Electron Heating Physics in Images and Variability of Sagittarius A*

Andrew Chael
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arXiv:1804.06416
Work with Michael Rowan, Ramesh Narayan,
Michael Johnson, and Lorenzo Sironi

Event Horizon Telescope

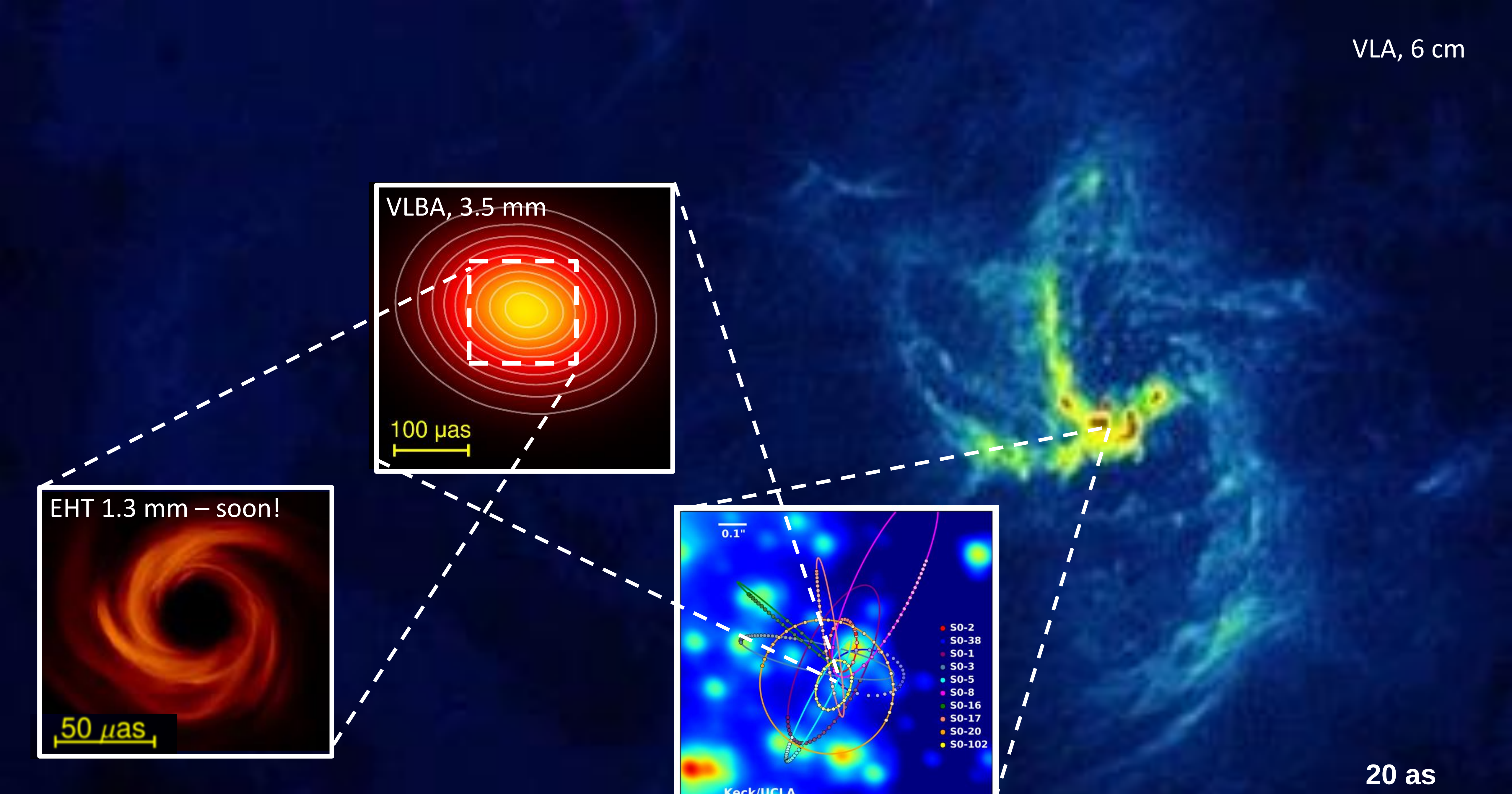
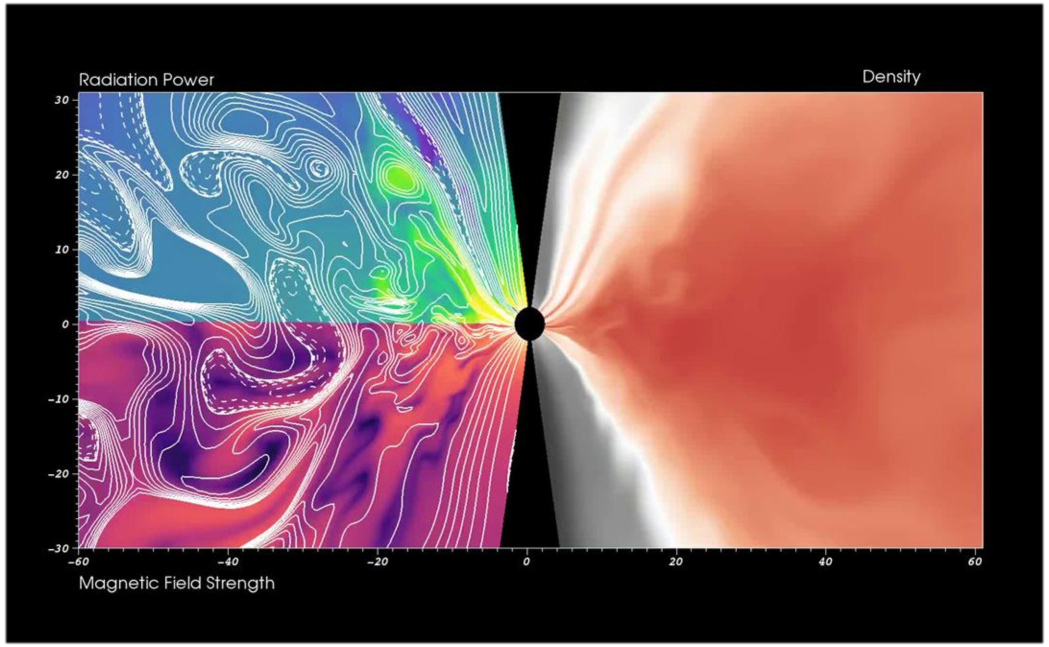
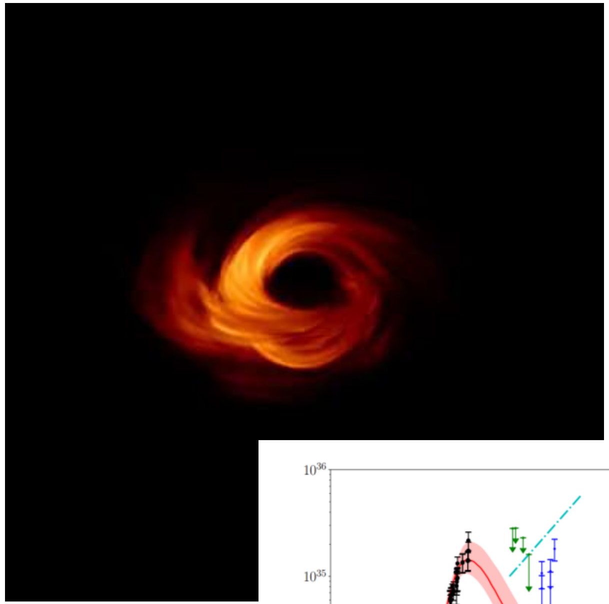


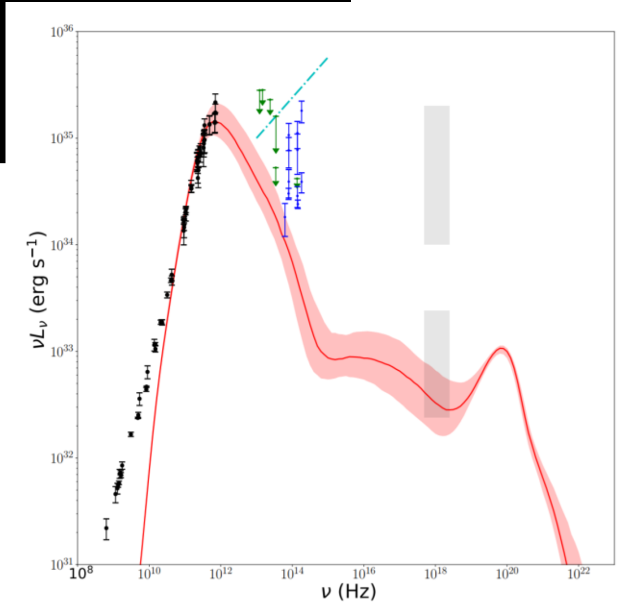
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck),
Gisela Ortiz-Leon (VLBA+LMT model fit),

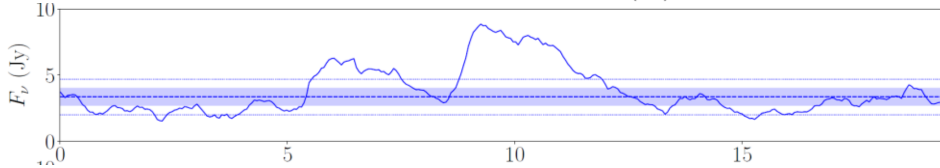
From simulations to observables



$T_e?$







Standard GRMHD evolves a **single** fluid and magnetic field

Raytraced Movie Credit: Hotaka Shiokawa

Goal: investigate different sources of microscale electron heating in self-consistent two-temperature simulations of Sgr A*.

