Electron Heating Physics in Images and Variability of Sagittarius A*

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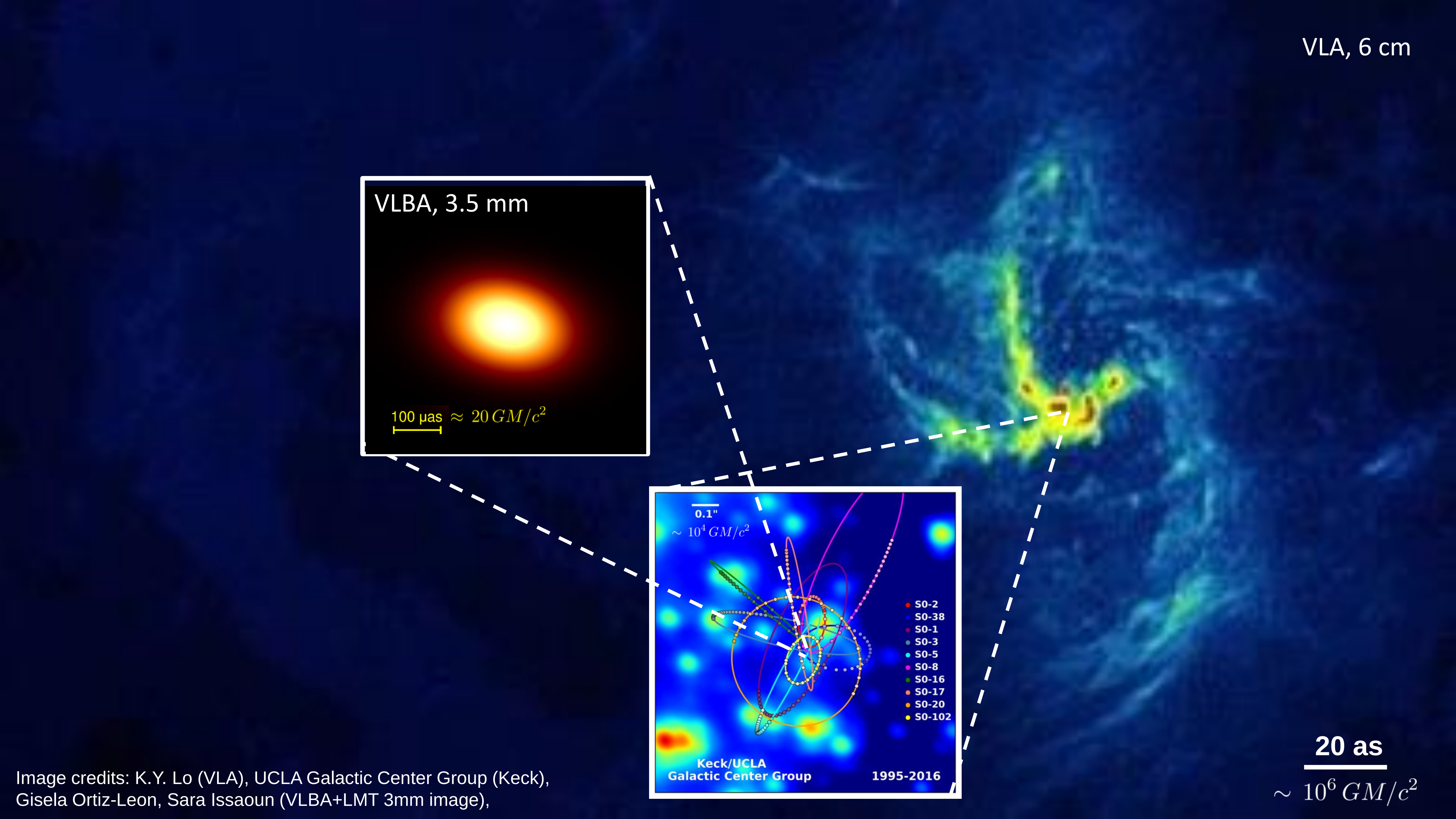
July 2, 2018

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

Event Horizon Telescope



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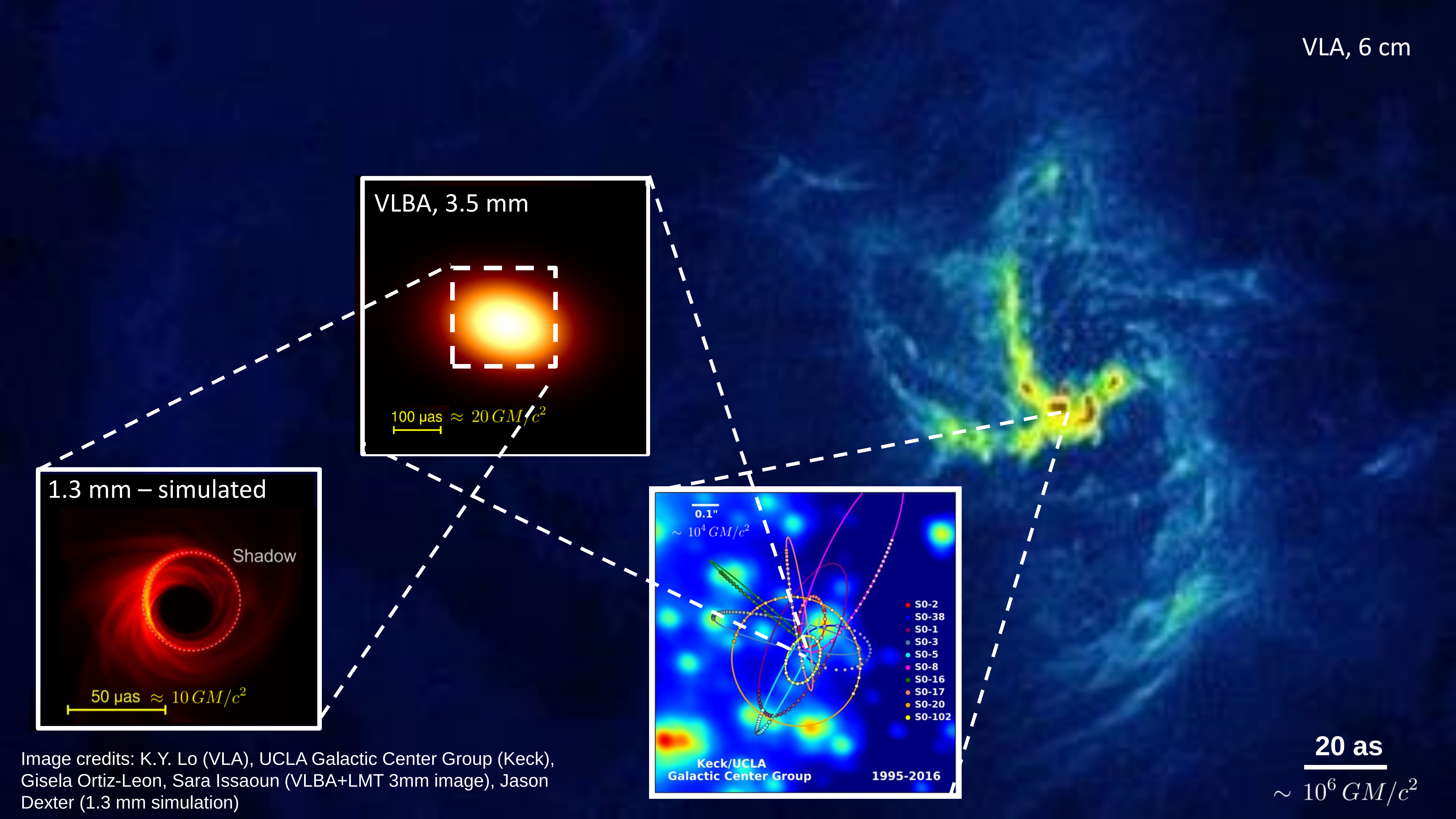
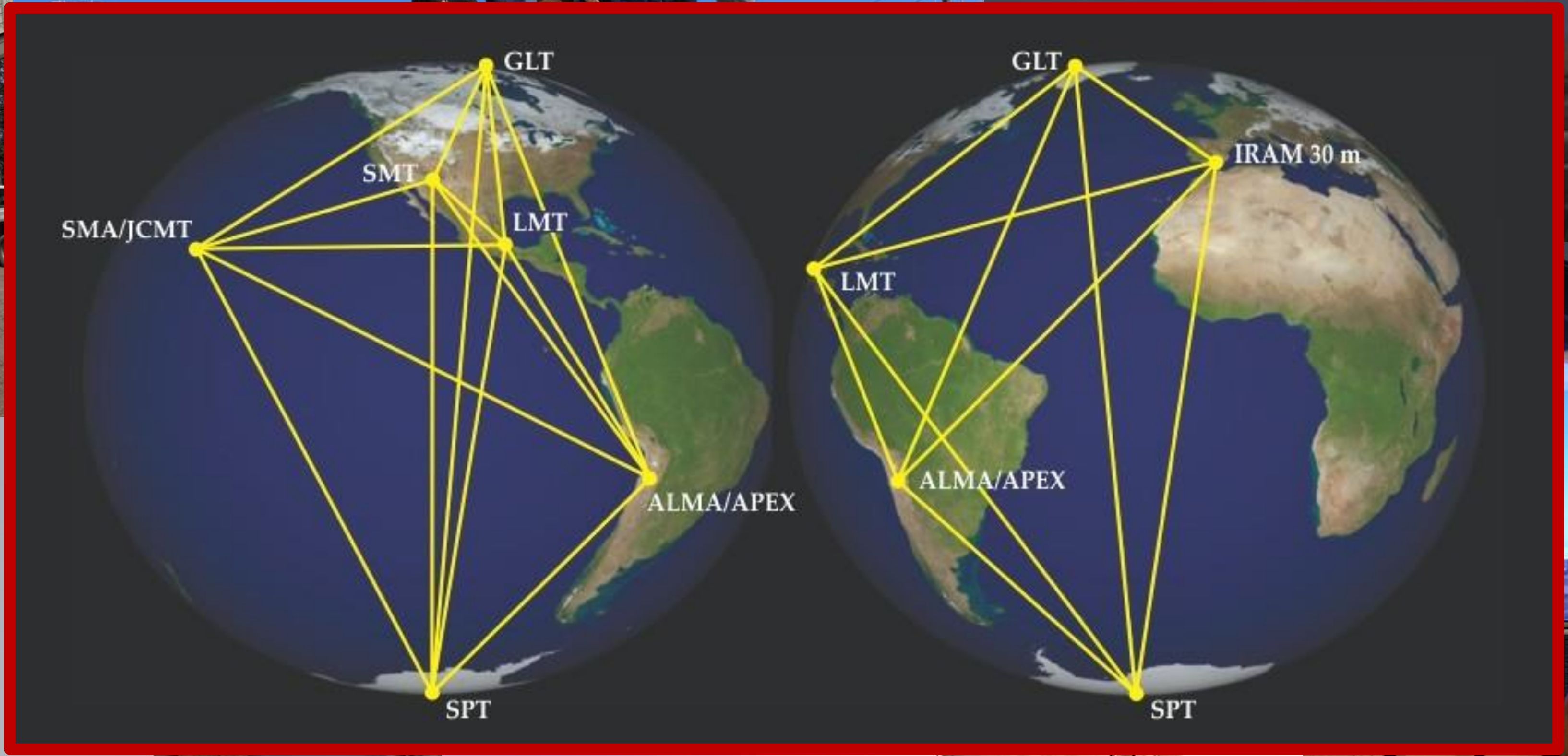


