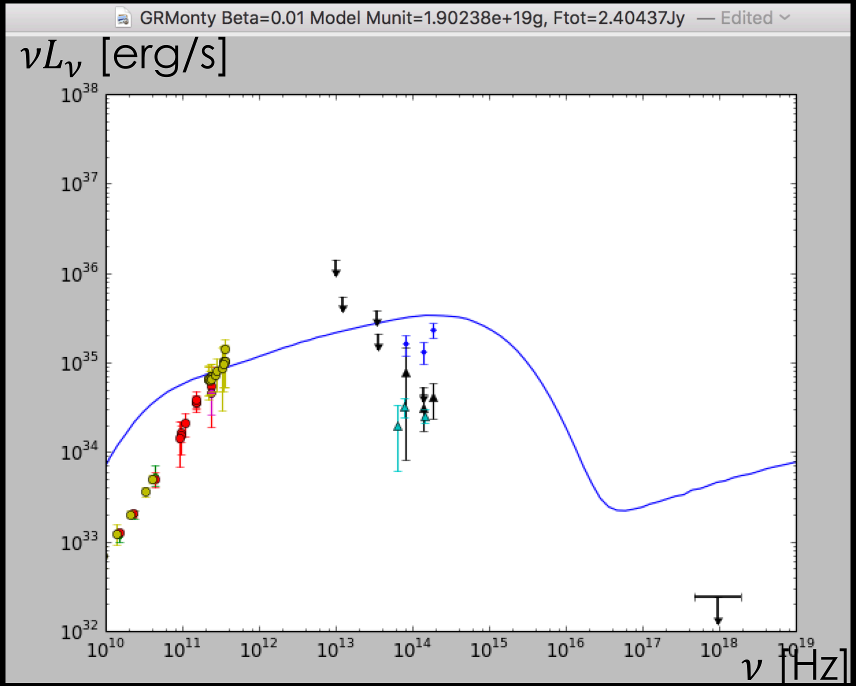
$(f_e\ ,\ \beta_c)$=(0.5,1)

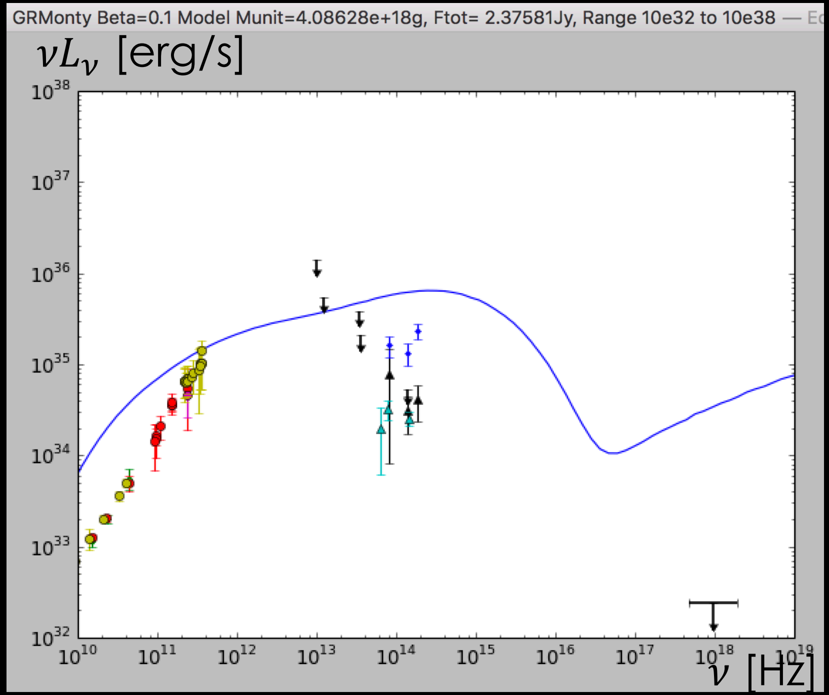




BETA MODEL SPECTRA

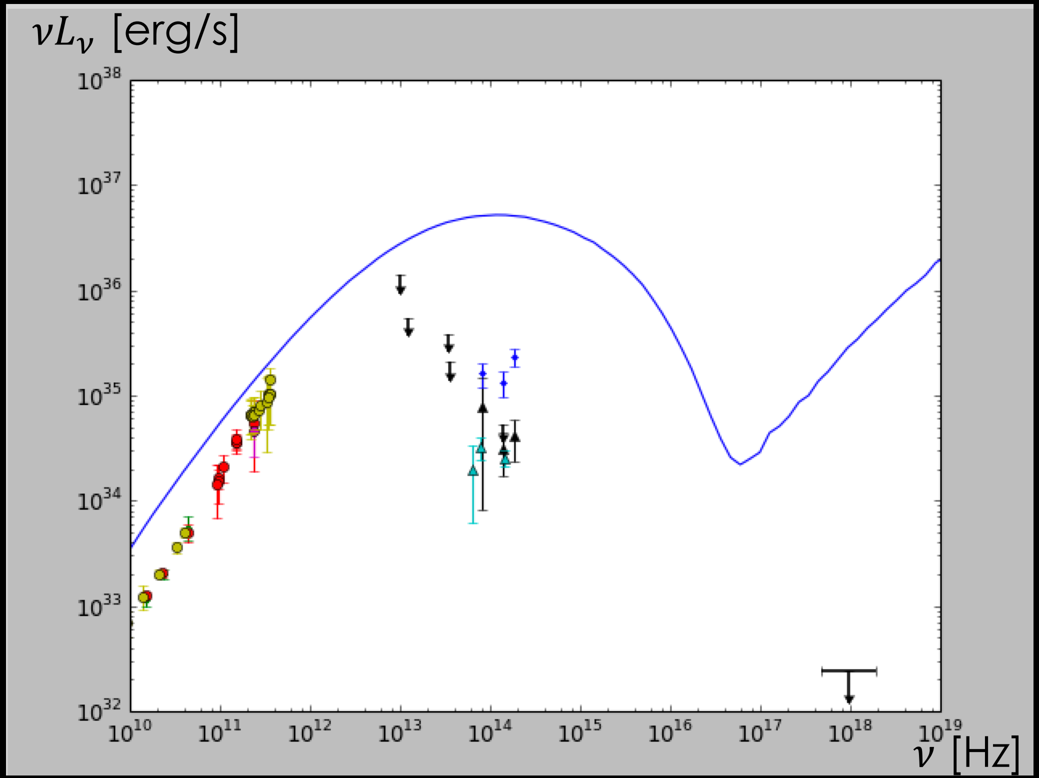
- Beta models have flatter-than-observed spectra near mm-bump, but similar slopes to observed spectrum after
  - $\beta = 0.01$, $\beta = 0.1$