-using the code KORAL: (Sądowski et al. 2017)

-see also: (Ressler et al. 2017)

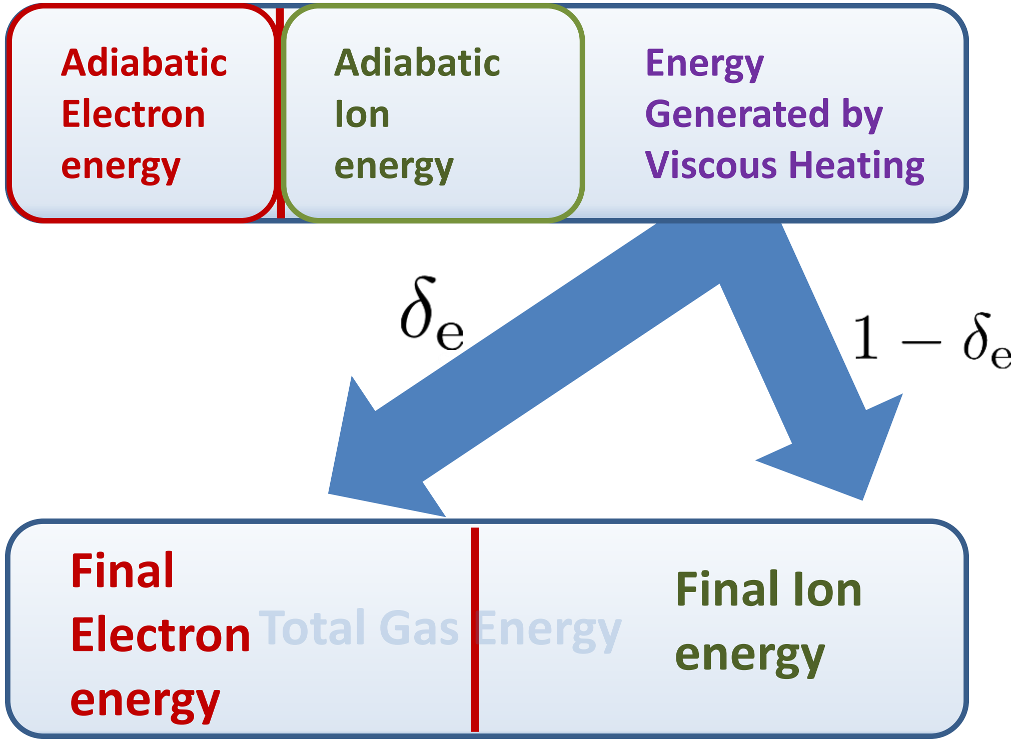
Comparing Sub-grid Heating Prescriptions

Landau-Damped Cascade (Howes 2010)

- Based on non-relativistic physics
- Predominantly heats electrons (ions) when magnetic pressure is high (low)

Magnetic Reconnection (Rowan 2017)

- Based on PIC simulations of trans-relativistic reconnection (appropriate for Sgr A*)
- **Always** puts more heat into ions



Sgr A* Simulations

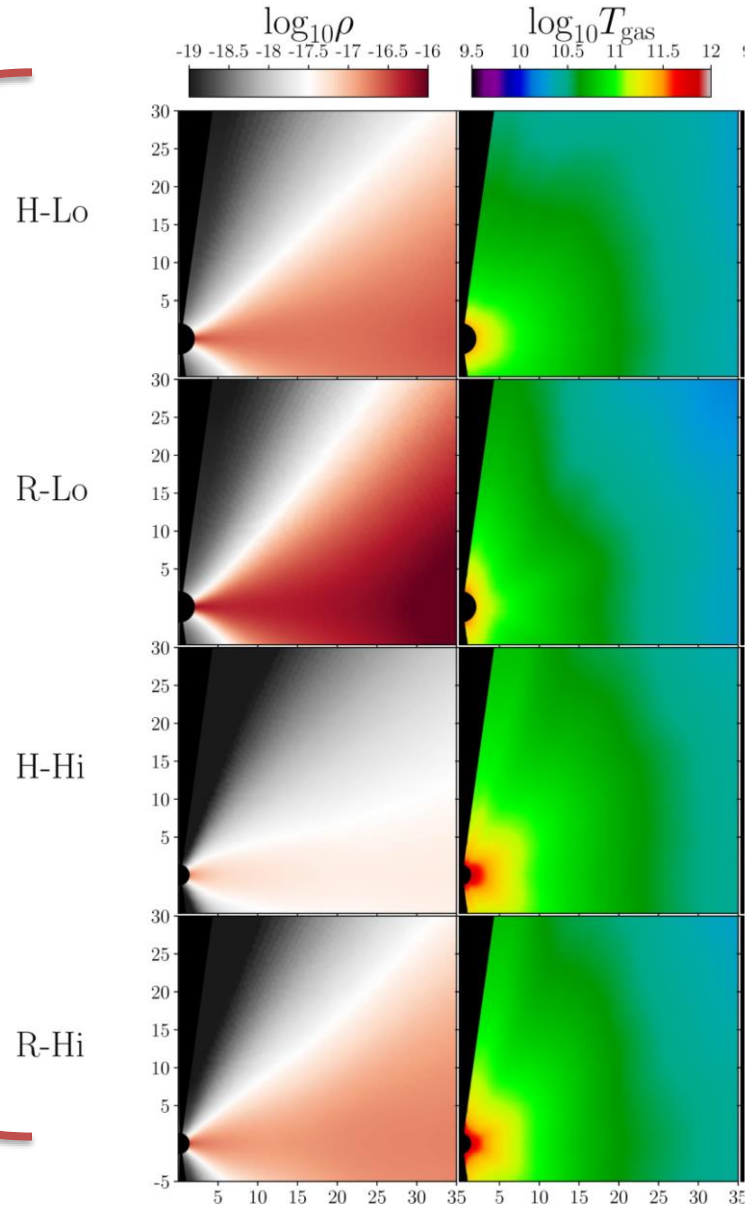
- Four 3D simulations using KORAL – one for each heating prescription at low (0) and high (0.9375) BH spins.

Model	Spin	Heating	$\dot{M}\,(\dot{M}_{\rm Edd})$	$\Phi_{\rm BH}$ $\left((\dot{M}c)^{1/2} r_{\rm g}\right)$
H-Lo	0	Turb. Cascade	3×10^{-7}	5
R-Lo	0	Mag. Reconnection	7×10^{-7}	4
H-Hi	0.9375	Turb. Cascade	2×10^{-7}	6
R-Hi	0.9375	Mag. Reconnection	3×10^{-7}	3