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Gisela Ortiz-Leon, Sara Issaoun (VLBA+LMT 3mm image), Jason Dexter (1.3 mm simulation)

The Event Horizon Telescope



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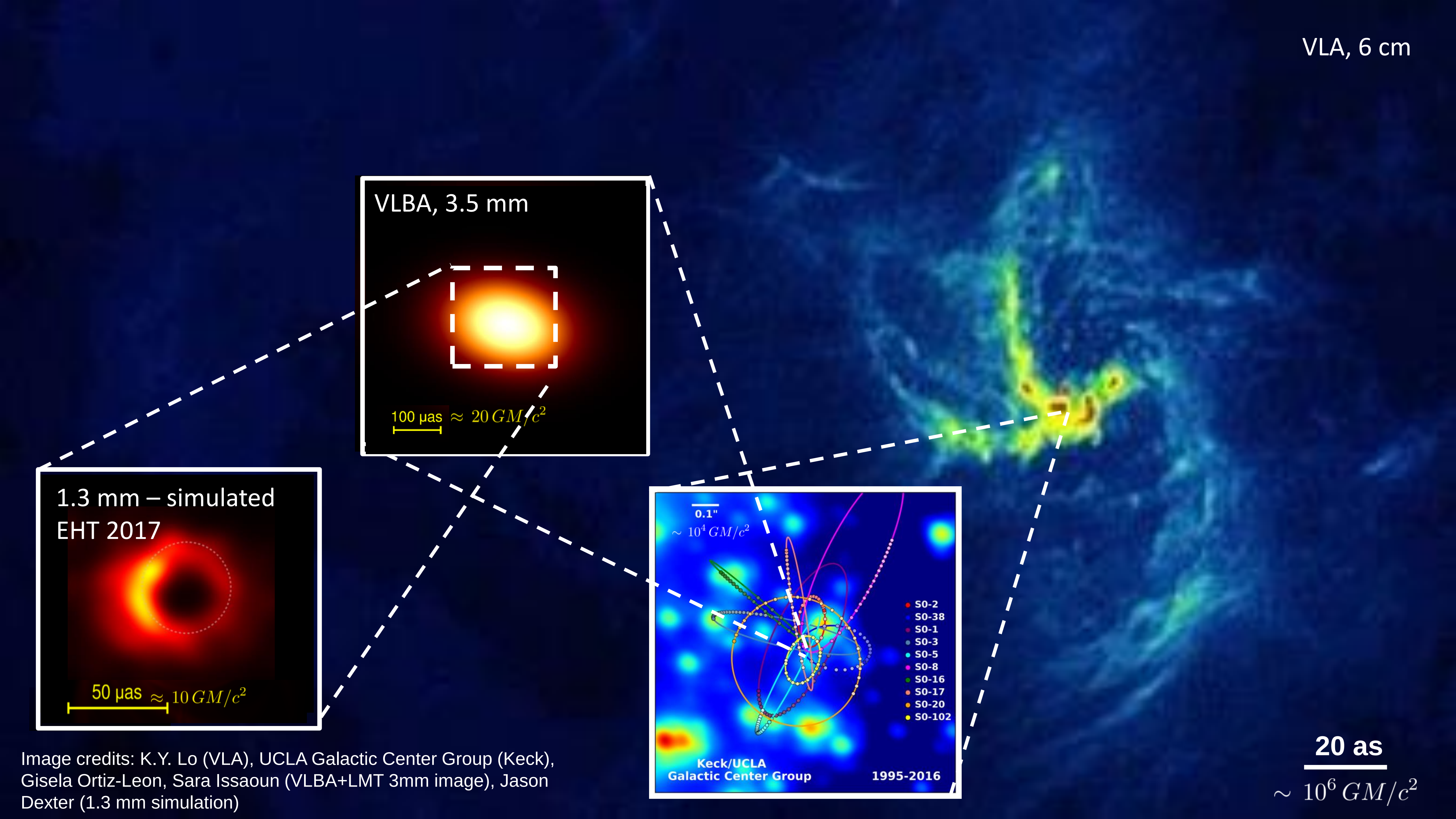

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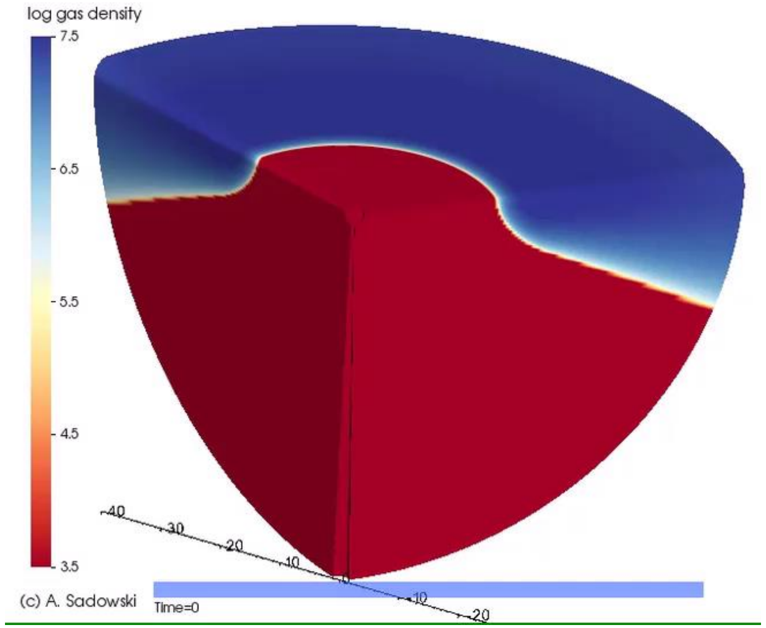
Two-Temperature Accretion Flows

- Low densities in hot flows → inefficient Coulomb coupling between ions and electrons.
- Generally expect electrons to be **cooler** than ions since they radiate.
- But if electrons are heated much more, they can remain hotter than ions for long times.