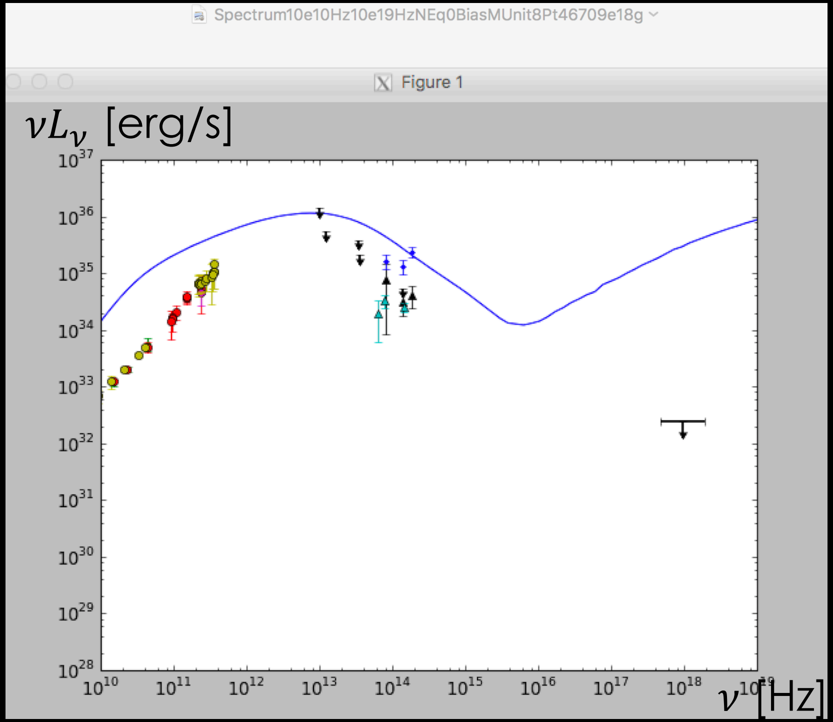
EQUIPARTITION MODEL SPECTRUM

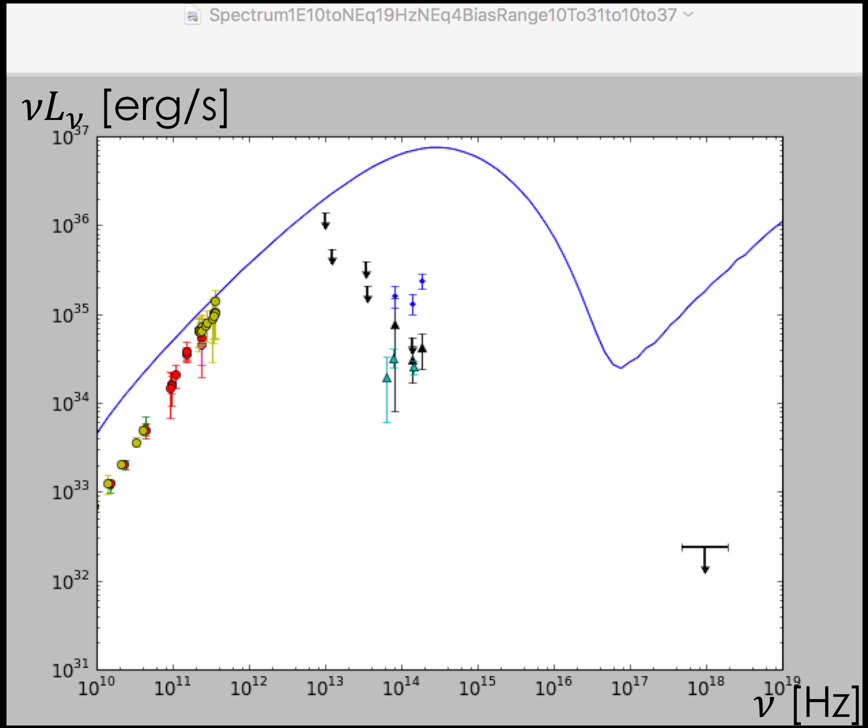
- Equipartition model



BIAS MODEL SPECTRA

- Bias model
  - N=0, N=4

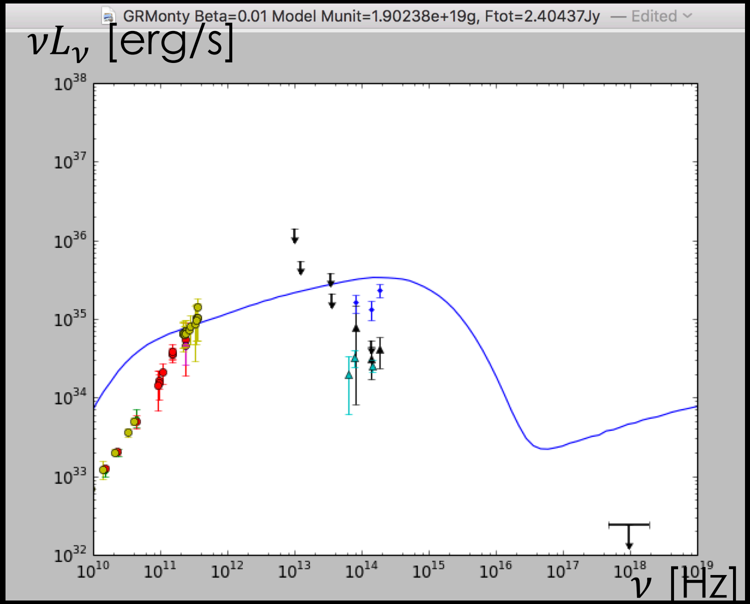




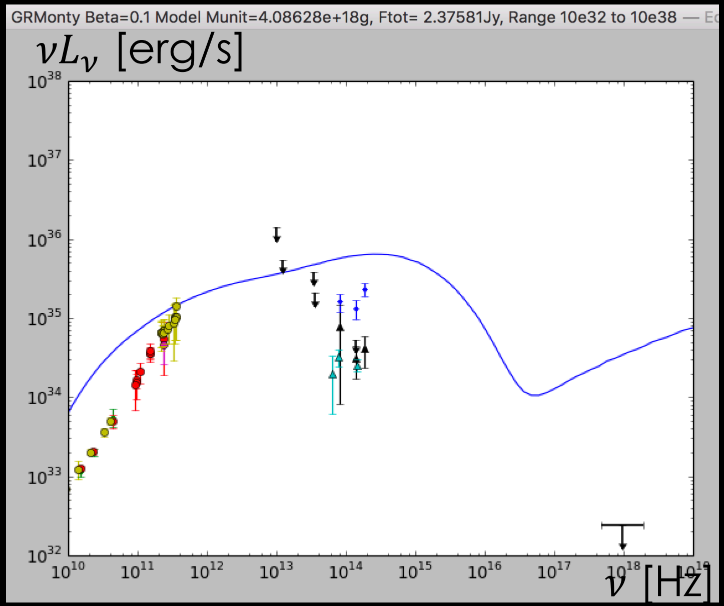
FLATTER SPECTRUM FOR LOWER BETA IN BETA MODELS