"MAD parameter"
~50 is saturation value for a Magnetically Arrested Disk

- Raytracing scaled to match ~3 Jy at 230 GHz

Results: *Density and Gas Temperature*

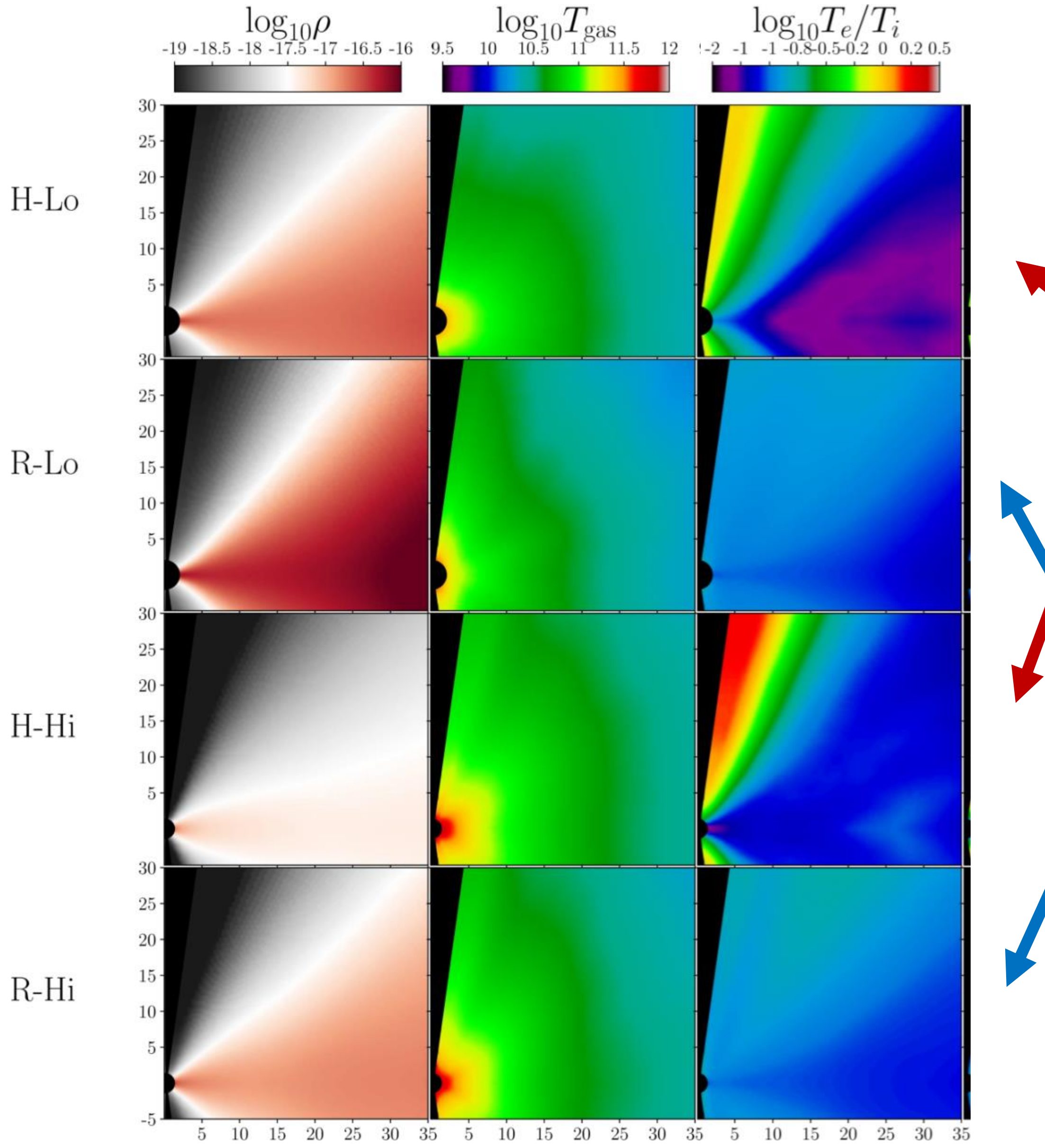


All thick disks: density lower at high spin

Gas is cooler everywhere for spin zero

Gas is hotter close to BH at high spin

Results: *Temperature ratio*

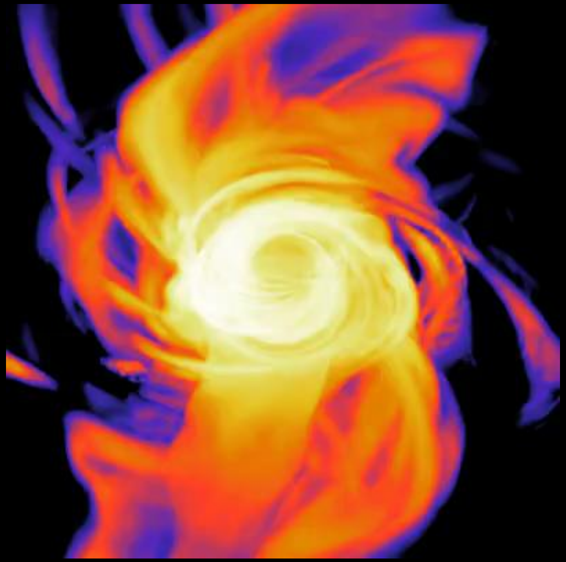


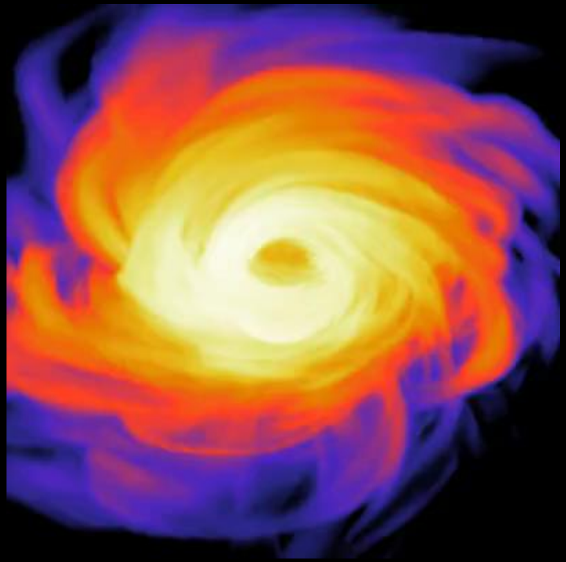
Highly stratified with polar angle
for turbulent heating
Electrons hotter than ions in the jet