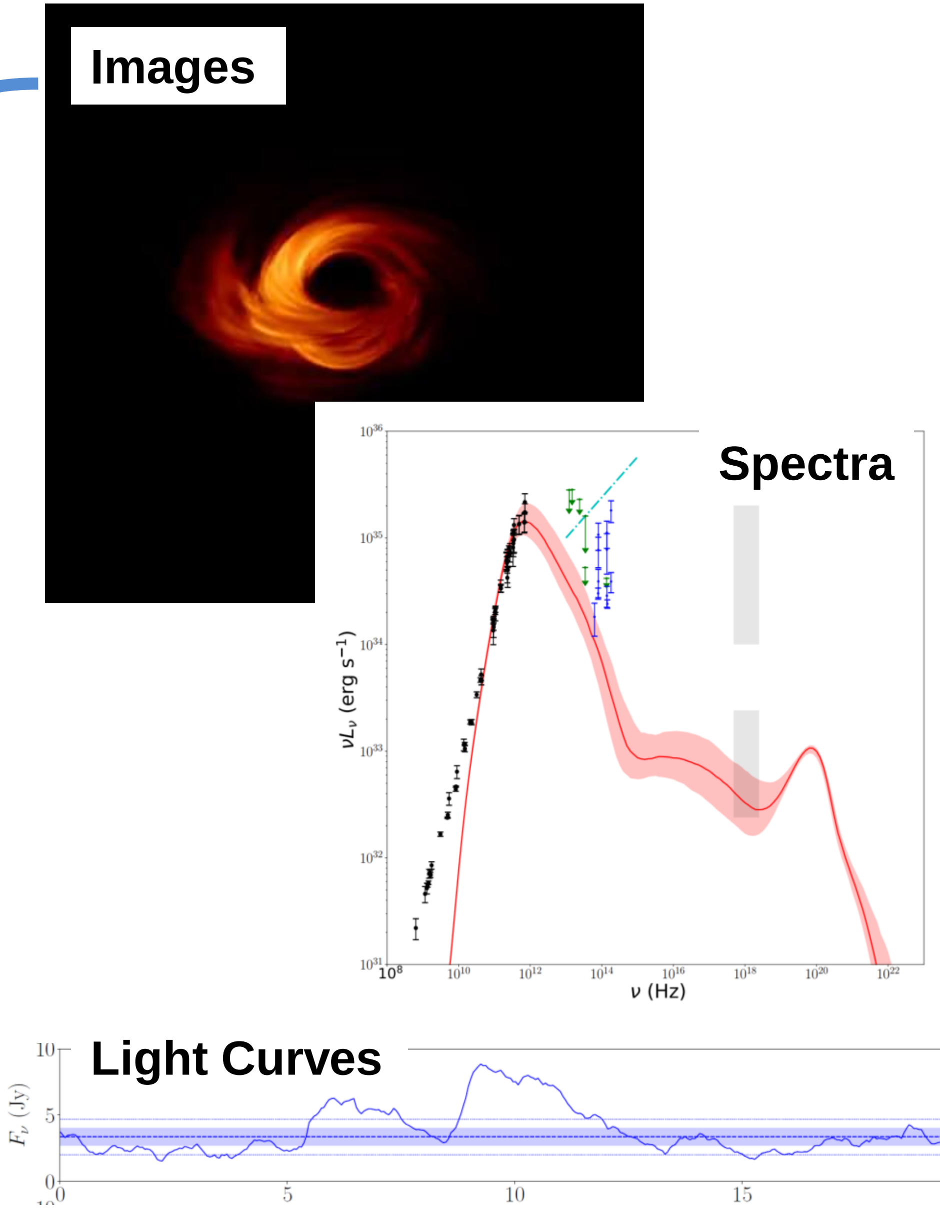
From simulations to observables

General Relativistic MHD Simulations

evolve a **single** fluid and magnetic field

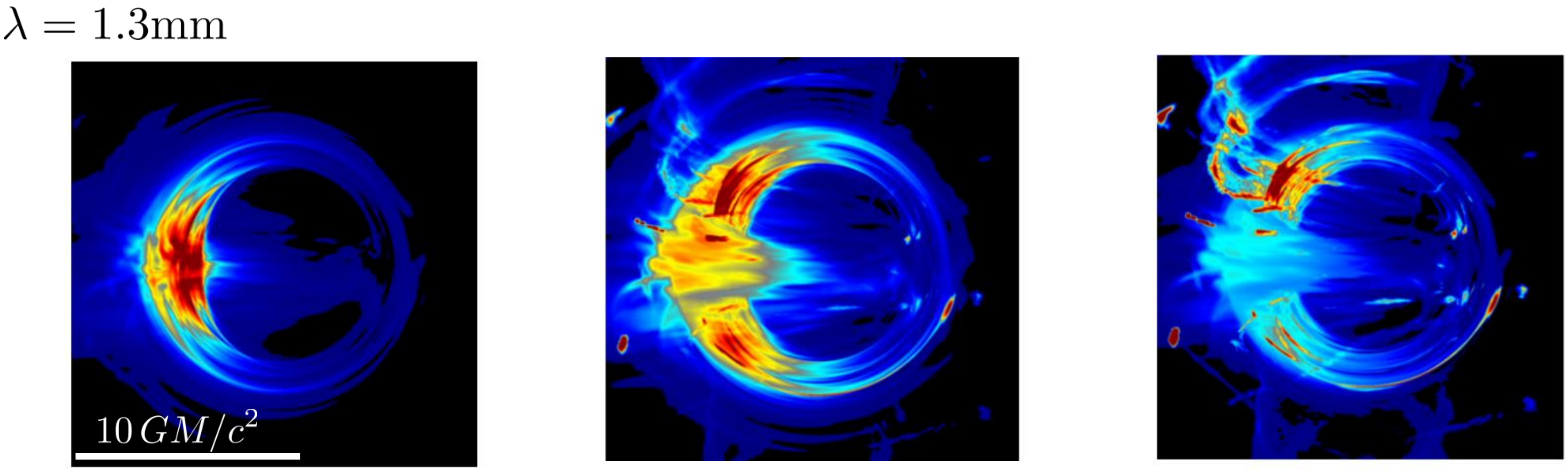


T_e?



Previous Work has used **fixed** temperature ratios.

Mościbrodzka et al. 2014



$$\frac{T_e}{T_i} = 0.2$$

$$\frac{T_e}{T_i} = 0.067$$

$$\frac{T_e}{T_i} = 0.04$$

Fixing electron-to-ion temperature ratios across the same simulation produces quite different 1.3 mm images

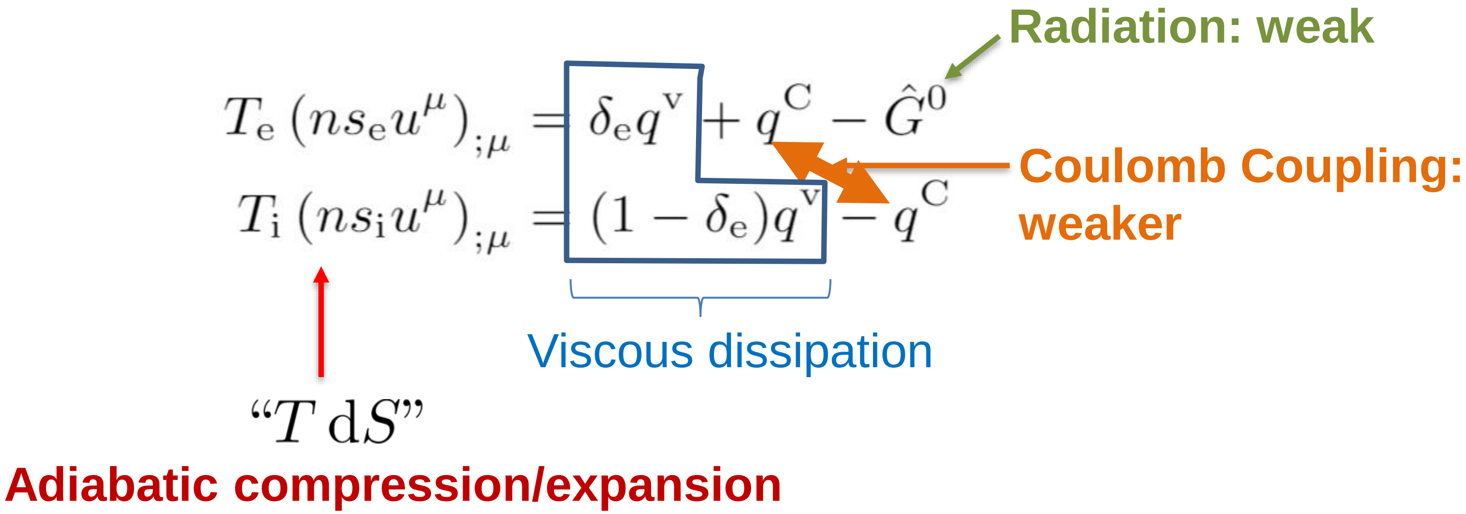
Goal: investigate different sources of microscale electron heating in self-consistent two-temperature simulations of Sgr A*.

-Using the code KORAL: (Sądowski et al. 2017)
-See also: (Ressler et al. 2017)

Two-Temperature GRRMHD Simulations

- Total fluid quantities are evolved as in single-temperature general relativistic MHD with radiation.