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

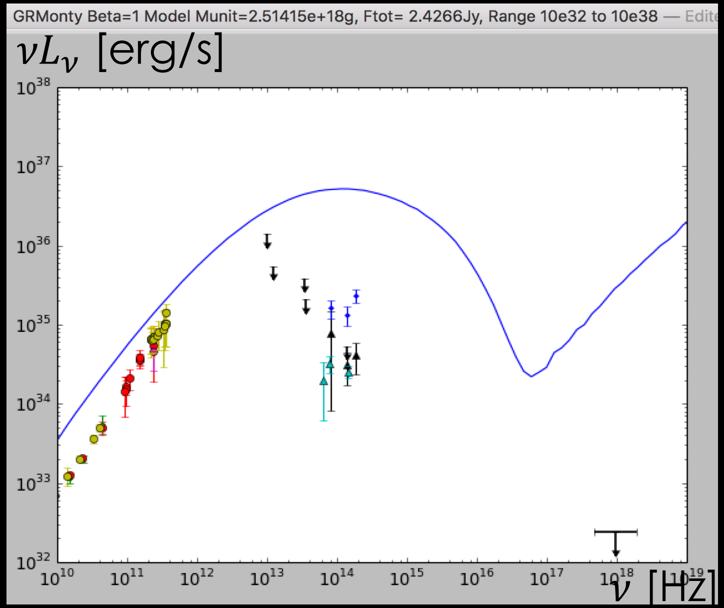
β=0.01



β=0.1

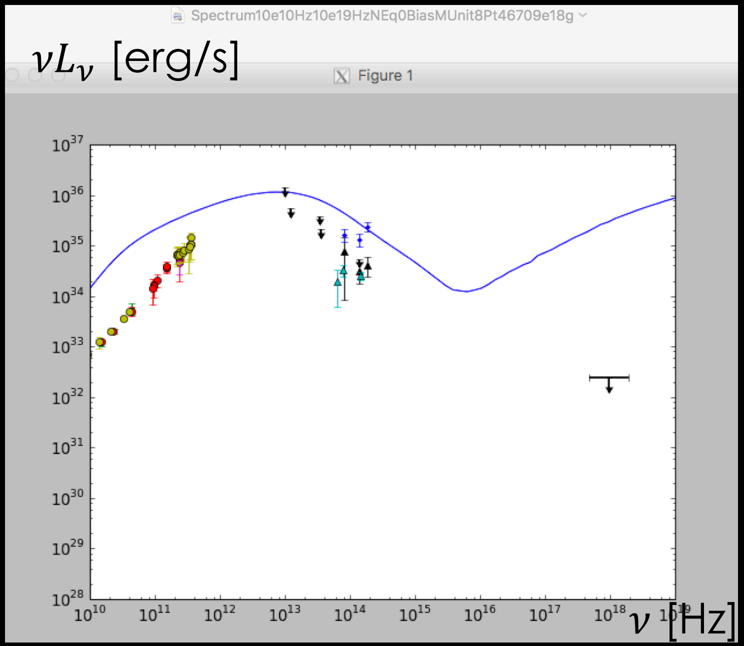


β=1

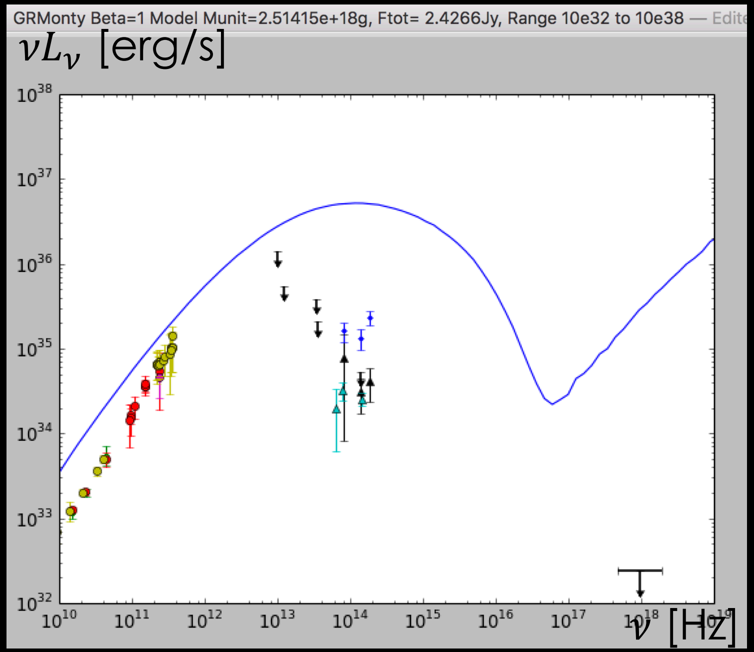


FLATTER SPECTRUM FOR LOWER N BIAS MODELS

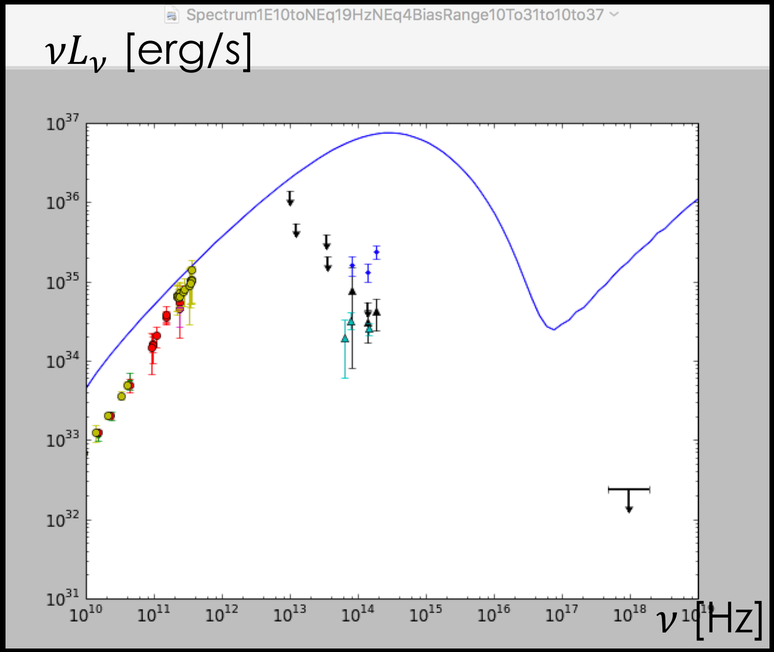
$N = 0$



$N = 2$



$N = 4$

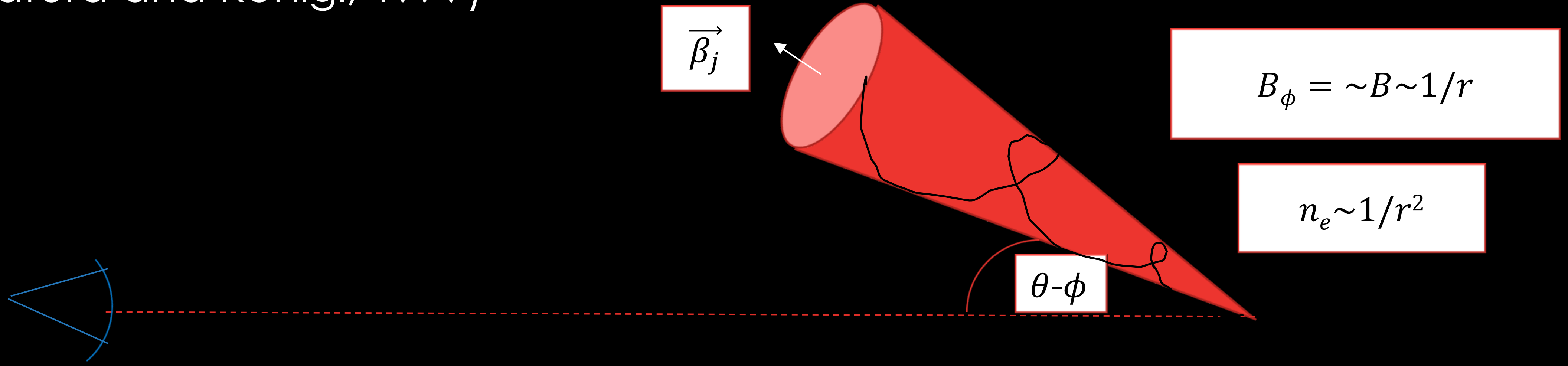


FLATTER SPECTRUM FOR BETA AND BIAS VS (f_e , β_c) MODELS

- 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 disk/corona emission

VIABLE MODEL: BLANDFORD-KONIGL JET

- (Blandford and Konigl, 1979)



VIABLE MODEL: BLANDFORD-KONIGL JET

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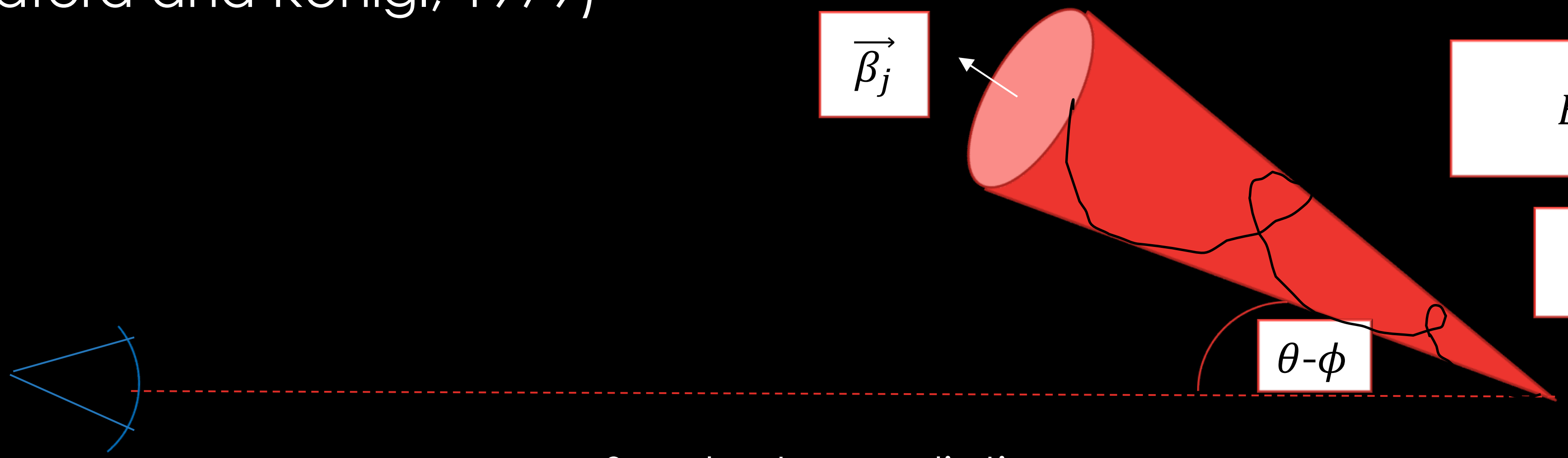


