Electrifying GRMHD Simulations

Modeling Sgr A* Using Self-Consistent Electron Thermodynamics

Sean Ressler[1]; Eliot Quataert[1]; Sasha Tchekhovskoy[1]; Mani Chandra[2]; Charles Gammie[2]

[1]University of California Berkeley, [2]University of Illinois Urbana-Champaign

What Do We Need To Compare Sims to Observations?

- GRMHD fluid evolution ✓

$$\Rightarrow T_g \equiv T_e + T_p, \rho, b^\mu, \text{etc.}$$

(Gammie+ 2003, De Villiers+ 2003, Komissarov 2009, White+ 2016, etc.)

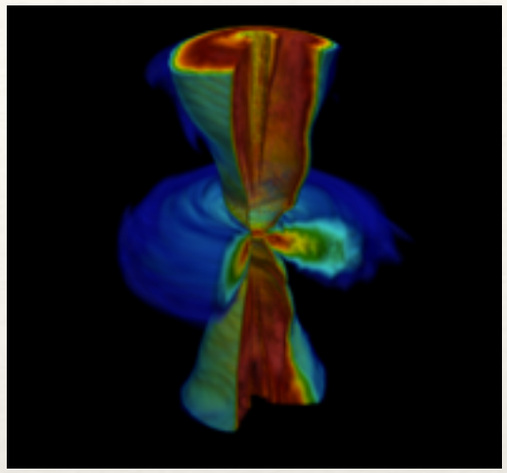
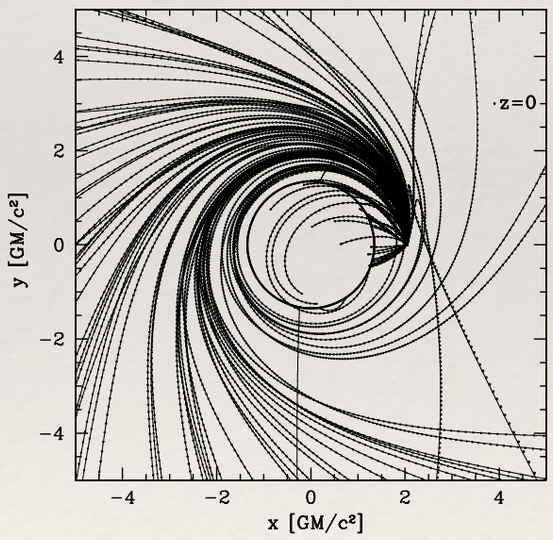


Image Credit: Josh Dolence



- Ray tracing + radiation transport ✓

(Noble+ 2007; Dolence+ 2009, Chan+ 2013; etc.)

All set, right?

No!!!

$$\tau_{ie} \gg \tau_{acc} \Rightarrow T_e \neq T_p$$

- Electron Thermodynamics ✓ (Ressler et al. 2015)

$$\Rightarrow T_e$$

Electron Model

- Add electron entropy equation to GRMHD evolution:

$$\rho T_e u^\mu \partial_\mu s_e = f_e Q - \nabla_\mu q_e^\mu - a_\mu q_e^\mu$$

$\sim \frac{ds_e}{dt}$

e-heating that depends on plasma conditions

Anisotropic electron conduction (See Manichandra's talk Friday + Chandra et al. 2015!)

$$Q = Q_{\rm sim} = \rho T_g u^\mu \partial_\mu s_g \qquad q_e^\mu \propto b^\mu$$