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



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

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

Radiation: weak

Coulomb Coupling: weaker

Viscous dissipation

“$T\,\mathrm{d}S$”

Adiabatic compression/expansion

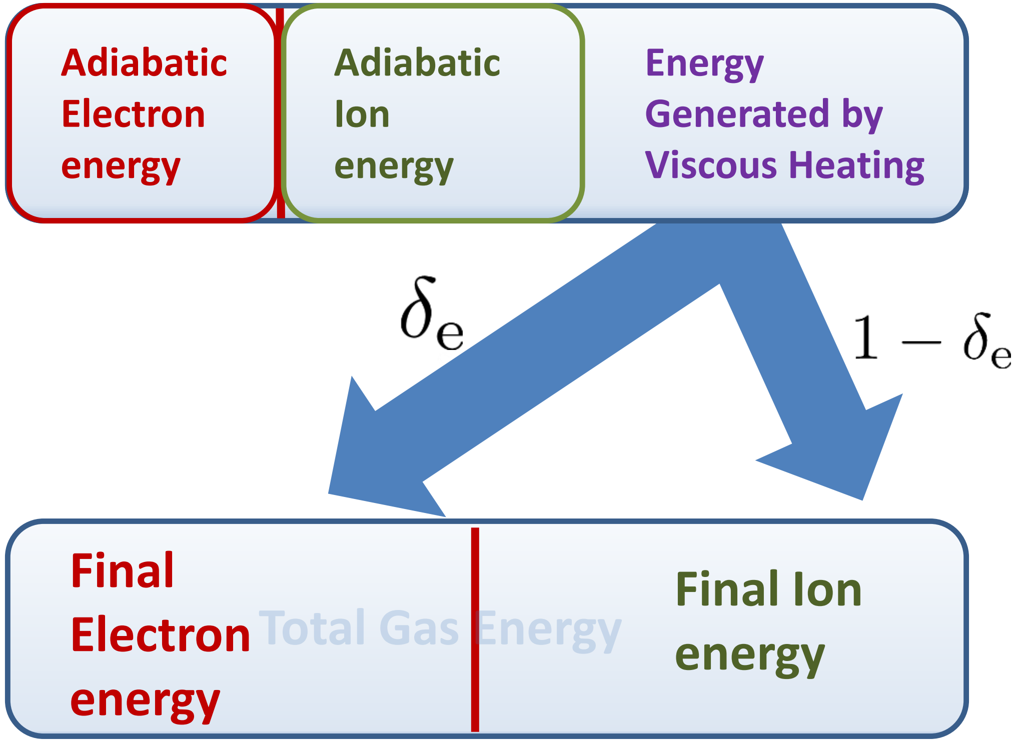
Comparing Sub-grid Heating Prescriptions

Previous work: Turbulent Heating (Howes 2010)

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

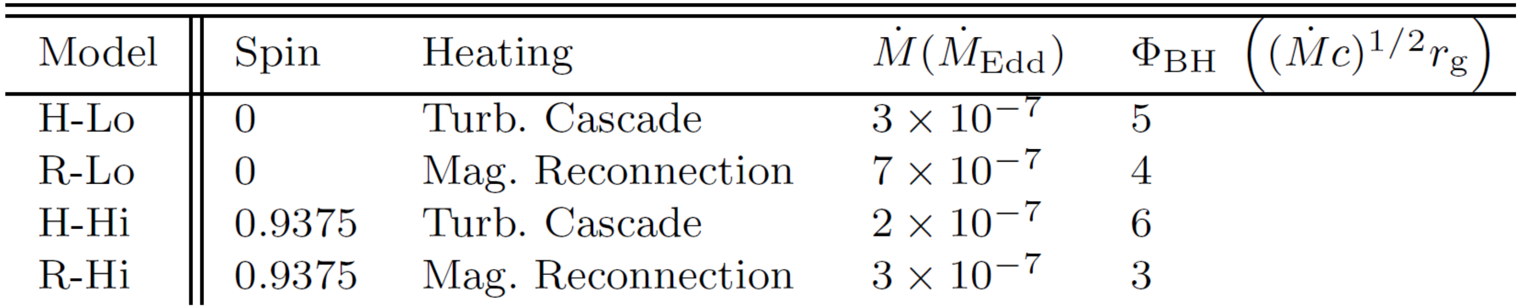
New Model: Magnetic Reconnection (Rowan 2017)

- 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.

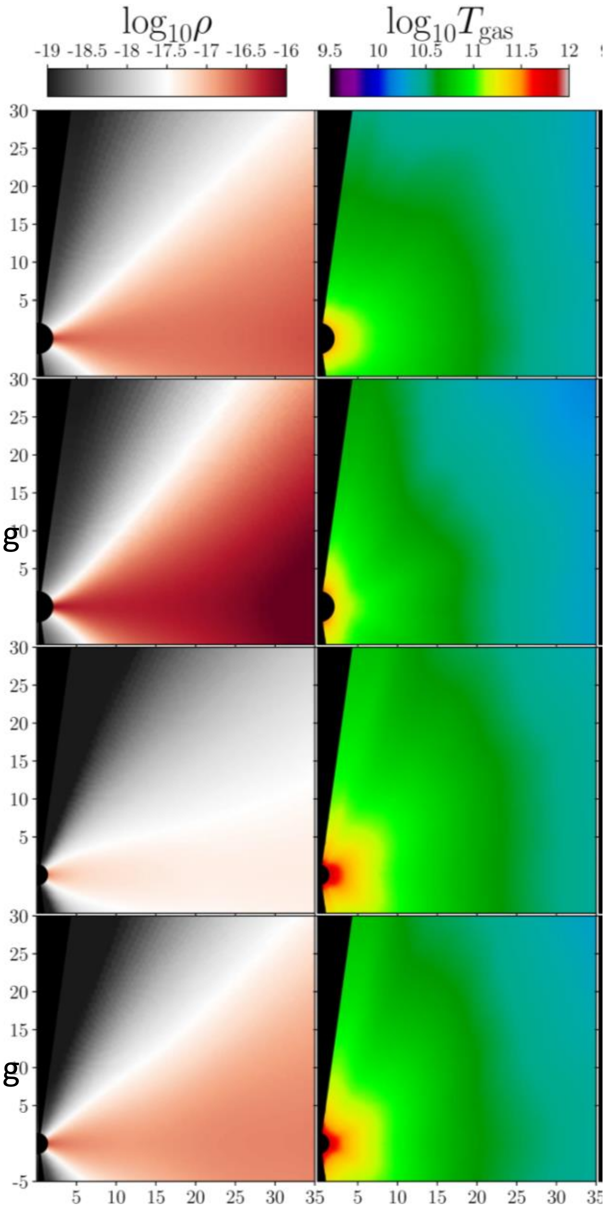


Model	Spin	Heating	$\dot{M}\,(\dot{M}_{\rm Edd})$	$\Phi_{\rm BH}$ $\left((\dot{M}c)^{1/2}r_{\rm g}\right)$
H-Lo	0	Turb. Cascade	3×10^{-7}	5
R-Lo	0	Mag. Reconnection	7×10^{-7}	4
H-Hi	0.9375	Turb. Cascade	2×10^{-7}	6
R-Hi	0.9375	Mag. Reconnection	3×10^{-7}	3

"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 are thick disks: density lower at high spin