$$B_\phi = \sim B \sim 1/r$$

$$n_e \sim 1/r^2$$

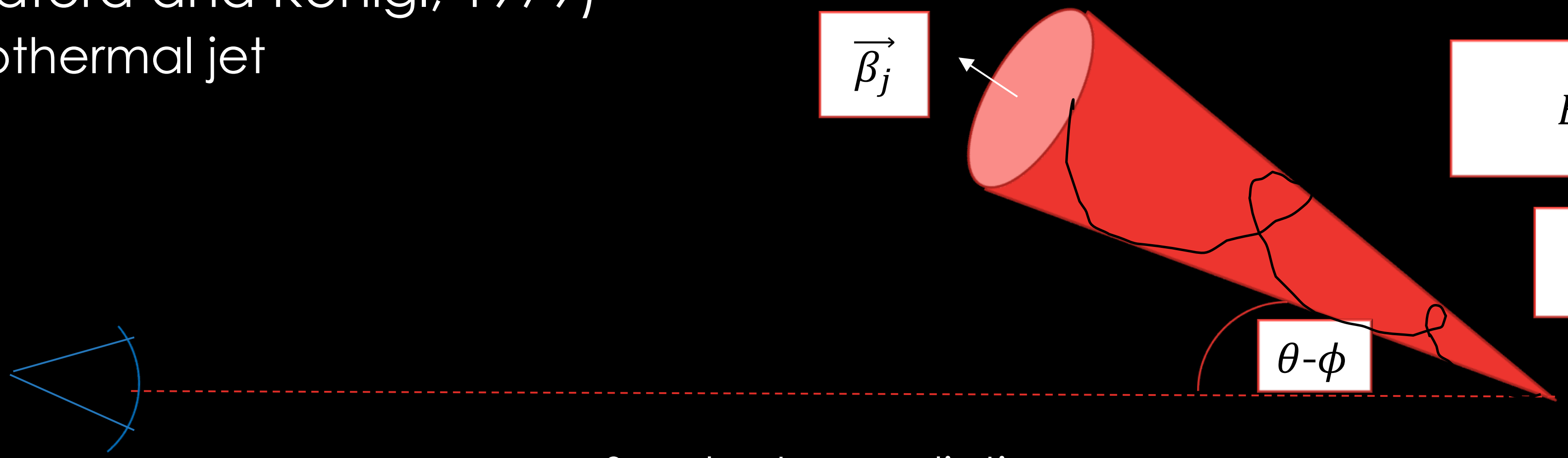
Synchrotron radiation:

$$\mathrm{N}(\gamma) = \mathrm{K}\gamma^2, \qquad \gamma_{\min} < \gamma < \gamma_{\max}$$
$$\rightarrow \quad \alpha = 1/2$$

$$u_e = Kmec^2 \ln \frac{\gamma_{\max}}{\gamma_{\min}}$$

VIABLE MODEL: BLANDFORD-KONIGL JET

- (Blandford and Konigl, 1979)
  - Isothermal jet



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$$\rightarrow \quad \alpha = 1/2$$

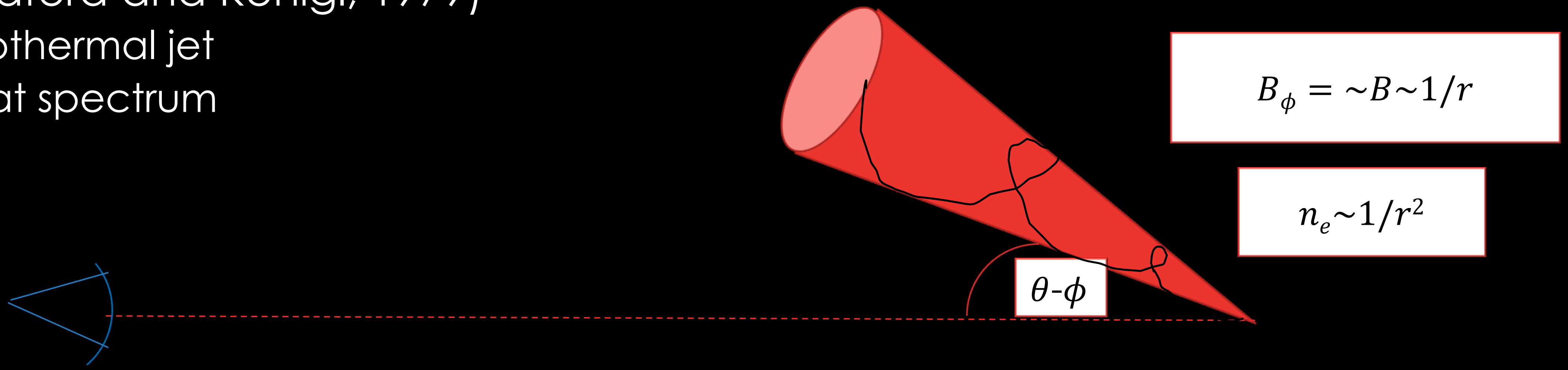
$$u_e = Kmec^2 \ln \frac{\gamma_{\mathrm{max}}}{\gamma_{\mathrm{min}}}$$

Assuming equipartition:

$$u_e = k_e \frac{B^2}{8\pi} \ln \frac{\gamma_{\mathrm{max}}}{\gamma_{\mathrm{min}}} \sim \frac{1}{r^2} \rightarrow \text{Isothermal Jet}$$

VIABLE MODEL: BLANDFORD-KONIGL JET

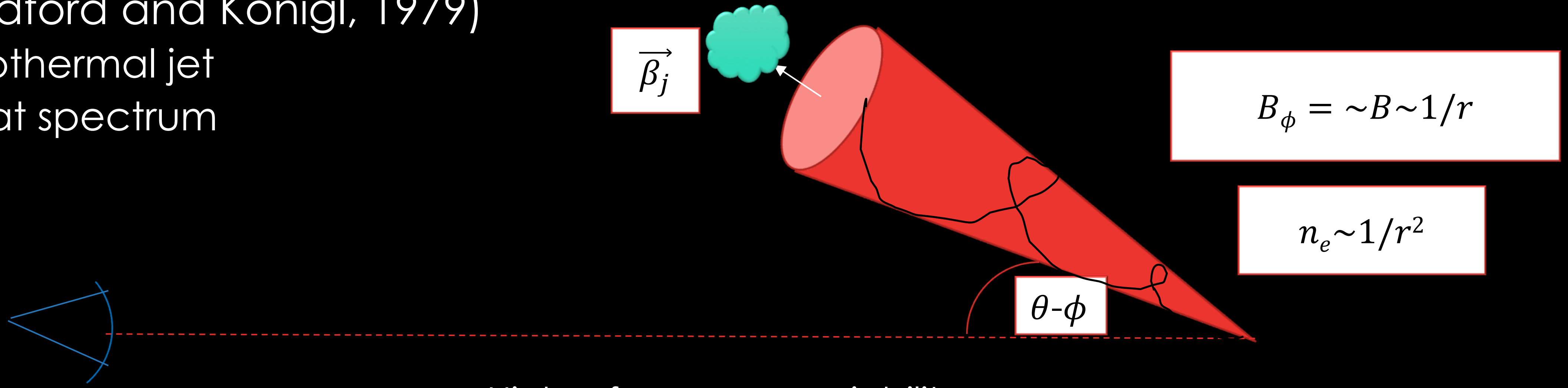
- (Blandford and Konigl, 1979)
  - Isothermal jet
  - Flat spectrum