Relatively constant ratio
for reconnection
Electrons are cooler everywhere

230 GHz movies – *log scale*

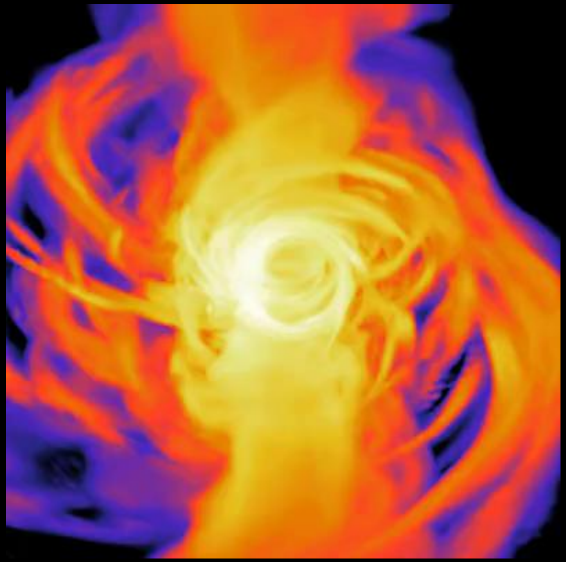
H-Lo

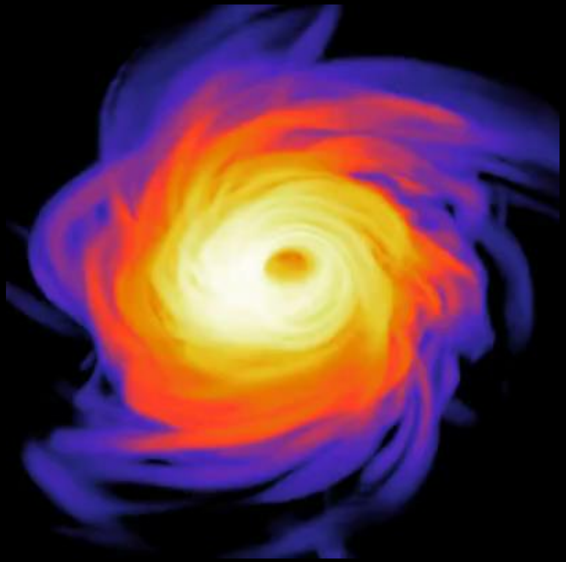




R-Lo

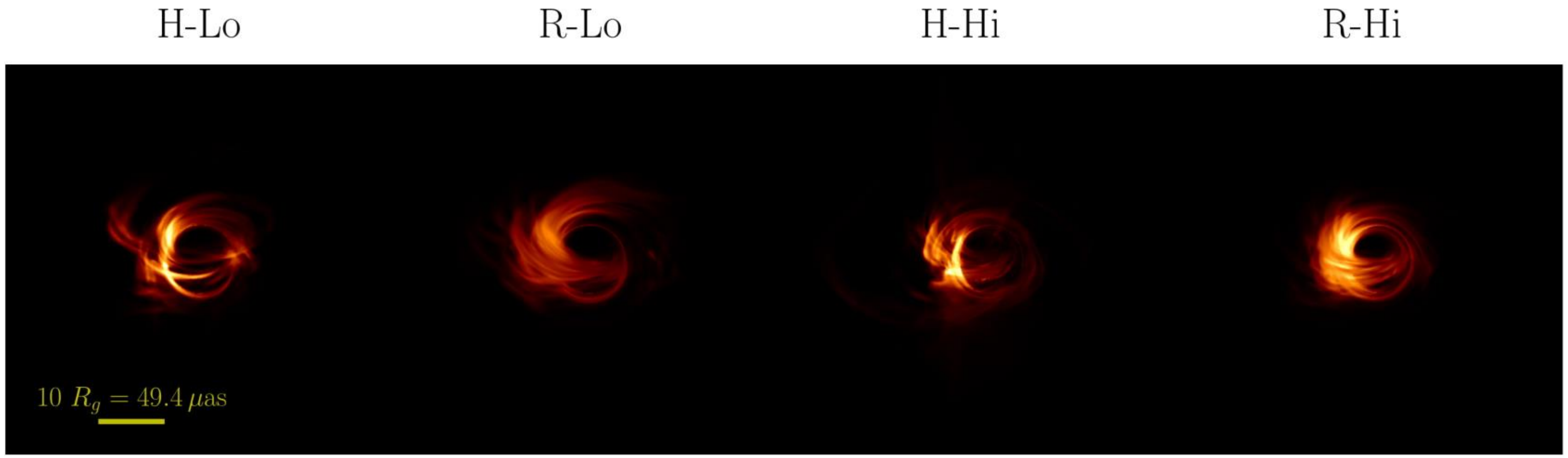
H-Hi





R-Hi

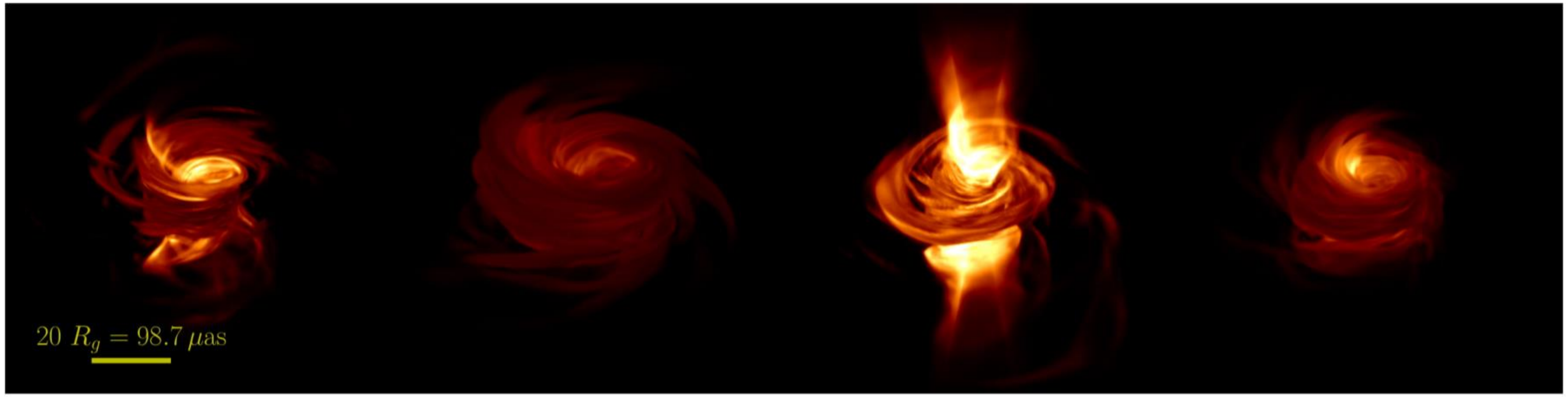
Image Anisotropy with wavelength



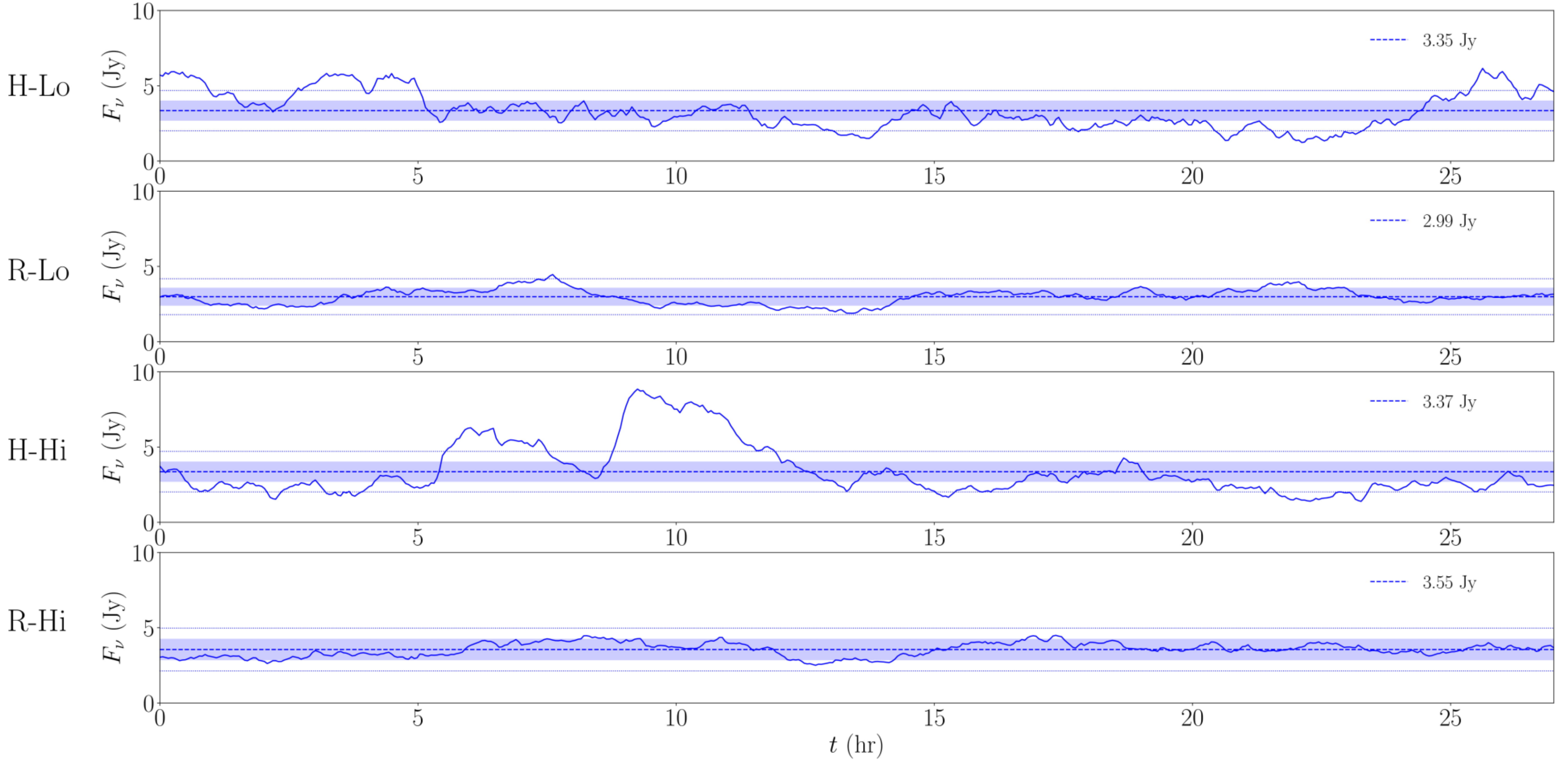
230 GHz

Jet emission makes turbulent heating models **anisotropic –** exceeding new estimates of intrinsic anisotropy at different frequencies (Johnson et al. 2018 in prep.)

43 GHz

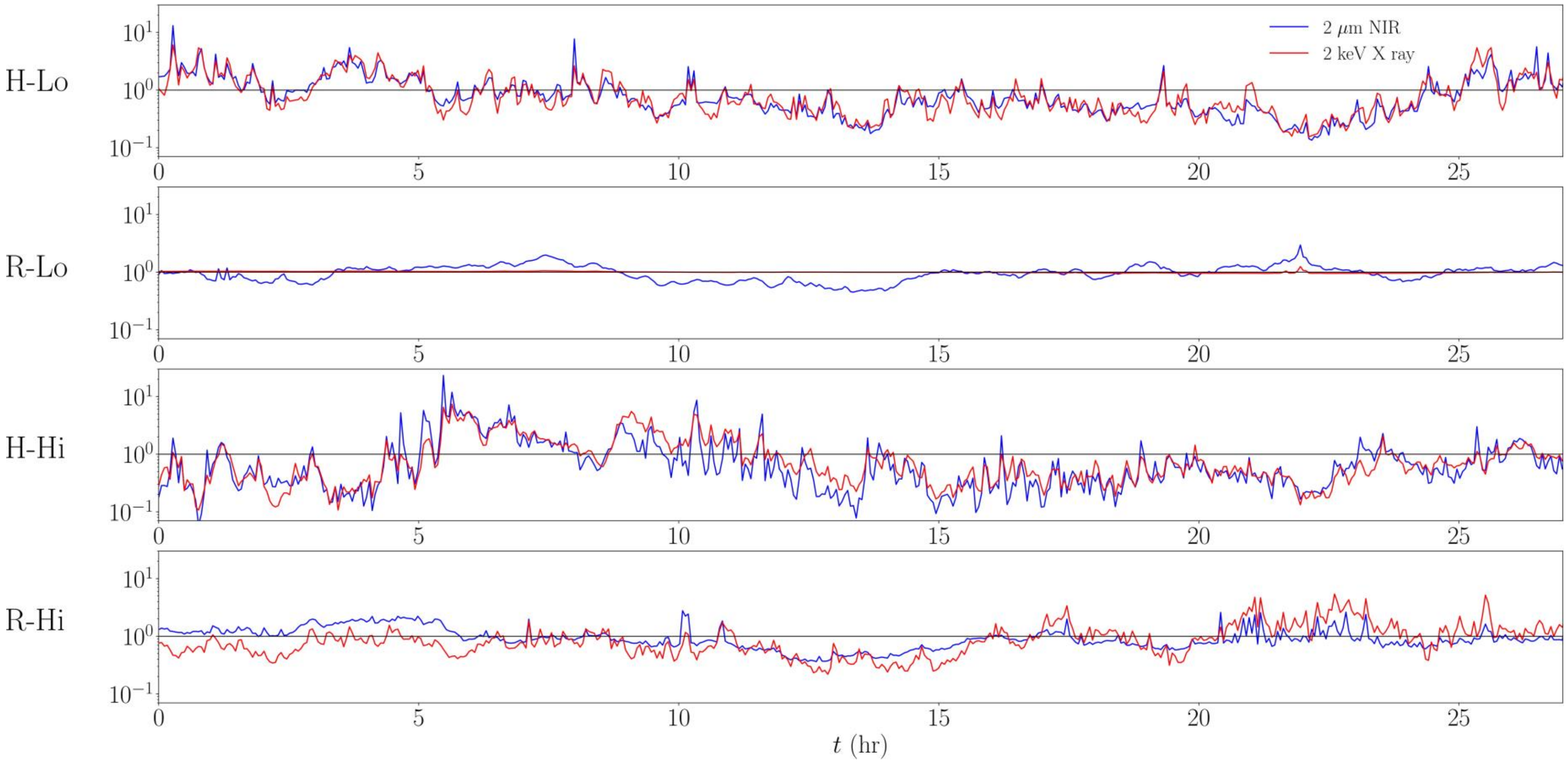


230 GHz variability:



Turbulent Heating models **exceed** ~20% observed variability

IR and X-ray variability: no large flares



No models reproduce quiescent IR or flaring IR and X-ray

→ Nonthermal Electrons

(for evolving non-thermal distributions in simulations, see Chael et al. 2017, arXiv 1704.05092)

Takeaways

- Flows around Sgr A* and M87 should be modeled with consistent electron & proton thermodynamics.

- Different plasma heating mechanisms produce qualitatively different variability and images
  - Turbulent heating prescription → disk/jet structure, more variable
  - Reconnection prescription → isotropic, steady

- Of all models considered, high spin + reconnection is most consistent with observations so far
  - But the parameter space is large.

- Many features remain unexplained by two-temperature models.
  - Need nonthermal electrons!