Spin 0
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Turbulent Heating

Spin 0.9375
Reconnection Heating

Gas is cooler everywhere for spin zero

Gas is hotter close to BH at high spin

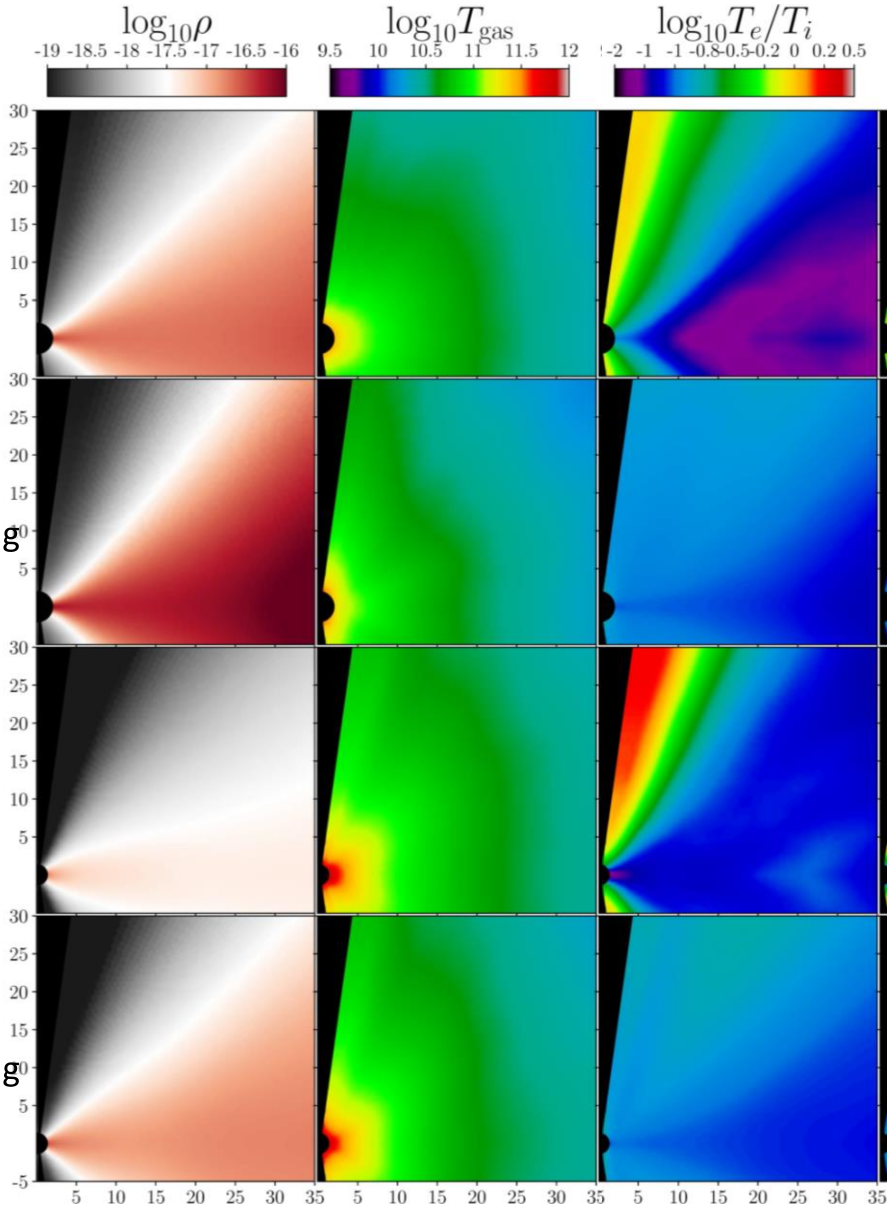
Results: *Temperature ratio*

Spin 0
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Turbulent Heating

Spin 0.9375
Reconnection Heating



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

Spin 0
Turbulent
Heating

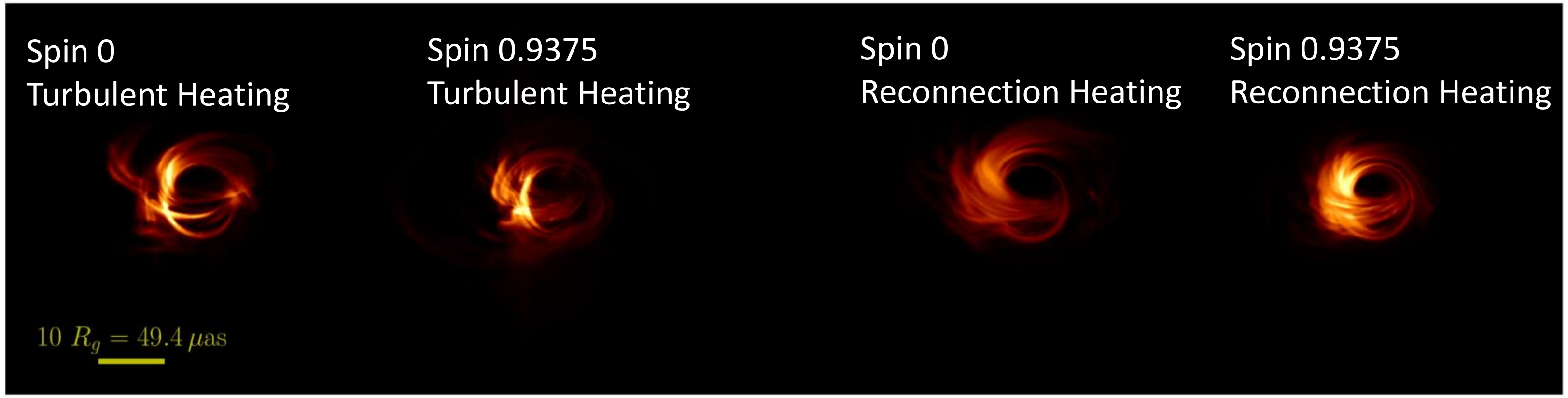
Spin 0.9375
Turbulent
Heating

Spin 0
Reconnection
Heating

Spin 0.9375
Reconnection
Heating

Image structure with wavelength

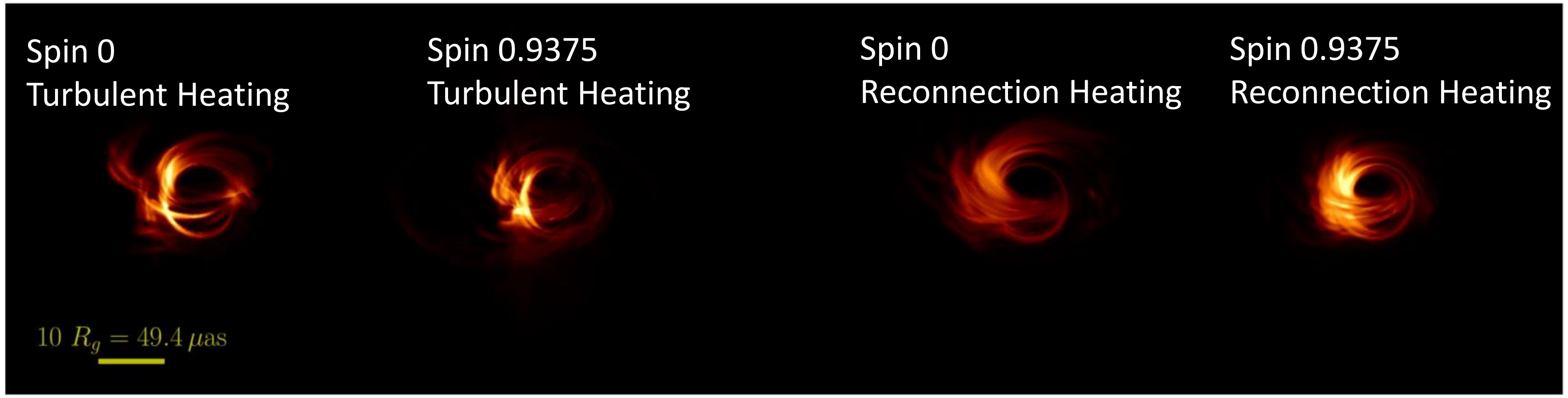
230 GHz



Where the EHT observes at 230 GHz, both heating prescriptions produce images with distinct black hole shadows

Image structure with wavelength

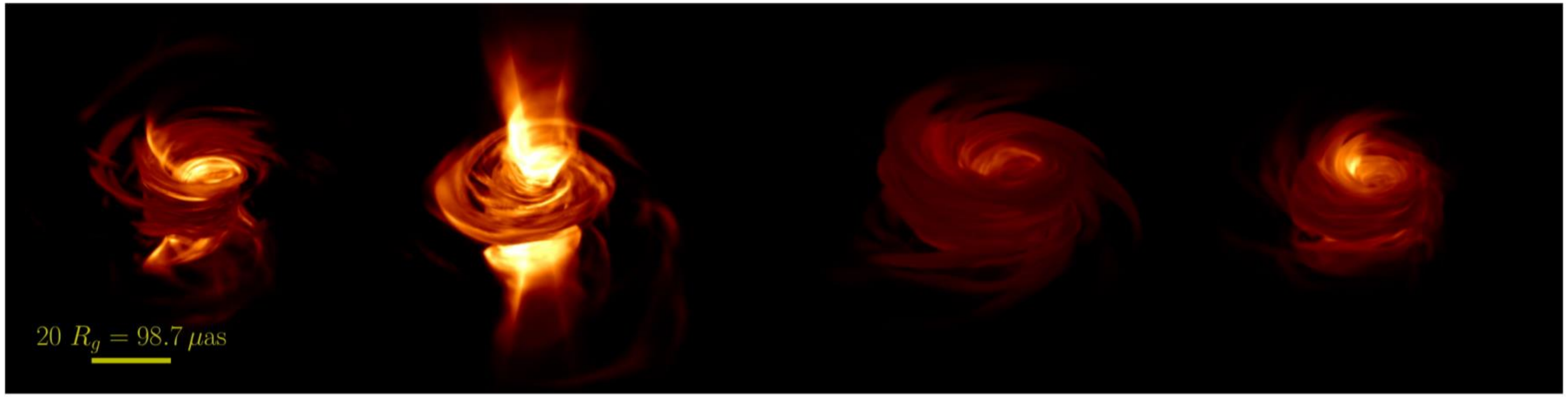
230 GHz



Where the EHT observes at 230 GHz, both heating prescriptions produce images with distinct black hole shadows

Conventional turbulent heating makes 43 GHz images **anisotropic and jet dominated –** exceeding recent estimates of intrinsic anisotropy (Johnson et al. 2018 in prep.)