GRMHD simulations (Moscibrodska and Falcke, 2013) confirm flat spectrum due to optically thick jet regions

VIABLE MODEL: BLANDFORD-KONIGL JET

- (Blandford and Konigl, 1979)
  - Isothermal jet
  - Flat spectrum



Higher frequency variability

BIAS MODELS WITH BLANDFORD-KONIGL JET

- The $N = 0$ bias model has constant pressure along the jet,

$$P_e = K_N$$

which may lead to jet regions dominating emission

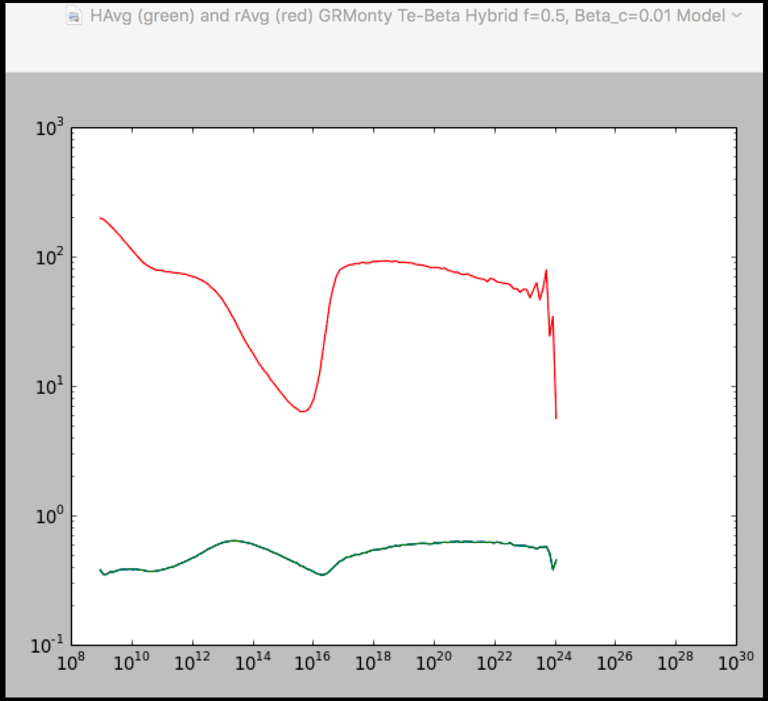
- $P_e \sim b^N, N > 0$ has electron gas pressure fall off with radius

$$P_e = K_N \left(\frac{b}{\sqrt{2}}\right)^N, B \sim 1/r$$

ISSUE: LOW FREQUENCY SPECTRUM OVERPRODUCED

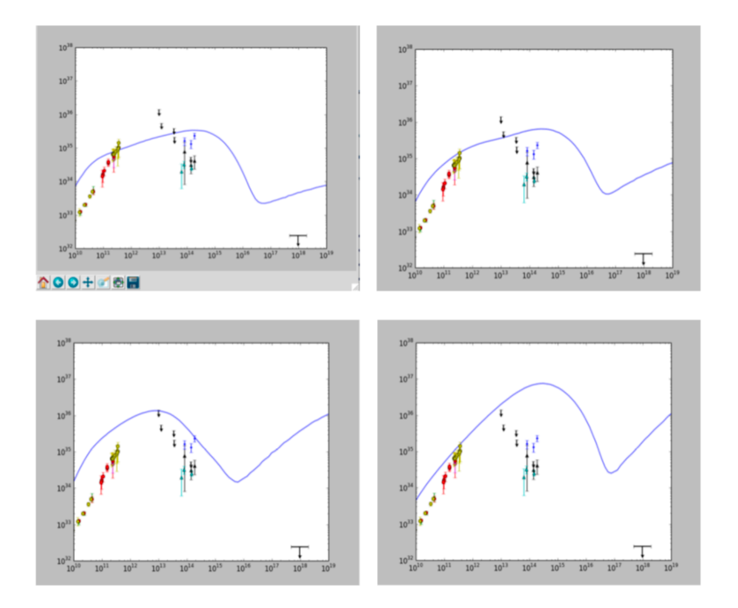
- Emission-weighted avg. polar angle (green) from jet axis ranges from
  - ~ 0.4 rad to ~ 0.4 rad for $10^{9} < \nu\ /\mathrm{Hz} < 10^{11}$
  - ~ 0.4 rad to ~0.6 rad to 0.3 rad for $10^{11} < \nu\ /\mathrm{Hz} < 10^{16}$
  - ~ 0.3 rad to ~0.5 rad $10^{16} < \nu\ /\mathrm{Hz} < 10^{18}$
  - ~ 0.3 rad to ~0.6 rad $10^{18} < \nu\ /\mathrm{Hz} < 10^{23}$
- Emission-weighted avg. radius (red) from:
  - 200M to 75M for $10^{9} < \nu\ /\mathrm{Hz} < 10^{11}$
  - 75M to 5M for $10^{11} < \nu\ /\mathrm{Hz} < 10^{16}$
  - 5M to 100M $10^{16} < \nu\ /\mathrm{Hz} < 10^{18}$
  - 100M to 80M $10^{18} < \nu\ /\mathrm{Hz} < 10^{23}$

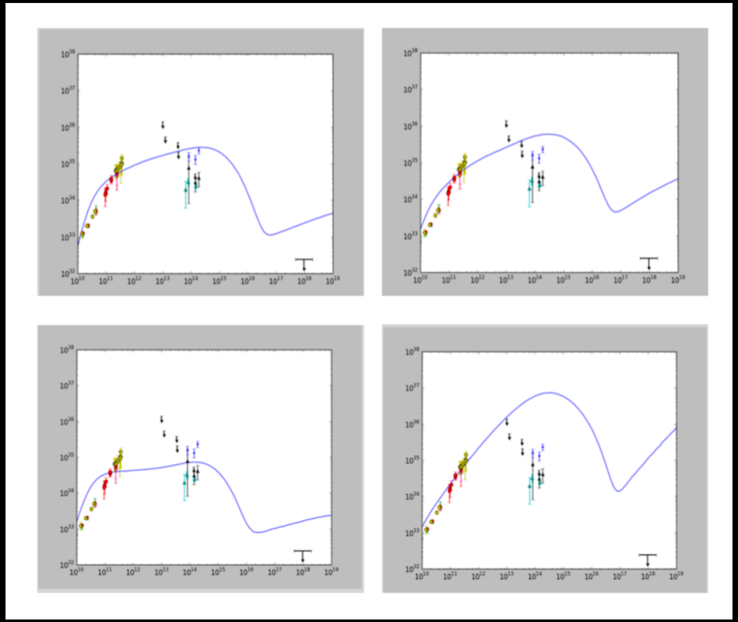
0.5 rad = 29°



POSSIBLE REMEDIES

- Excise region beyond r=50M





CONCLUSIONS

- Our parameterized models reproduce some aspects of Sgr A* observed 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 region for β=0.01, closest to satisfying EHT size constraint

FUTURE DIRECTIONS

- Sgr A* variability
- Other EHT sources: M87, 3C 279, Cen A, NGC 1052, OJ 287

EXTRA SLIDES

SGR A* OBSERVATIONS: LUMINOSITY

- Sgr A* is a low luminosity active galactic nucleus (AGN)