Two-Temperature GRRMHD Simulations

- Total fluid quantities are evolved as in single-temperature GRRMHD

- Electron and ion energy densities are evolved via the 1st law of thermodynamics:

$$T_{\mathrm{e}}\,(n s_{\mathrm{e}} u^{\mu})_{;\mu} = \delta_{\mathrm{e}} q^{\mathrm{v}} + q^{\mathrm{C}} - \hat{G}^{0}$$

$$T_{\mathrm{i}}\,(n s_{\mathrm{i}} u^{\mu})_{;\mu} = (1-\delta_{\mathrm{e}}) q^{\mathrm{v}} - q^{\mathrm{C}}$$

Radiation: weak

Coulomb Coupling: weaker

Viscous dissipation

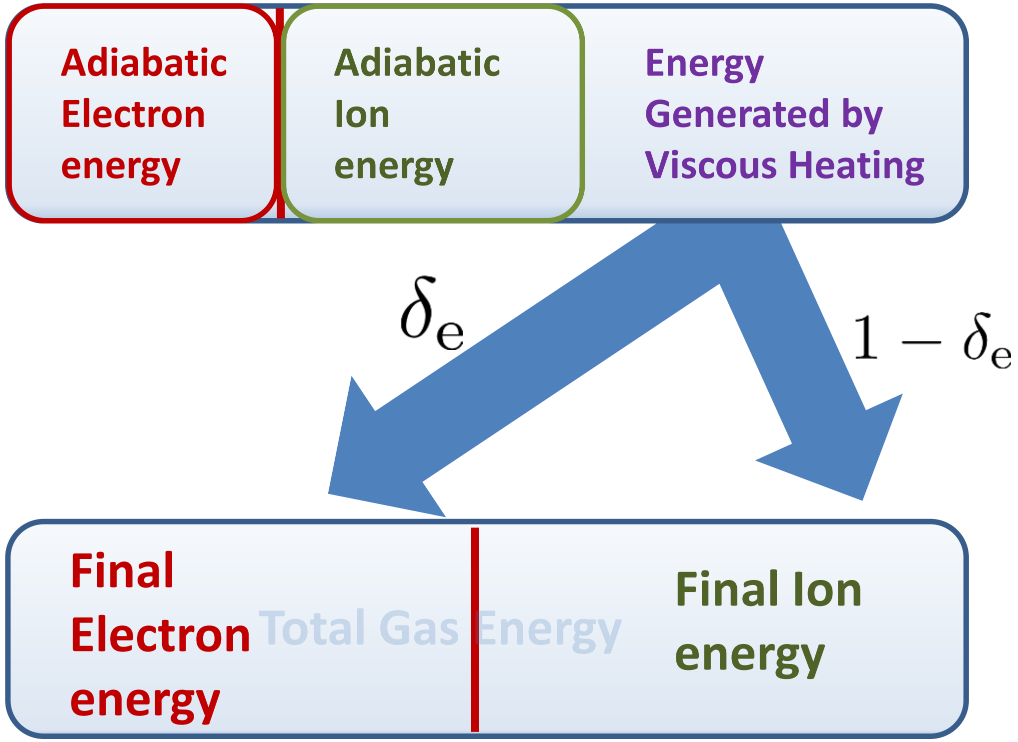
"$T\,\mathrm{d}S$"

Adiabatic compression/expansion

Electron & Ion Heating

- We can compute **total** dissipative heating in the simulation by comparing the internal energy of the total fluid to the internal energy of the components **evolved adiabatically.**

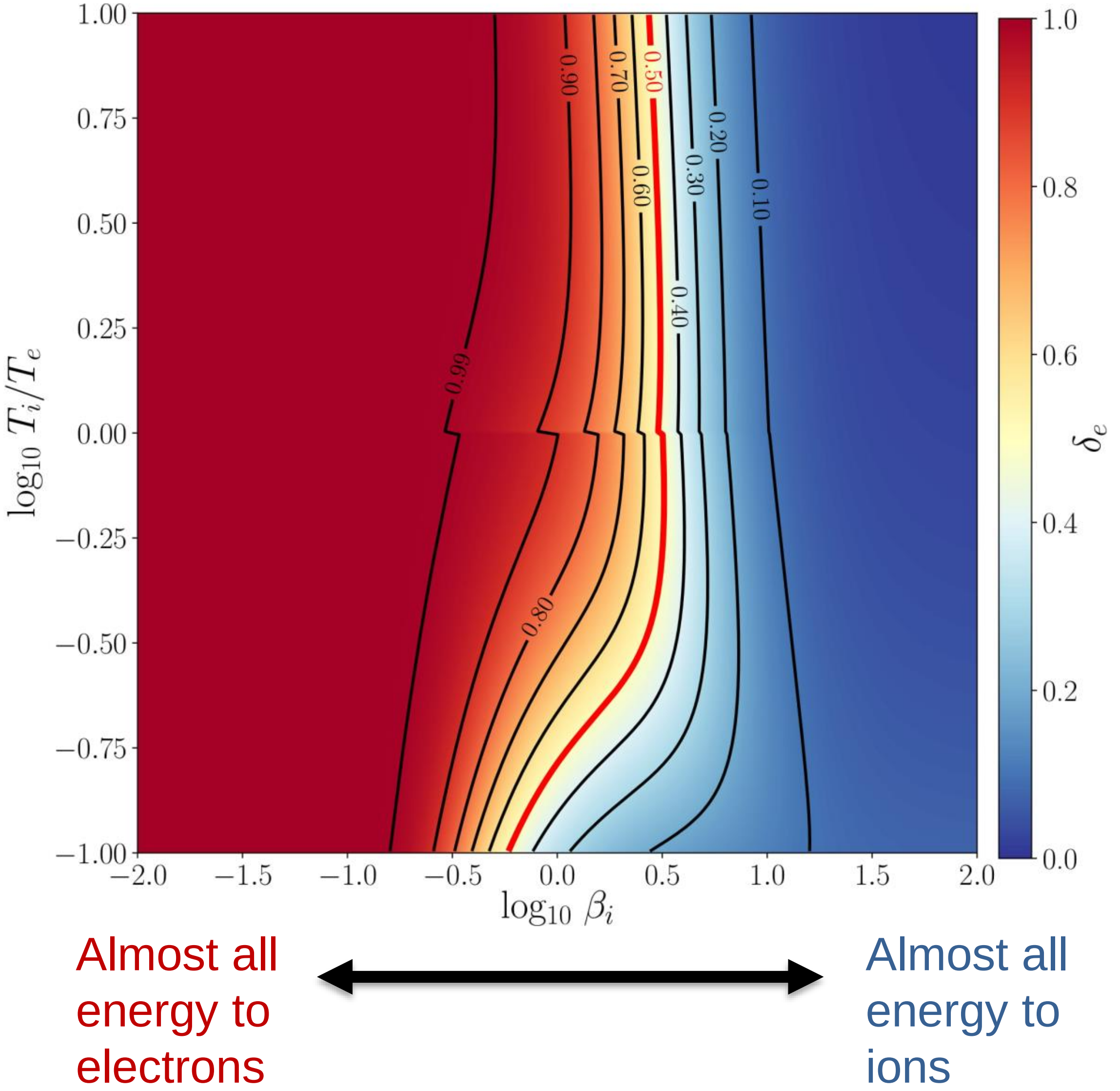
- **Sub-grid physics** must be used to determine what fraction of the dissipation goes into the electrons.



Sub-grid Heating Prescriptions

Landau-Damped Cascade (Howes 2010)

- Turbulent cascade of energy to small scales truncated by Landau damping.
- Predominantly heats electrons when magnetic pressure exceeds thermal (low beta).
- Used in all previous work (Sadowski 2016, Ressler 2015, 2017)



Sub-grid Heating Prescriptions

Magnetic Reconnection (Rowan 2017)

- Simulations parametrized with magnetization w.r.t. enthalpy density

$$\sigma_w = \frac{|B|^2}{4\pi\, w} = \frac{|B|^2}{4\pi\,(n_{\rm i} m_{\rm i} c^2 + \Gamma_{\rm i} u_{\rm i} + \Gamma_{\rm e} u_{\rm e})}$$

At high temperatures, $\sigma_w < \sigma_{\rm i}$

- **Always** puts more heat into ions
- $\delta_{\rm e} \to 1/2$ at **high** beta for a fixed σ_w