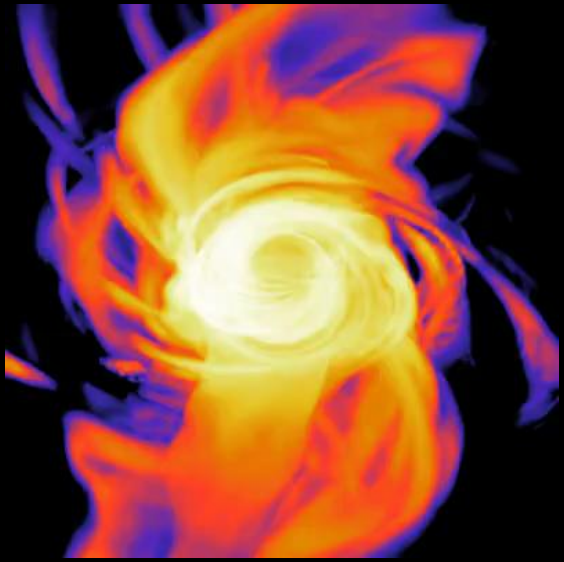
43 GHz

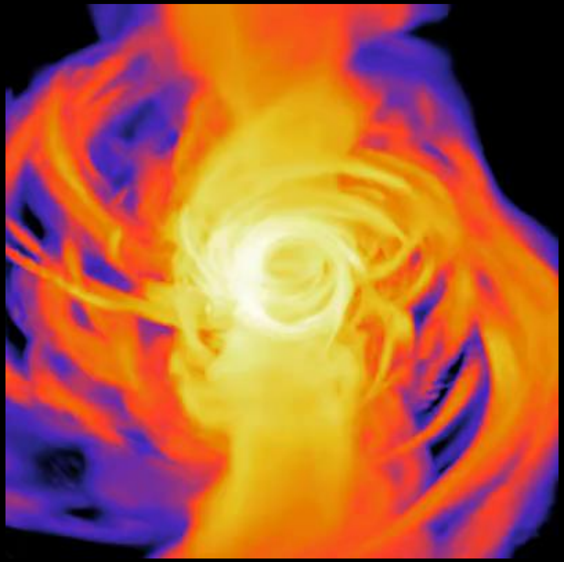


230 GHz movies

log scale

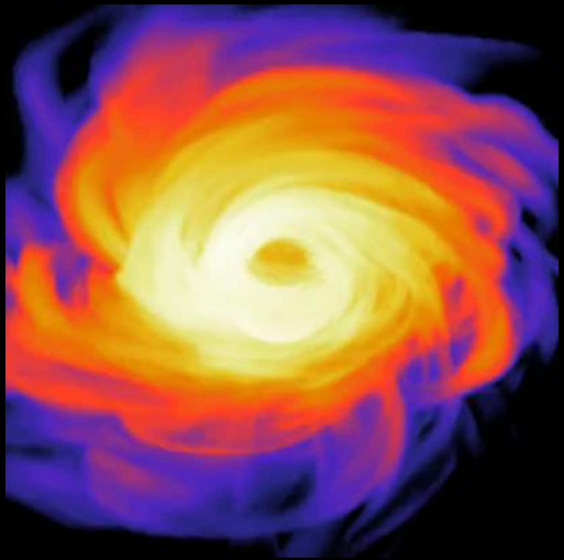
Spin 0
Turbulent
Heating

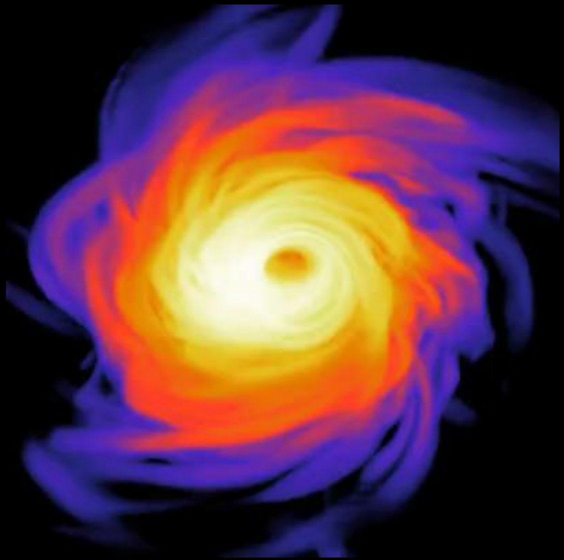




Spin 0.9375
Turbulent
Heating

Spin 0
Reconnection
Heating





Spin 0.9375
Reconnection
Heating

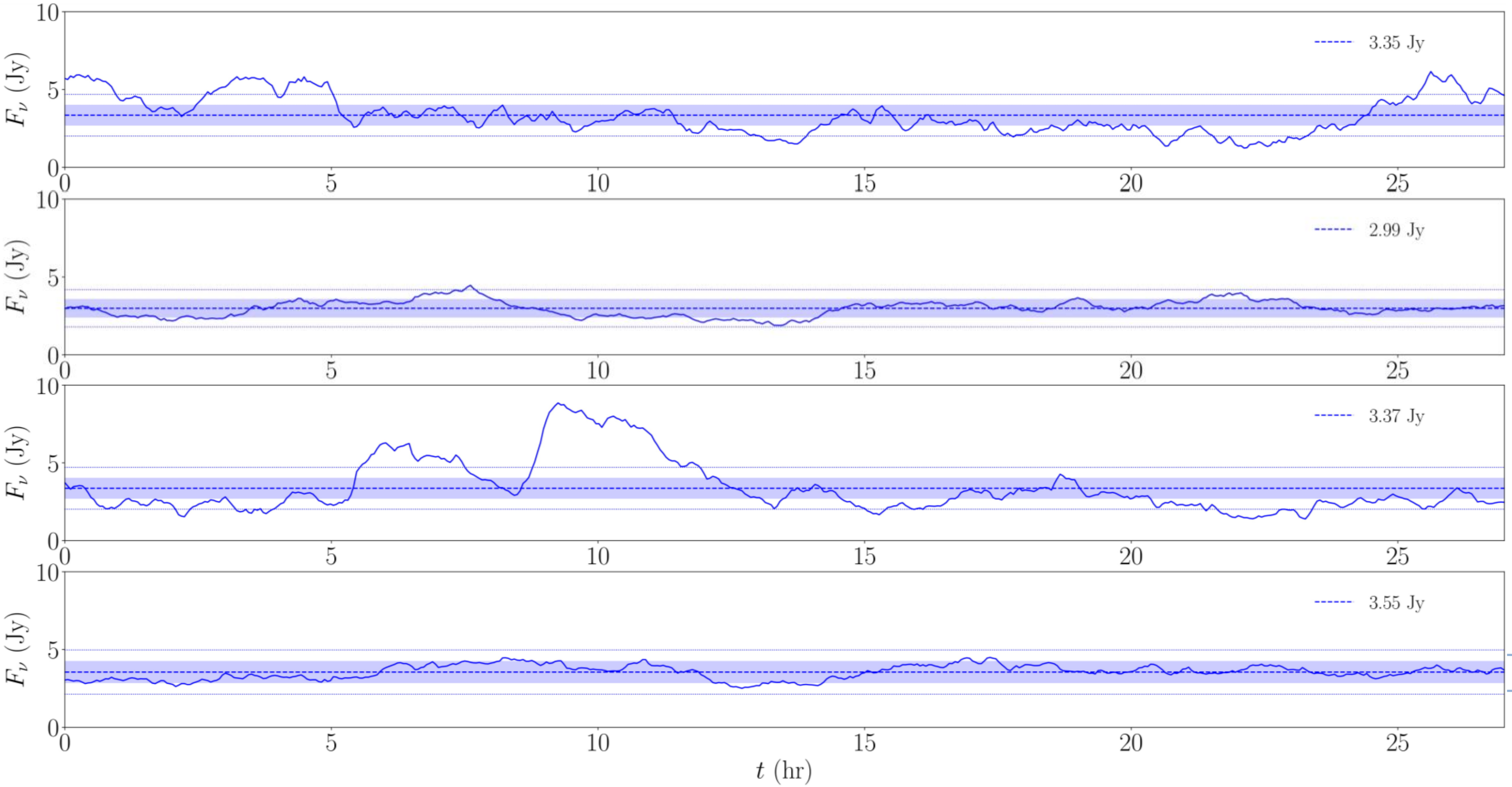
230 GHz variability

Spin 0
Turbulent Heating

Spin 0.9375
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Reconnection Heating