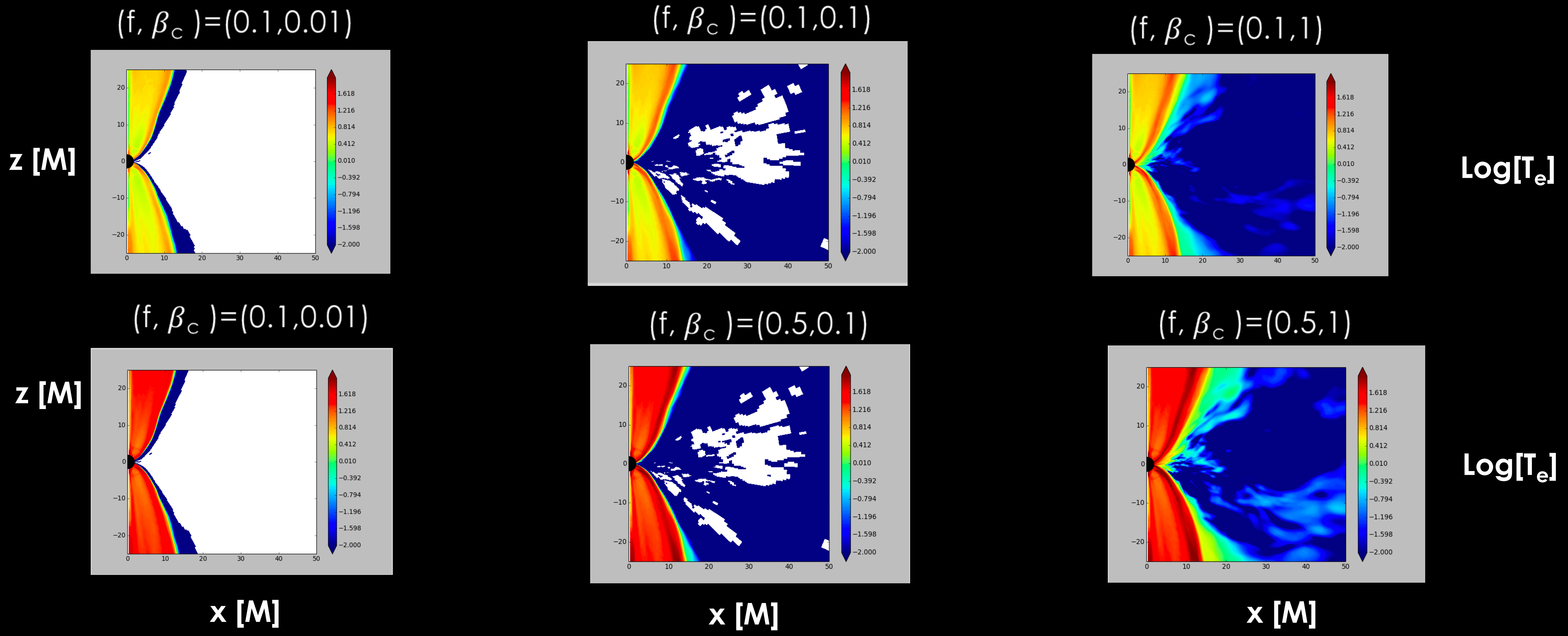
POSTPROCESSING: RADIATIVE TRANSFER

- IBOTHROS (Noble et al. 2007) solves general relativistic radiative transfer equations for photon geodesics between source and "camera"

$$\boxed{\frac{d^2x^\mu}{ds^2} = -\Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{ds}\frac{dx^\beta}{ds}}$$

$$\boxed{\frac{dN^\mu}{ds} = -\Gamma^\mu_{\alpha\beta}N^\alpha N^\beta, \qquad N^\mu = \frac{dx^\mu}{ds}}$$

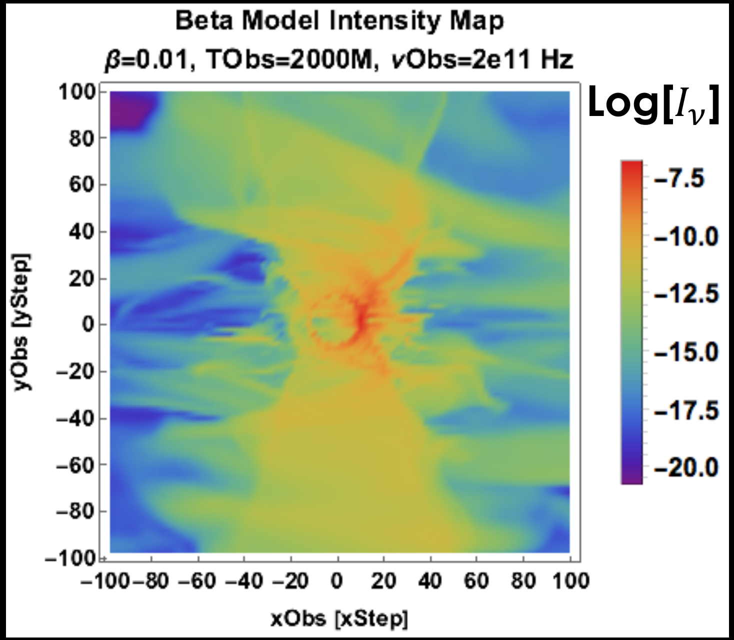
SIMULATION ELECTRON TEMPERATURE PROFILES

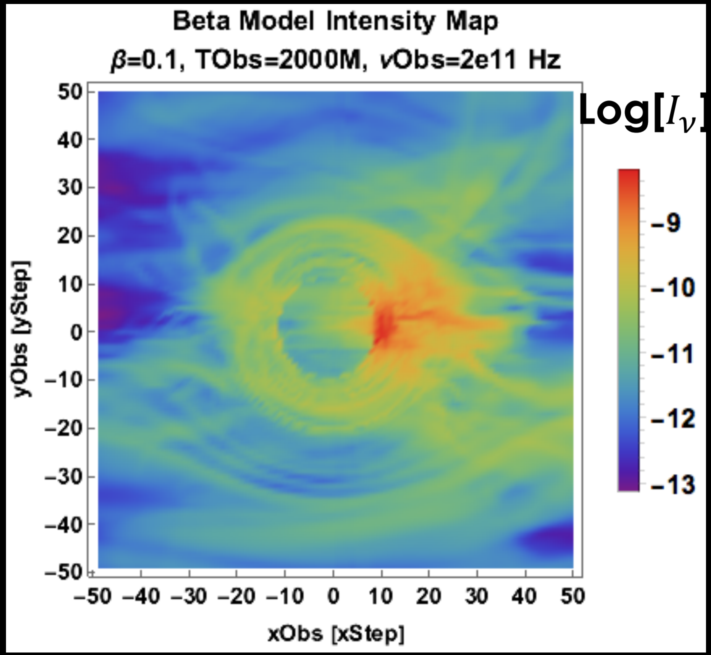


RESULTS: SYNTHETIC IMAGES

BETA MODEL IMAGES

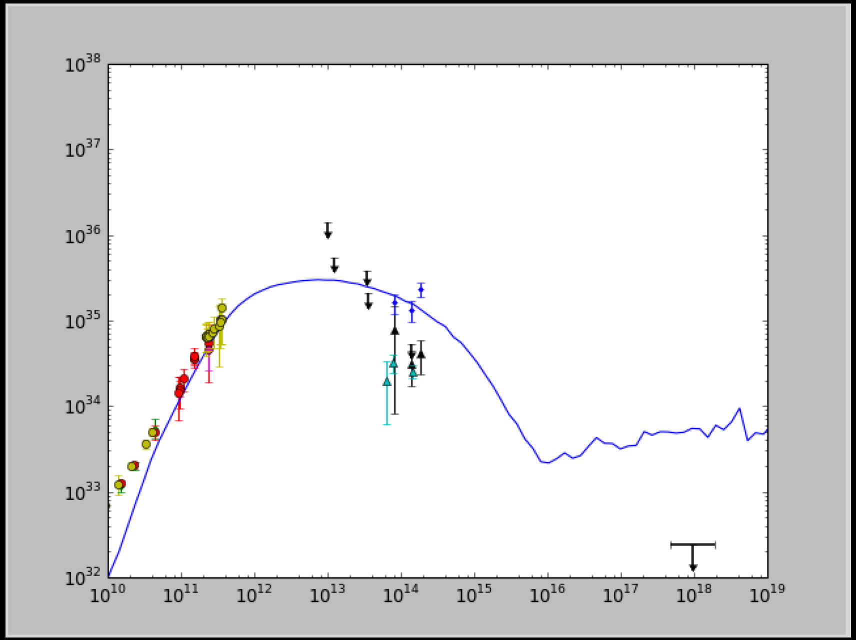
- Beta models light up the extended outflow at low β and small radii (photon ring) at high β
  - $\beta = 0.01$, $\beta = 0.1$