Assuming **equal** temperatures

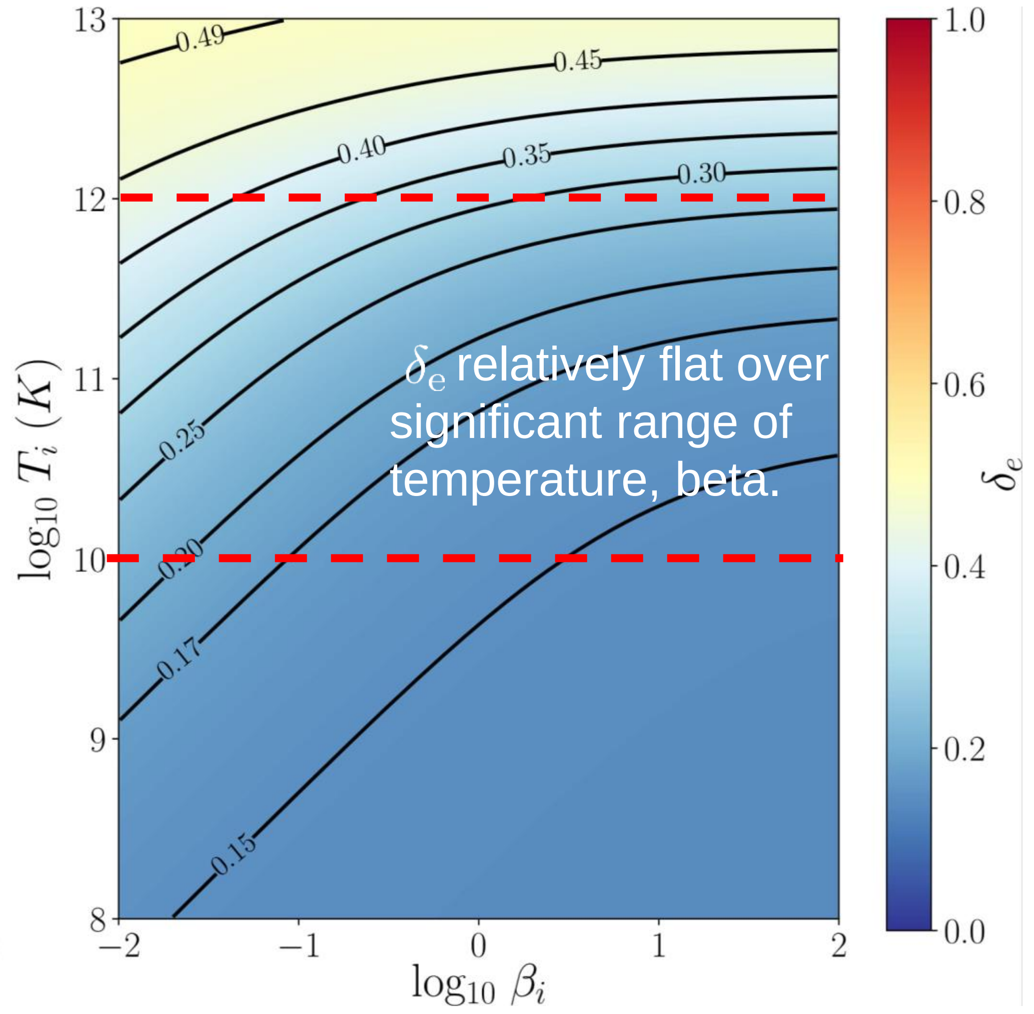
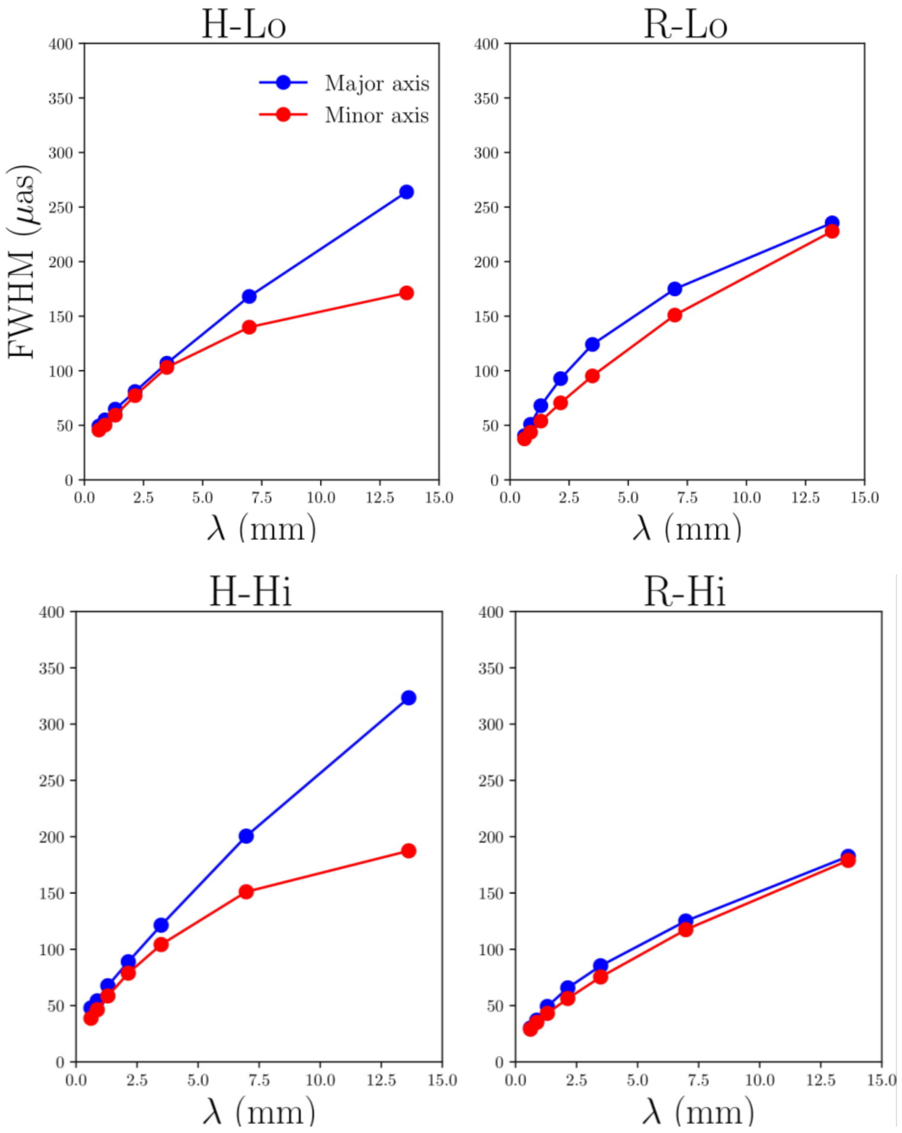
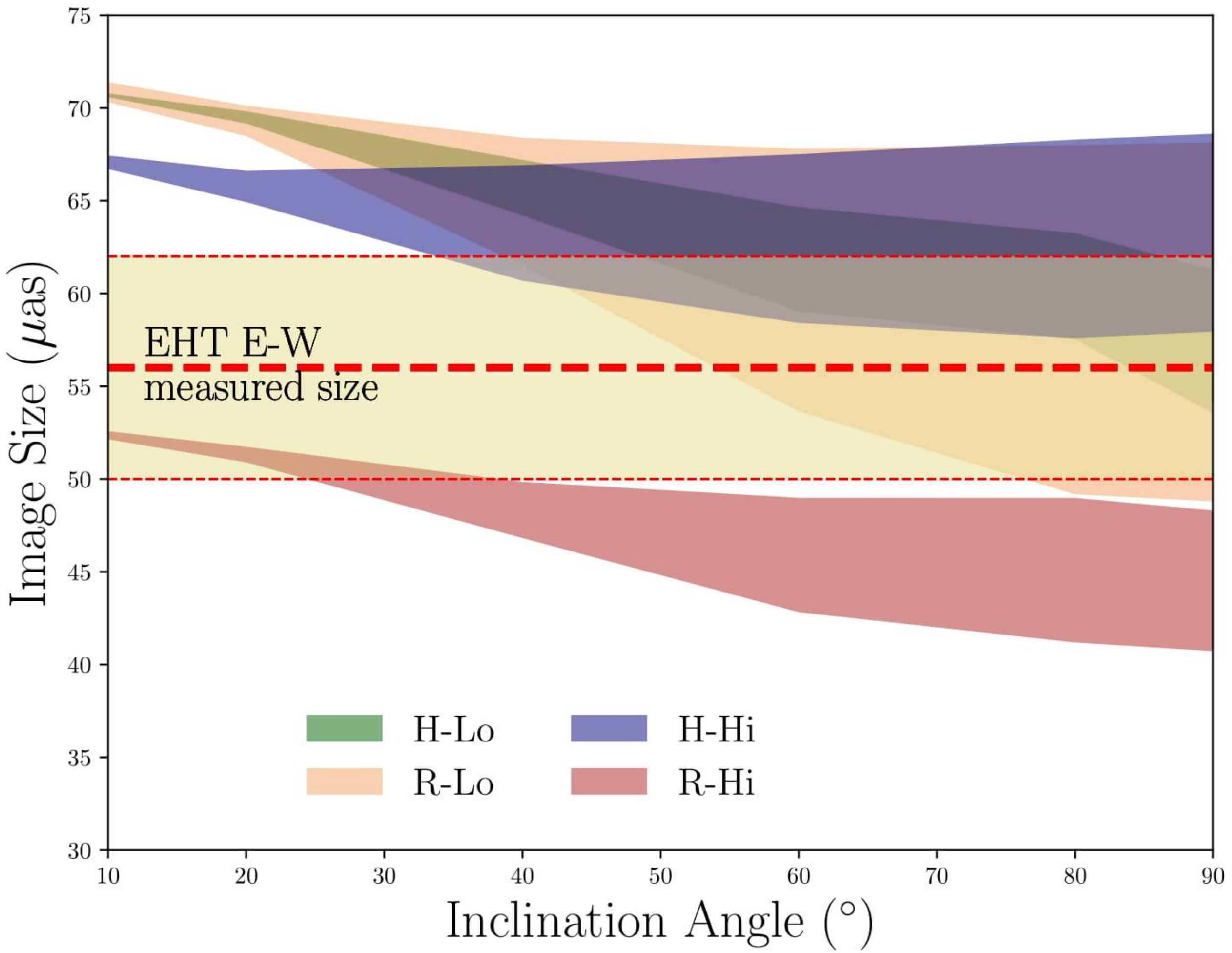


Image Anisotropy with wavelength

- Emergence of jet at low frequencies makes Howes models anisotropic
- See Johnson+2018 (in prep) for new measurements of intrinsic size/anisotropy with wavelength



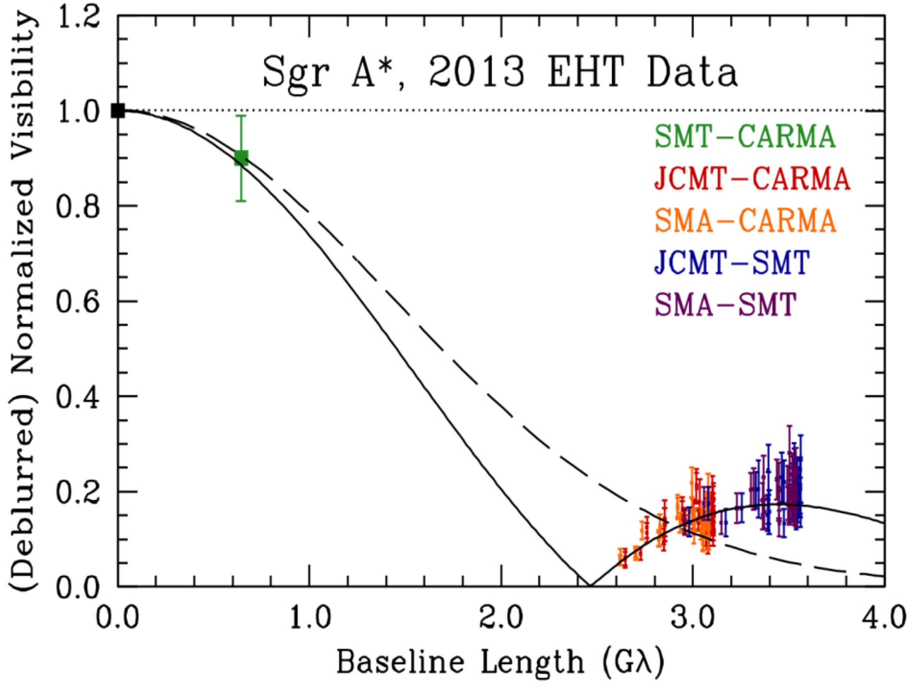
Comparison with EHT 230 GHz measurements