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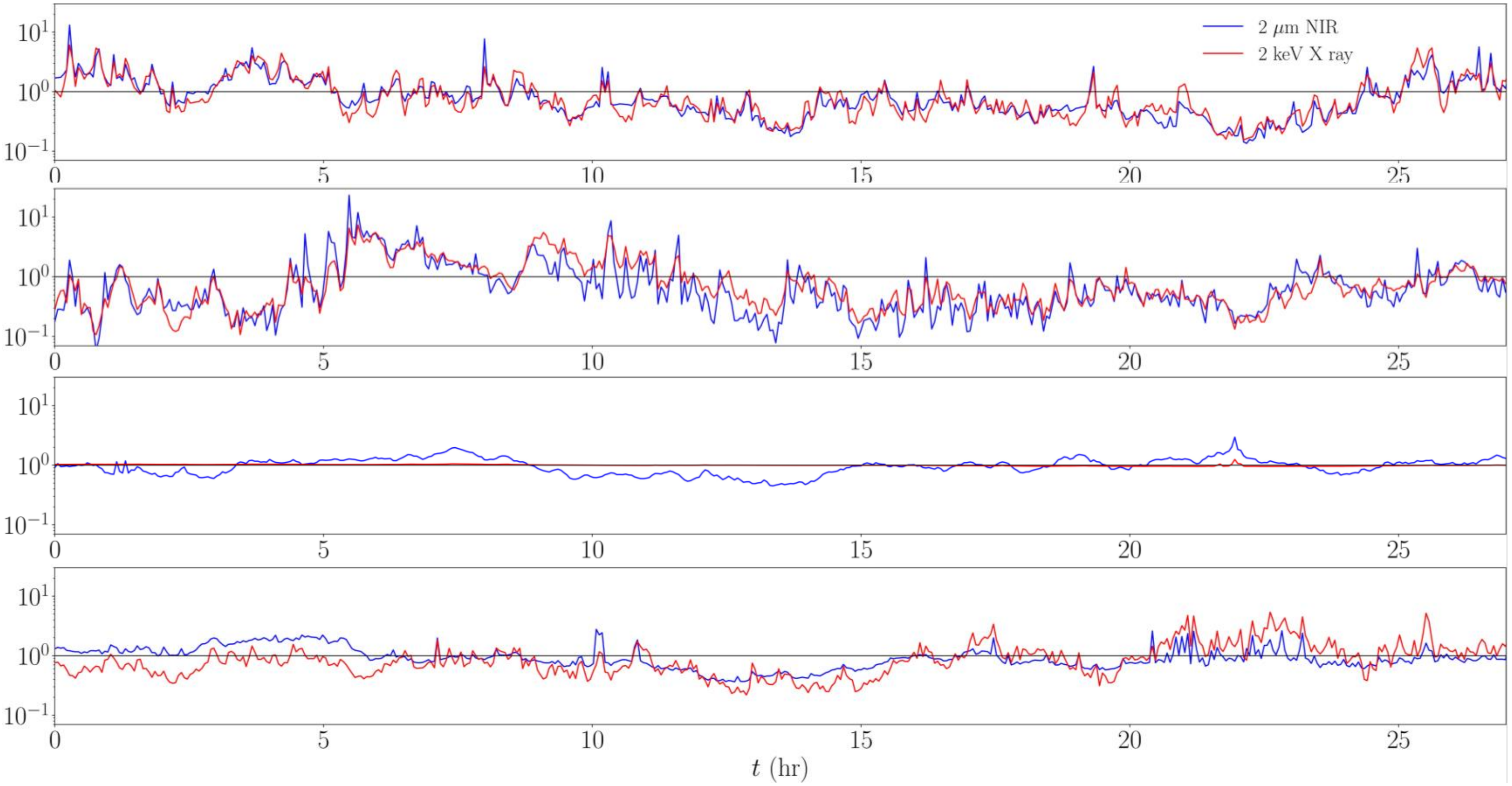
Turbulent Heated disks **exceed** ~20% observed variability

Rough estimate of 230 GHz intraday RMS flux variability (Bower et al. 2015)

IR and X-ray variability: no large flares


Spin 0
Turbulent Heating

Spin 0.9375
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Reconnection Heating

No models reproduce strong IR and X-ray flares →Nonthermal Electrons

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

Takeaways

- Different plasma heating mechanisms produce qualitatively different images and variability from Sgr A*
  - Turbulent heating prescription → disk-jet structure, more variable
  - Reconnection prescription → isotropic & steady

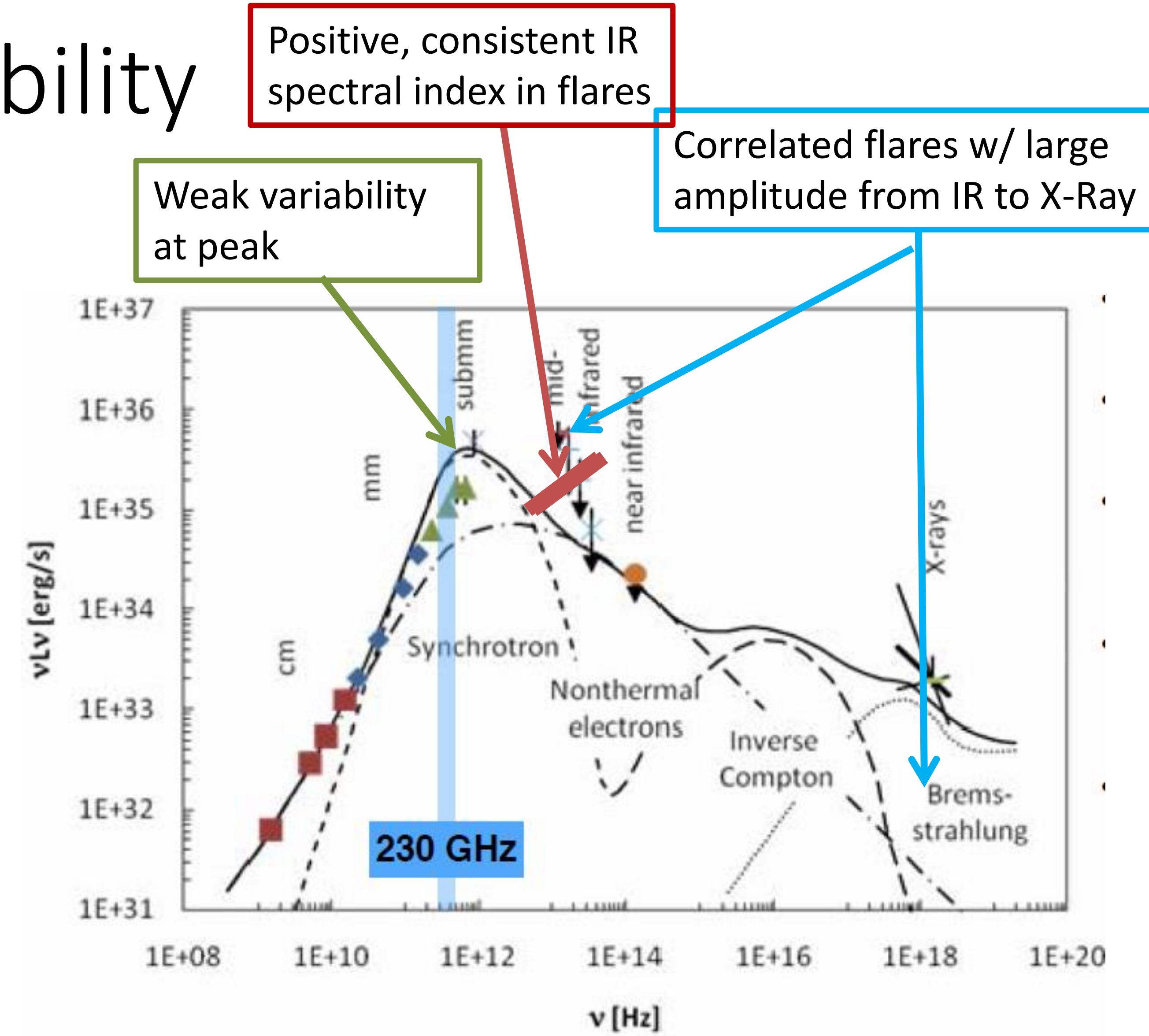
- Optically thin emission at 230 GHz means BH shadow should be visible to the EHT regardless of underlying electron heating.

- 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!

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)



Positive, consistent IR spectral index in flares

Weak variability at peak

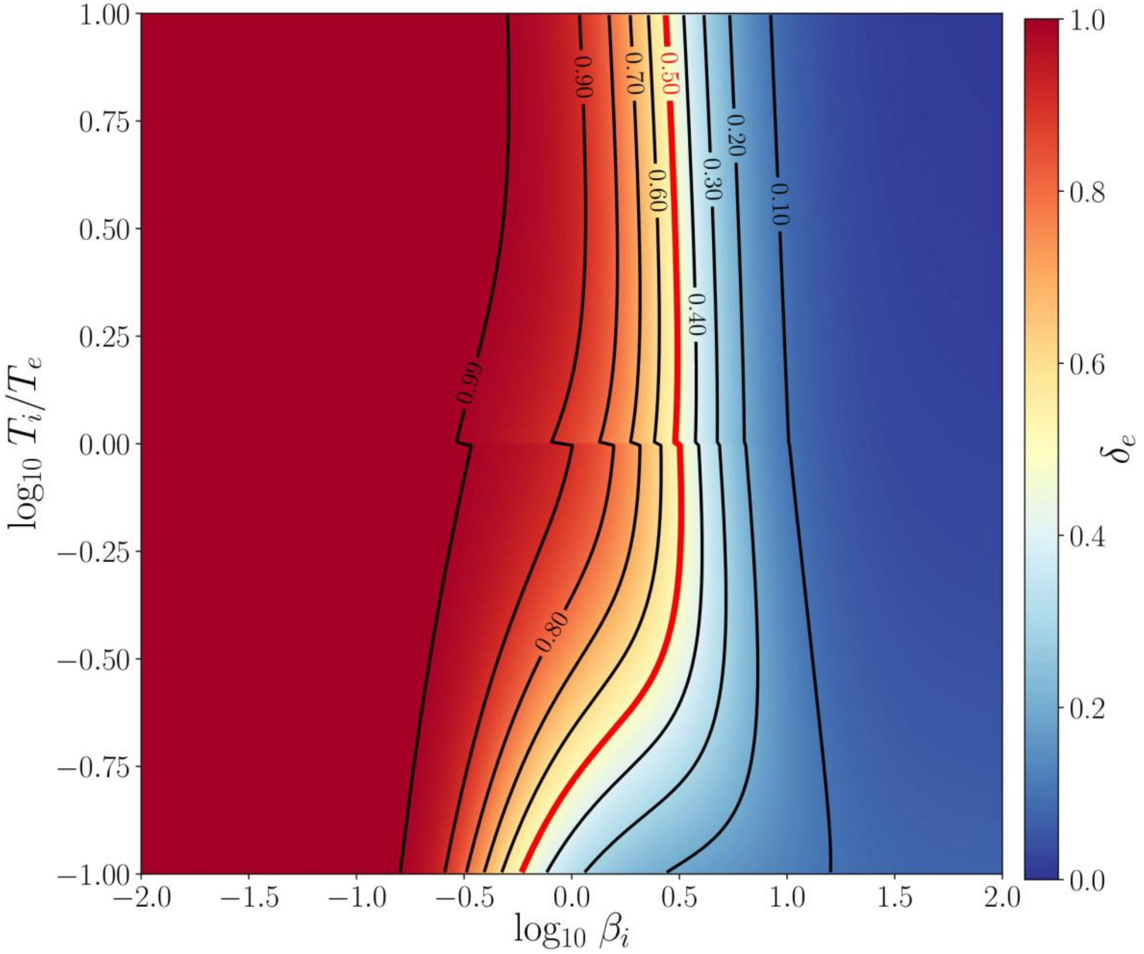
Correlated flares w/ large amplitude from IR to X-Ray