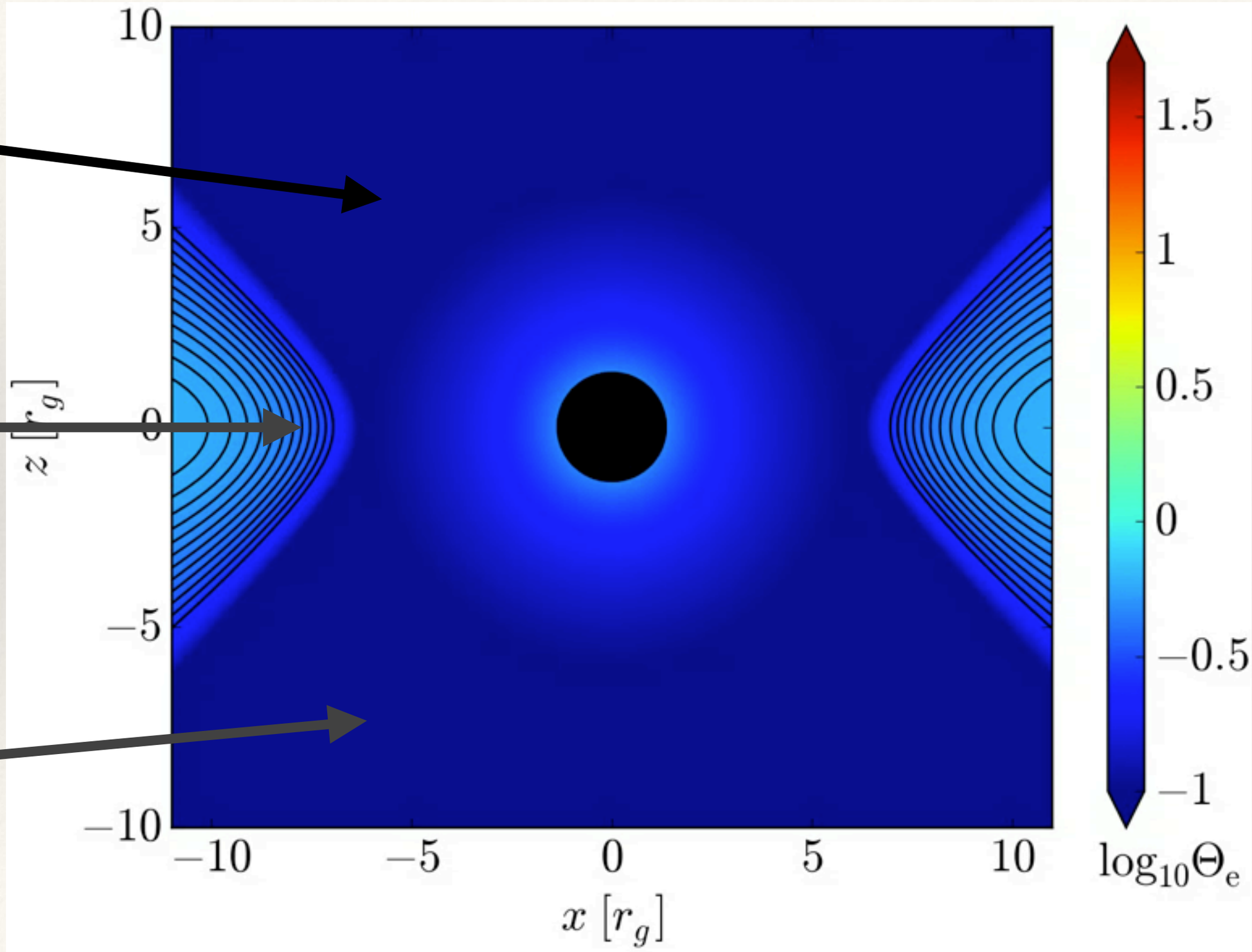
$$f_e \sim \begin{cases} 1 & \beta \lesssim 1 \\ f(T_p/T_e) \ll 1 & \rho \kappa_e \beta \left(\hat{b}^\mu \nabla_\mu T_e + \hat{b}^\mu a_\mu T_e \right) \end{cases} \qquad |q_e^\mu| \sim$$