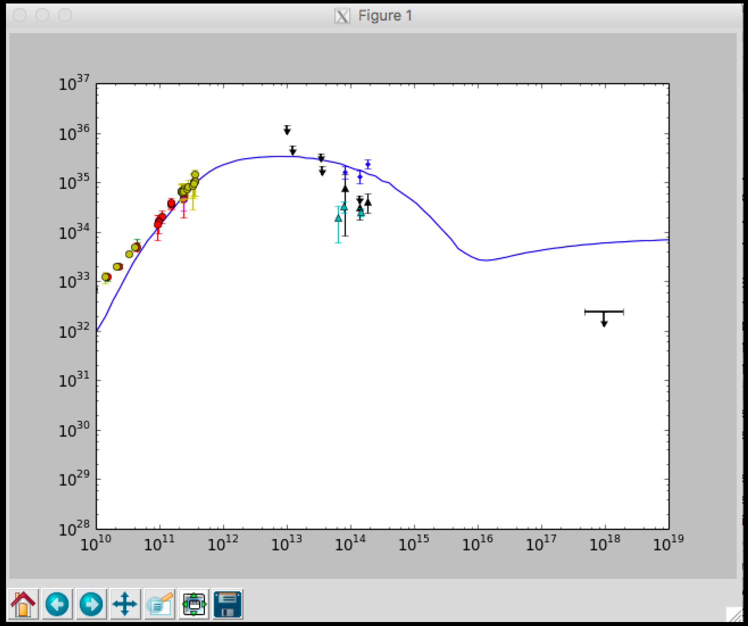


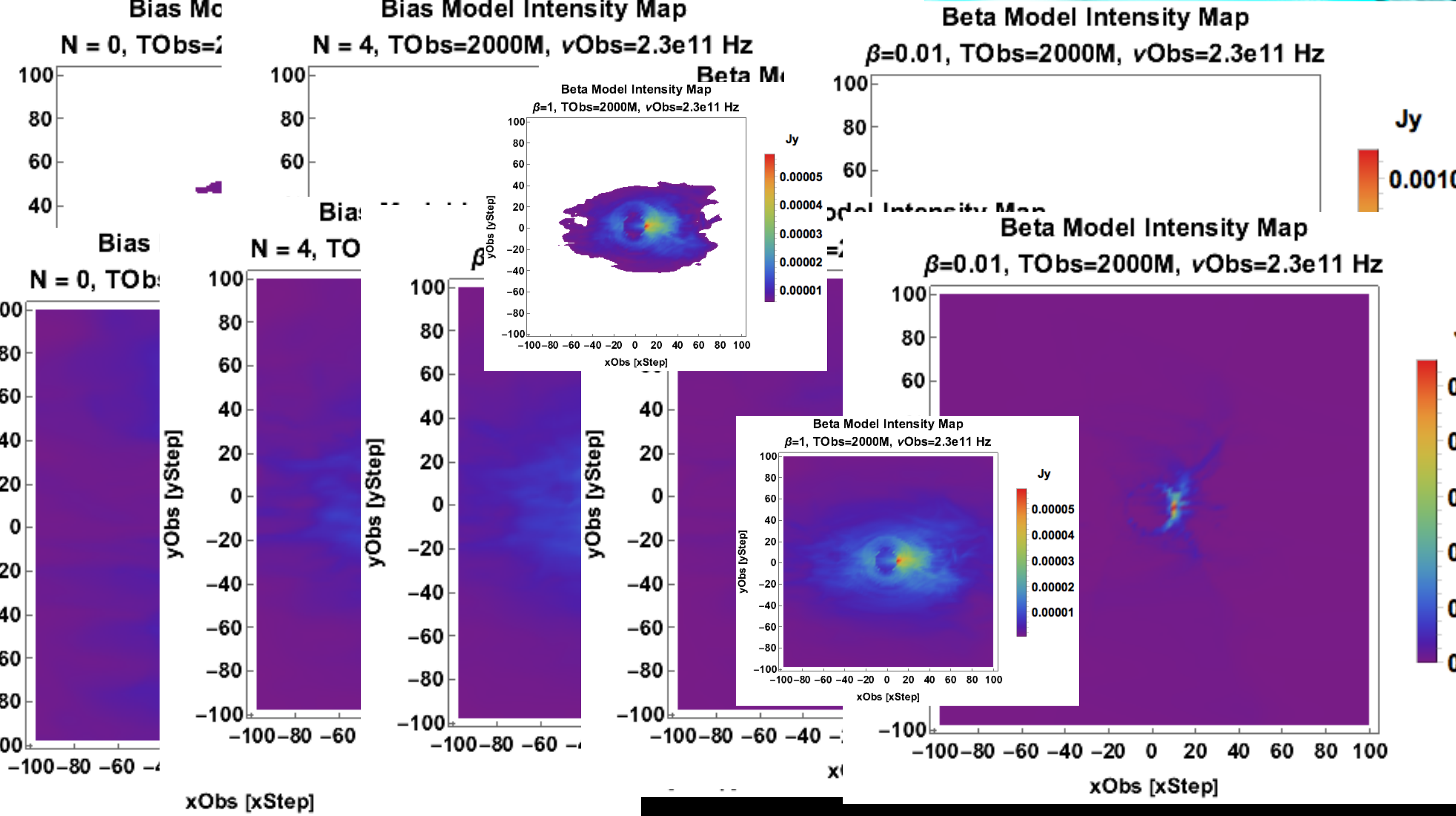


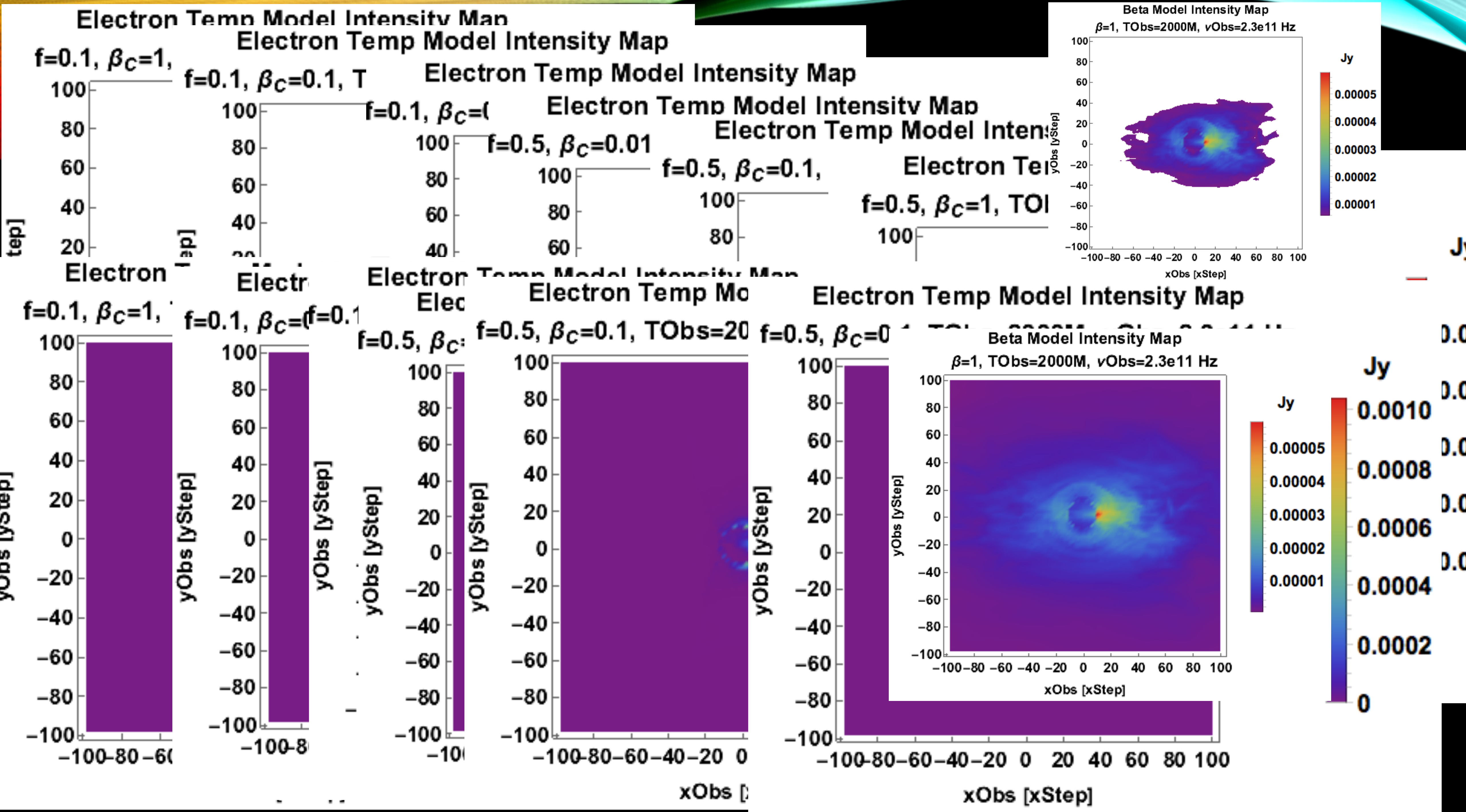
RESULTS: SYNTHETIC SPECTRA

- Electron evolution model (detailed calculation)






Bias Model Intensity Map
N = 4, TObs=2000M, νObs=2.3e11 Hz
Beta Model Intensity Map
β=0.01, TObs=2000M, νObs=2.3e11 Hz
Jy
Beta Model Intensity Map
β=1, TObs=2000M, νObs=2.3e11 Hz
Jy
0.00005
0.00004
0.00003
0.00002
0.00001
yObs [yStep]
xObs [xStep]
Beta Model Intensity Map
β=0.01, TObs=2000M, νObs=2.3e11 Hz
Beta Model Intensity Map
β=1, TObs=2000M, νObs=2.3e11 Hz
Jy
0.00005
0.00004
0.00003
0.00002
0.00001
yObs [yStep]
xObs [xStep]
yObs [yStep]
xObs [xStep]



Electron Temp Model Intensity Map
f=0.1, βC=1,
f=0.1, βC=0.1, T
f=0.5, βC=0.01
f=0.5, βC=0.1,
f=0.5, βC=1, TO
f=0.5, βC=0.1, TObs=20
Beta Model Intensity Map
β=1, TObs=2000M, νObs=2.3e11 Hz
Jy
0.00005
0.00004
0.00003
0.00002
0.00001
0.0010
0.0008
0.0006
0.0004
0.0002
0
yObs [yStep]
xObs [xStep]

OTHER OBSERVATIONS

- The EHT may show for the BL-Lac M87
  1) Collimation for inner ~10M
  2) Strong, ordered B-field

Consistent with:
1.) jet held together by thick disk