Most models are consistent with measured size over a range of inclinations

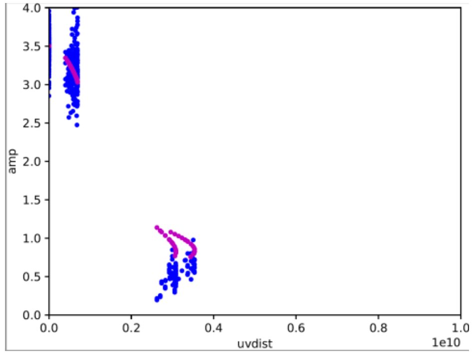
R-Hi is the most compact, so it is only consistent with the measured size near-face on

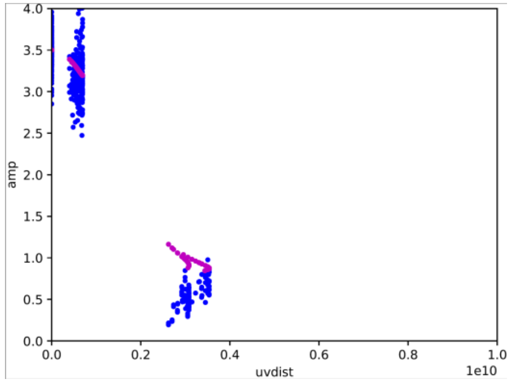
Comparison with EHT 2013 230 GHz measurements



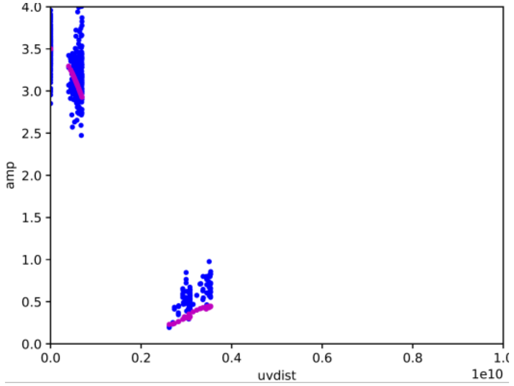
Johnson+ (2015)

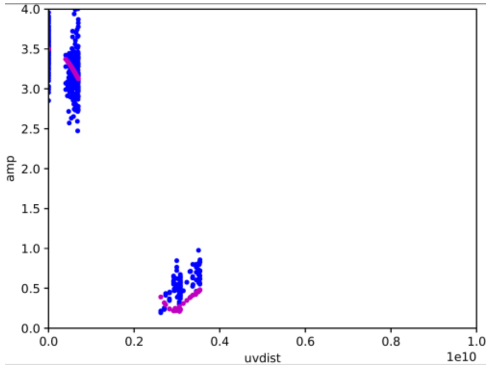
60 degree inclination – no visibility null





10 degree inclination – visibility null from symmetric ring





Sgr A* Spectrum & Variability

- Radio: self-absorbed optically thick synchrotron.
- Sub-mm: Peaks and transitions from optically thick → optically thin synchrotron.
  - Variable, RMS ~ 20%
- NIR and X-ray: strongly variable.
  - X-ray flares can exceed 100x quiescence
  - Flares are correlated
  - Measured synchrotron break between IR and X-ray? (Ponti et al. 2017)

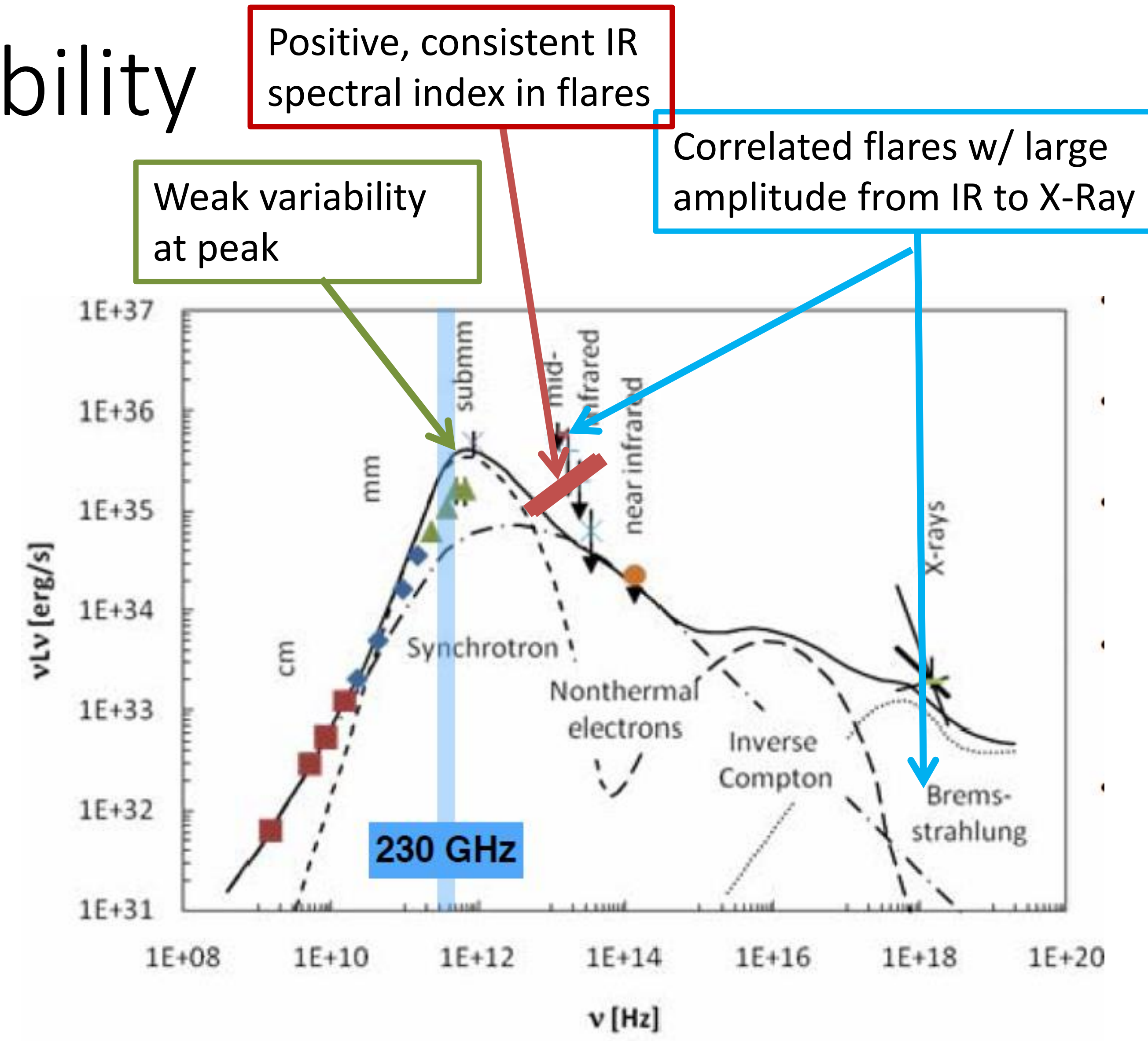
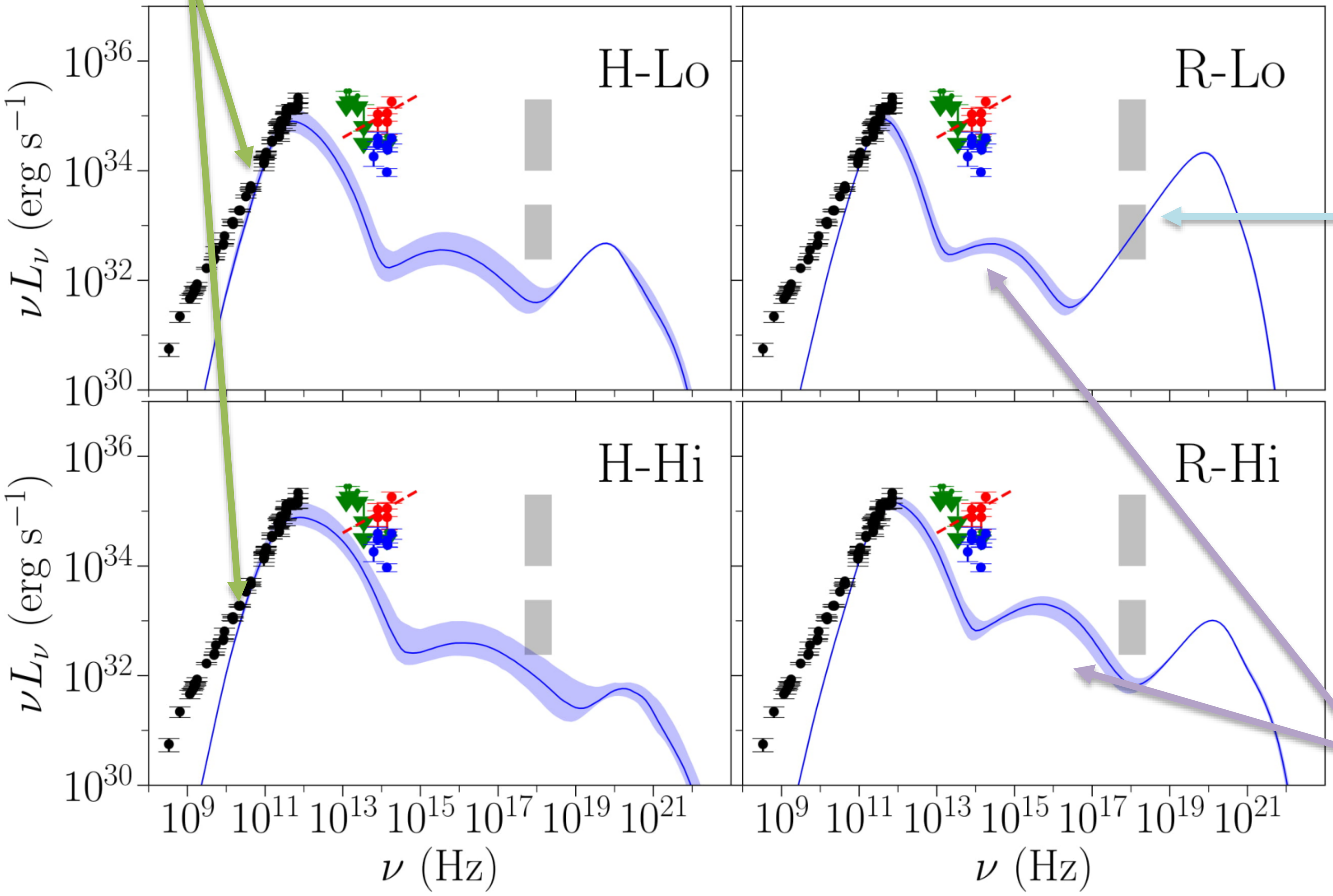


Image Credit: Genzel et al. (2010), Yuan et al. (2003).