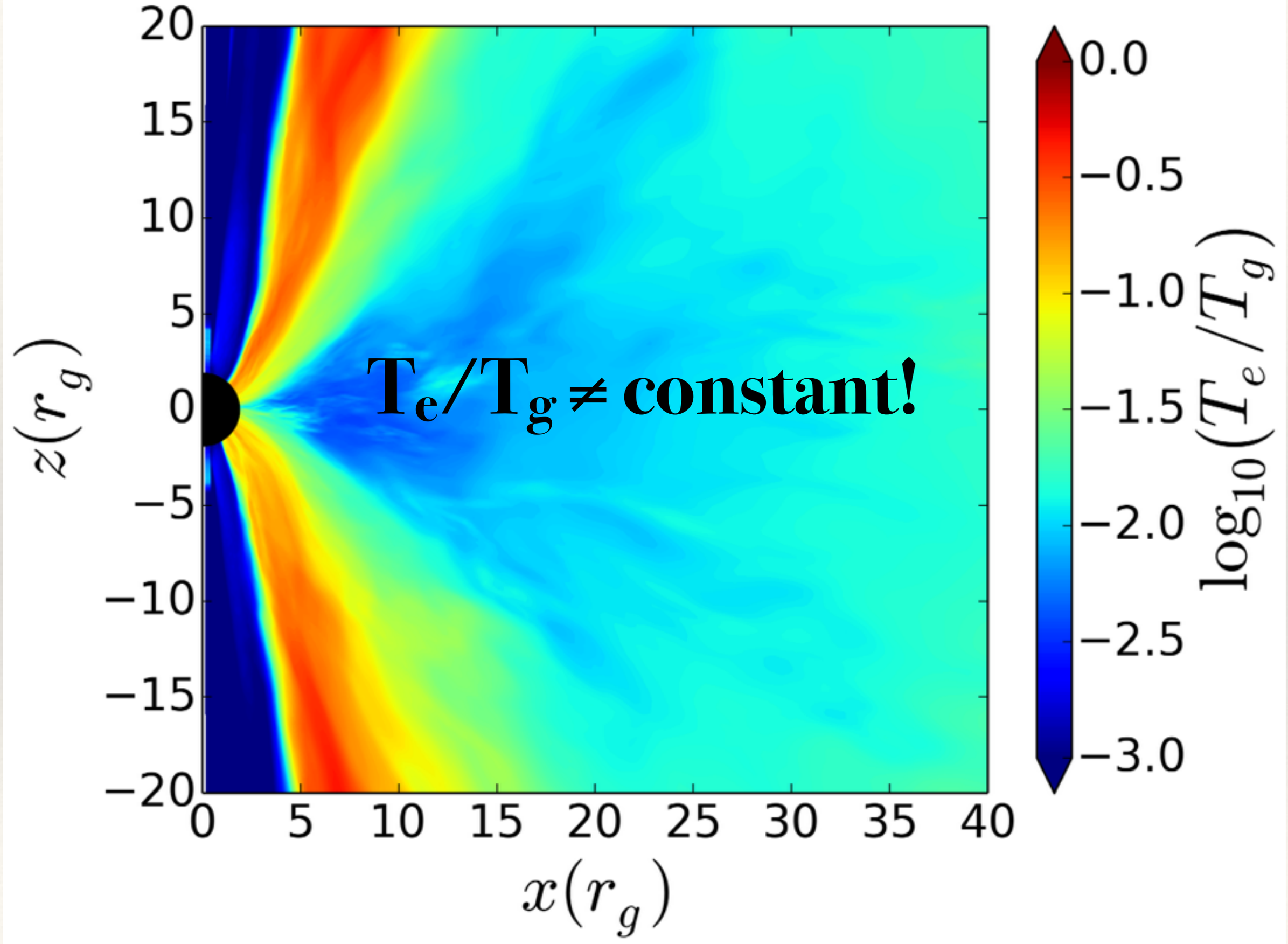
3D Electron Temperature

Corona: Hot

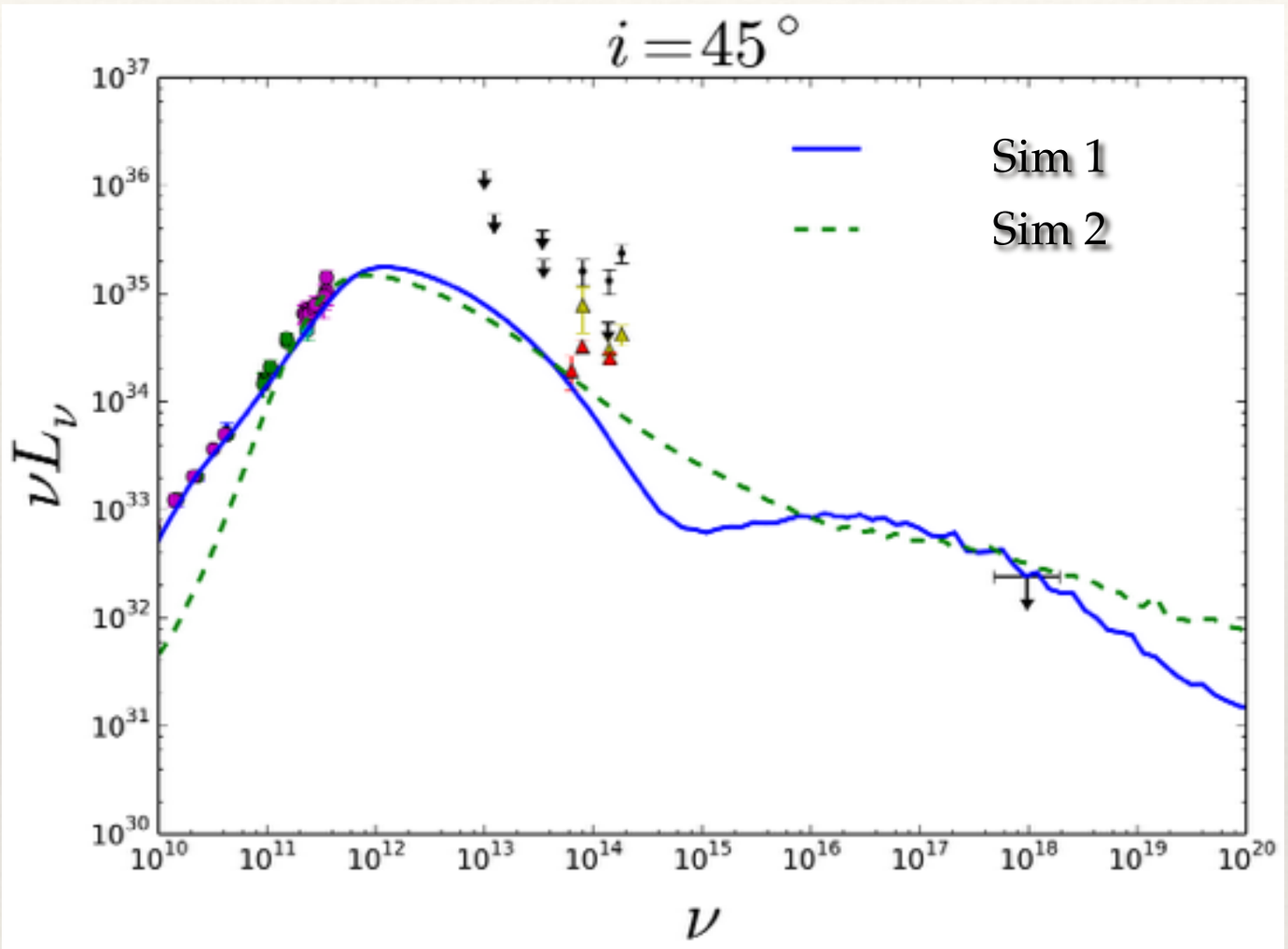
Midplane: Cold

Corona: Hot

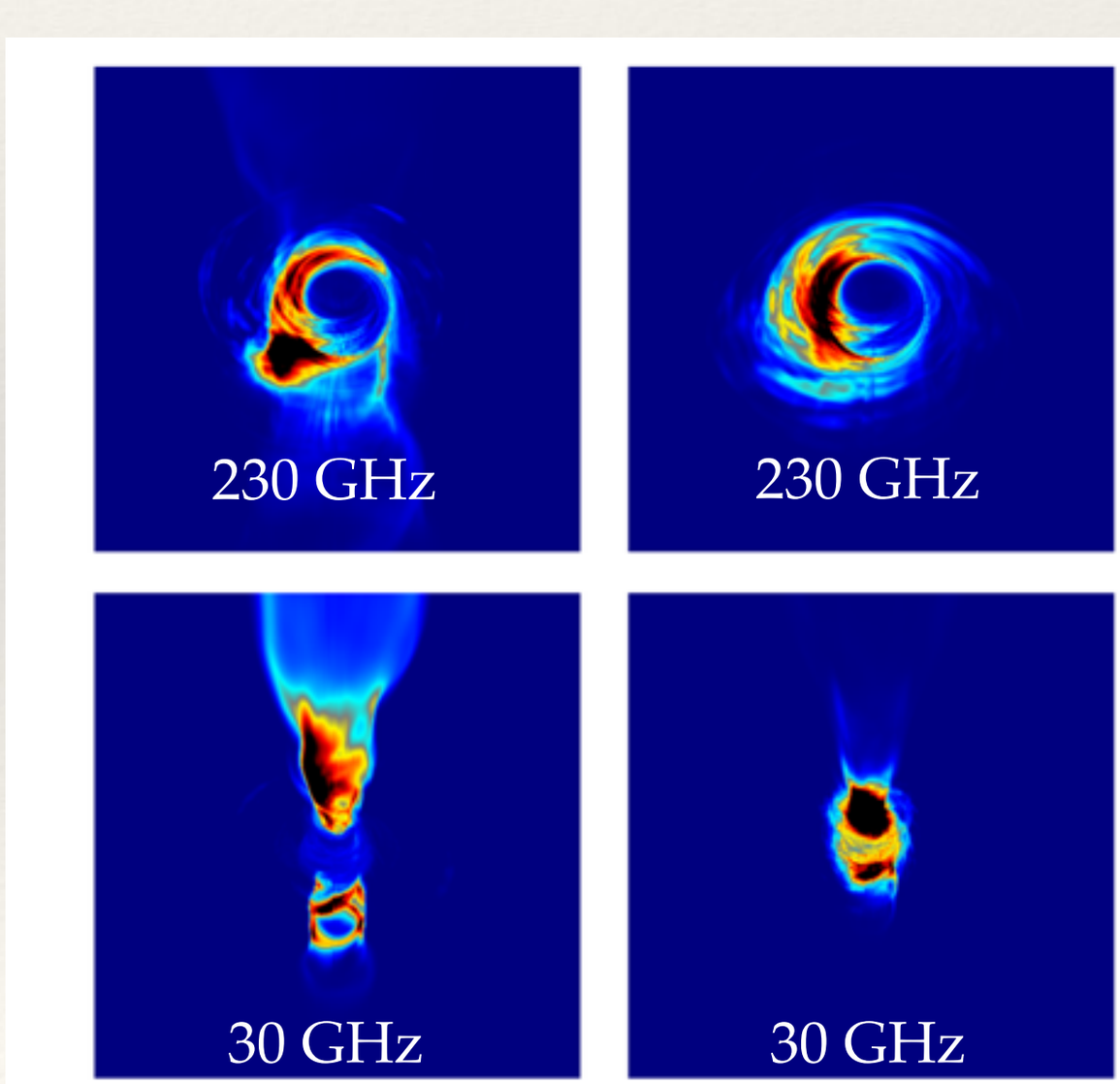



$T_e/T_g \neq$ constant!
$z(r_g)$
$x(r_g)$
$\log_{10}(T_e/T_g)$
20
15
10
5
0
−5
−10
−15
−20
0
5
10
15
20
25
30
35
40
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0

Predictive Spectra and Images



Davidson+ 1996; Telesco+ 1996; Falcke+ 1998; Cotera+ 1999; Genzel+ 1999; Genzel+ 2003; An+ 2005; Schödel+ 2007; Doeleman+ 2008; Schödel+ 2011; Neilsen+ 2013; Bower+ 2015



Conclusions and Future Work

Take Away Message:

Physically motivated e^- heating can naturally reproduce Sgr A* low frequency radio slope via emission from strongly magnetized disk corona/jet and is vital for more robust predictions

…And we have only scratched the surface:

- X-ray, IR time variability
- X-ray flares?
- More detailed parameter surveys
- EHT image size constraints
- MAD disks
- Field ordering EHT constraints

Plus applications to higher $\dot{M}$ systems: M87, X-ray binaries, etc. using e^- energy equation + Monte Carlo RT for cooling (Ryan, Ressler+ in prep)