2.) powered by BH spin and B-flux threading horizon (Blandford and Znajek, 1977)

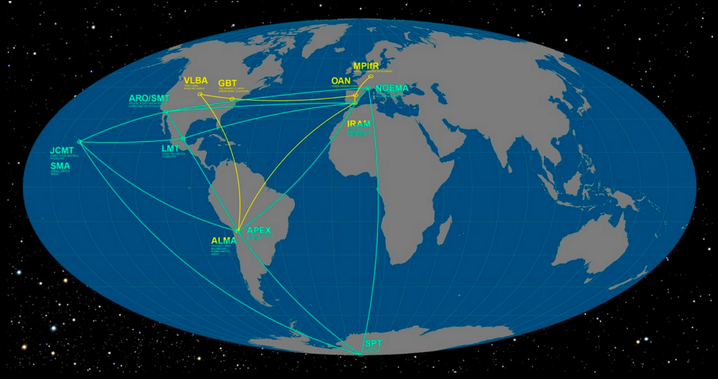
QUESTIONS

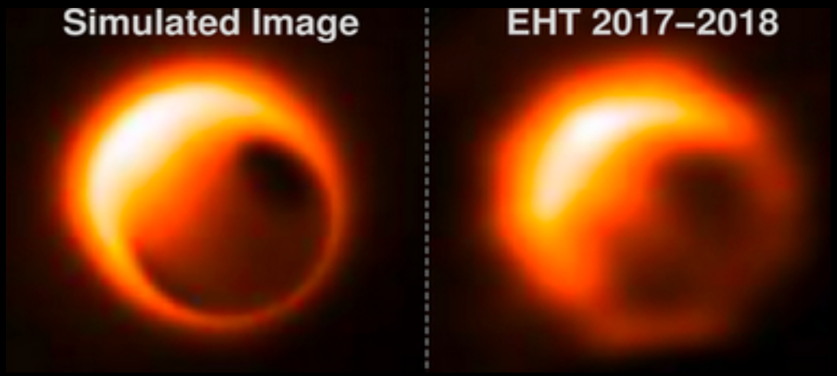
- *Can a single parametric model describe Sgr A* emission over regions including disk, disk wind and outflow?*

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

BLACK HOLES - OBSERVATIONS

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





- Read: http://news.nationalgeographic.com/2017/04/black-hole-event-horizon-telescope-pictures-genius-science/
- Exercise: Can you explain why baselines of radio telescopes are so long in view of the angular resolution limit below?

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

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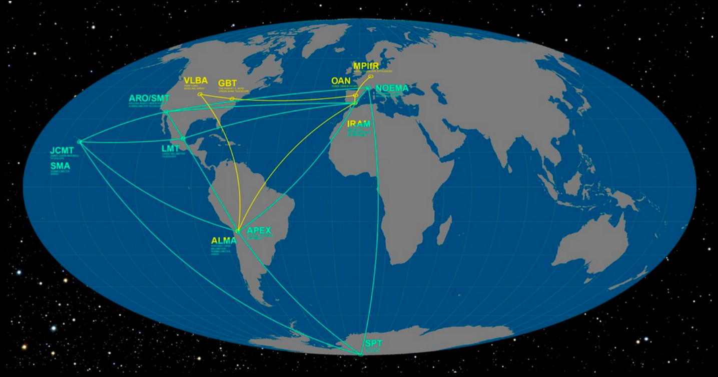

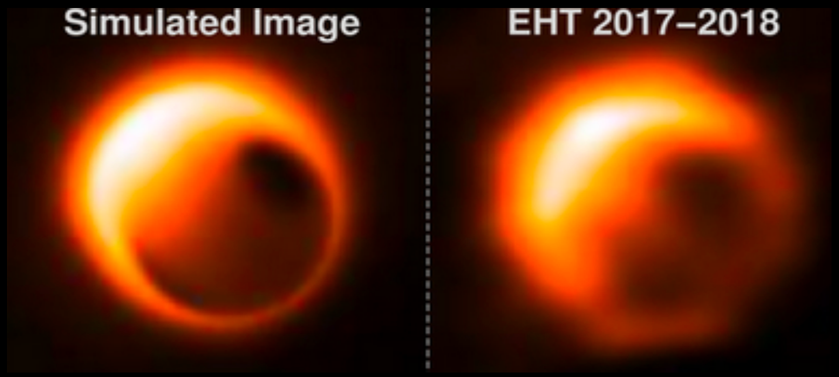

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- Exercise: Can you explain why baselines of radio telescopes are so long in view of the angular resolution limit below?
  - The ability to disting … aration increases with aperture diameter

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