Results: *Spectra*

No models reproduce quiescent IR or flaring IR and X-ray
→ Nonthermal Electrons

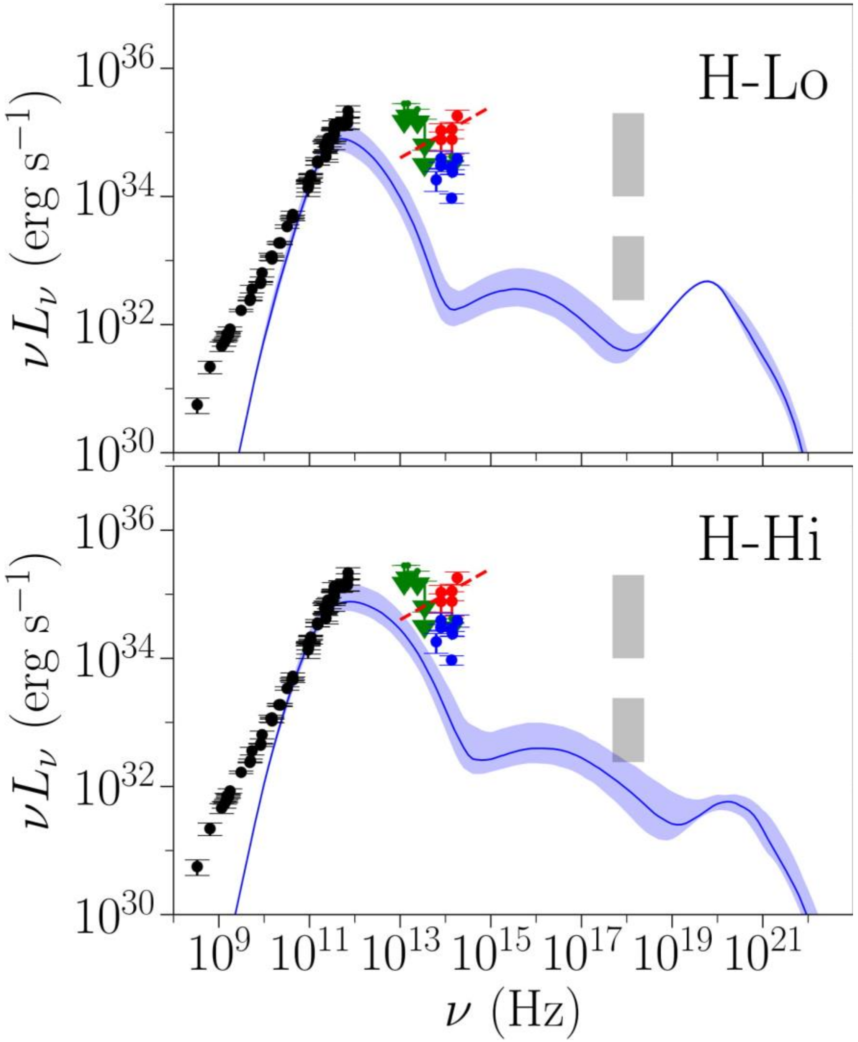
Howes models with funnel emission do slightly better at low frequencies



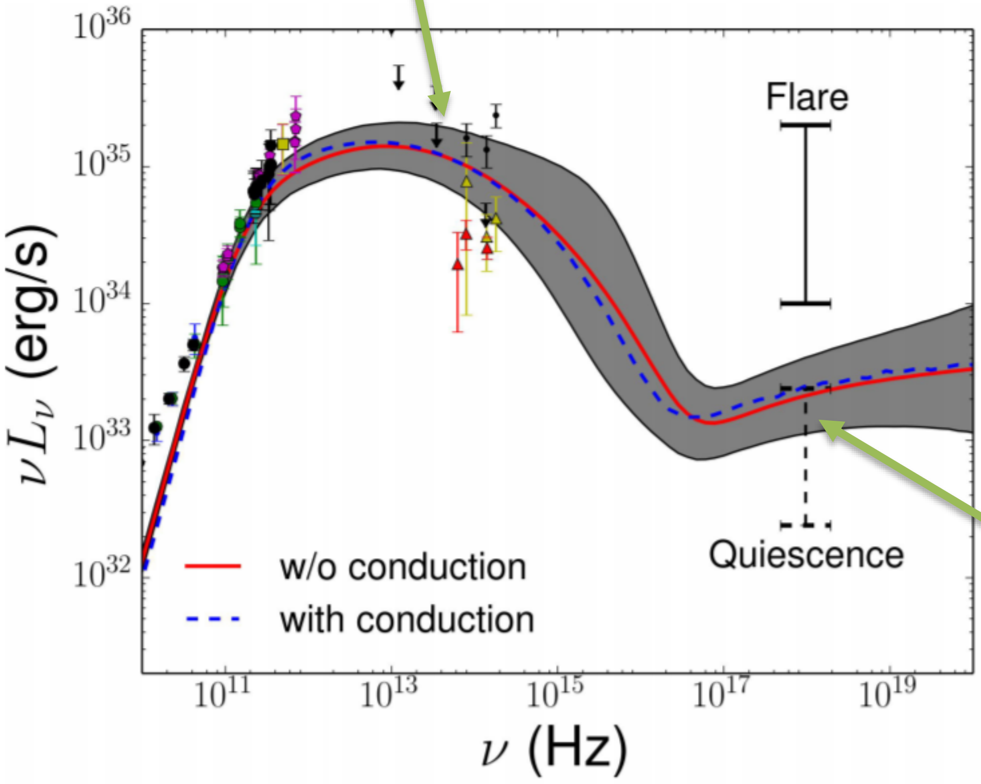
Free-free X-ray emission set by density scaling needed to match sub-mm peak.

With fewer hot electrons in funnel, Rowan models have less variability

Results: *Spectra – comparison to Ressler+ 2017*

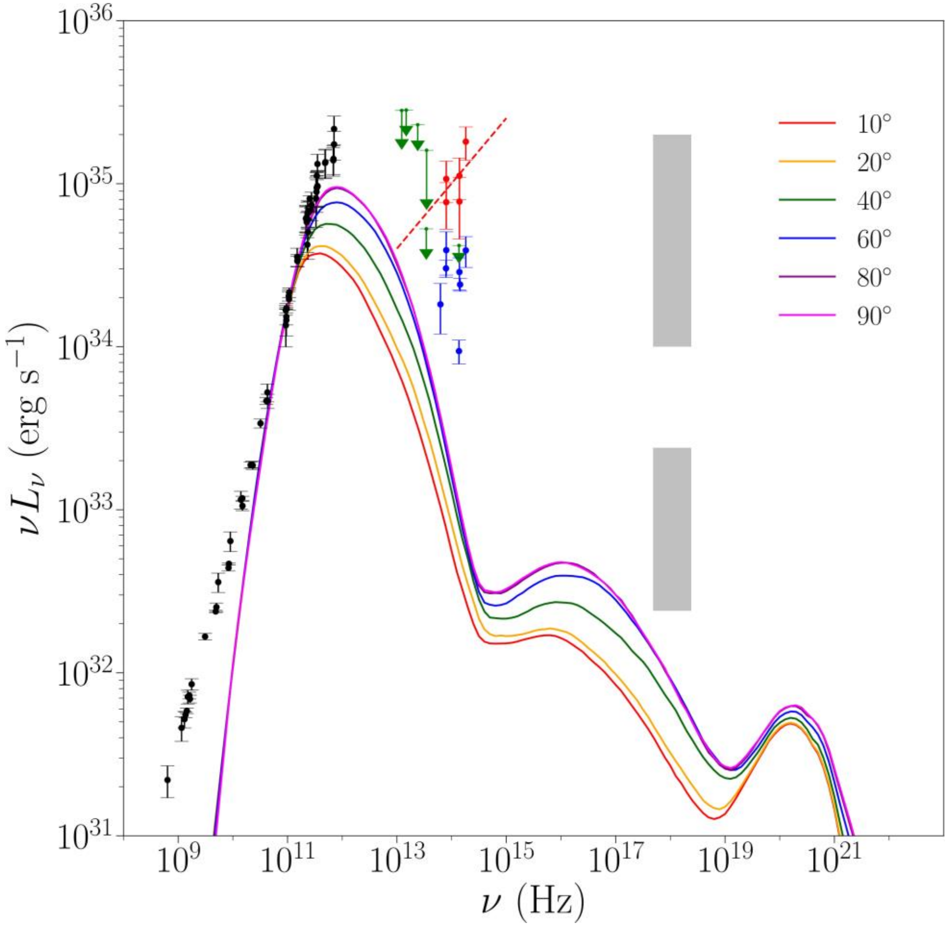


With much more magnetization (MAD parameter ~40), Ressler+17 are able to hit/exceed quiescent IR points but do not match the measured spectral index



No free-free included

Spectrum with inclination



230 GHz movies

H-Lo

R-Lo

H-Hi

R-Hi