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

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)



Almost all energy to electrons ⟷ Almost all energy to ions

Sub-grid Heating Prescriptions

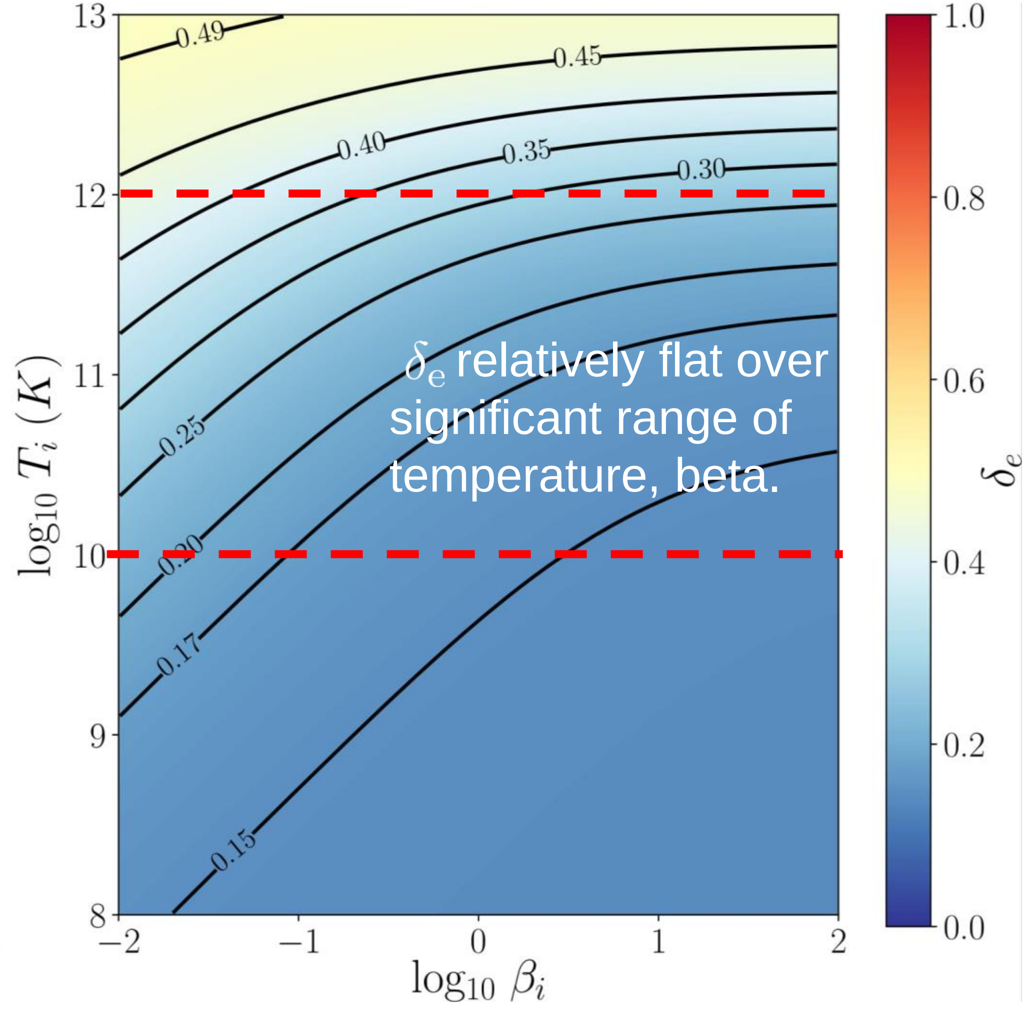
Magnetic Reconnection
(Rowan 2017)

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

$$\sigma_w = \frac{|B|^2}{4\pi\, w} = \frac{|B|^2}{4\pi\left(n_{\mathrm{i}} m_{\mathrm{i}} c^2 + \underbrace{\Gamma_{\mathrm{i}} u_{\mathrm{i}} + \Gamma_{\mathrm{e}} u_{\mathrm{e}}}_{\text{At high temperatures, } \sigma_w < \sigma_{\mathrm{i}}}\right)}$$

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

Assuming **equal** temperatures

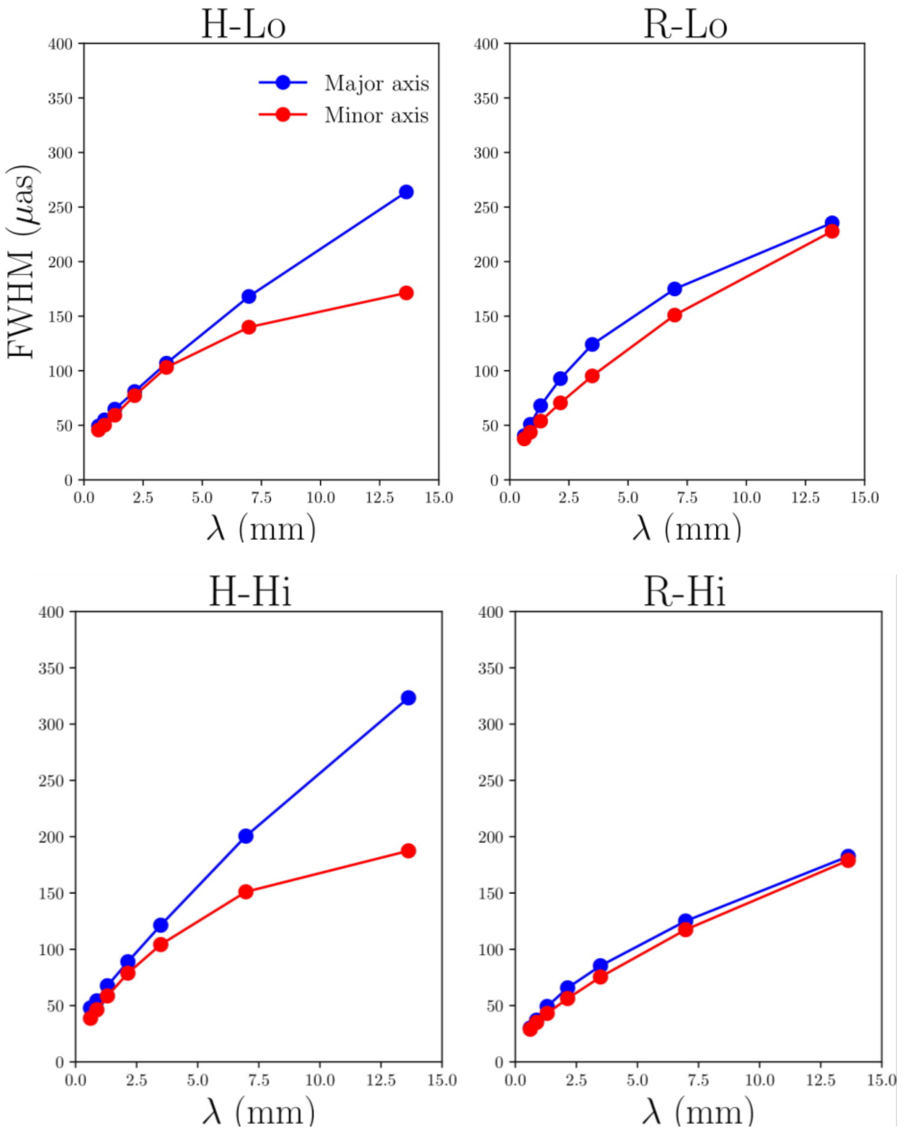


δ_{e} relatively flat over significant range of temperature, beta.

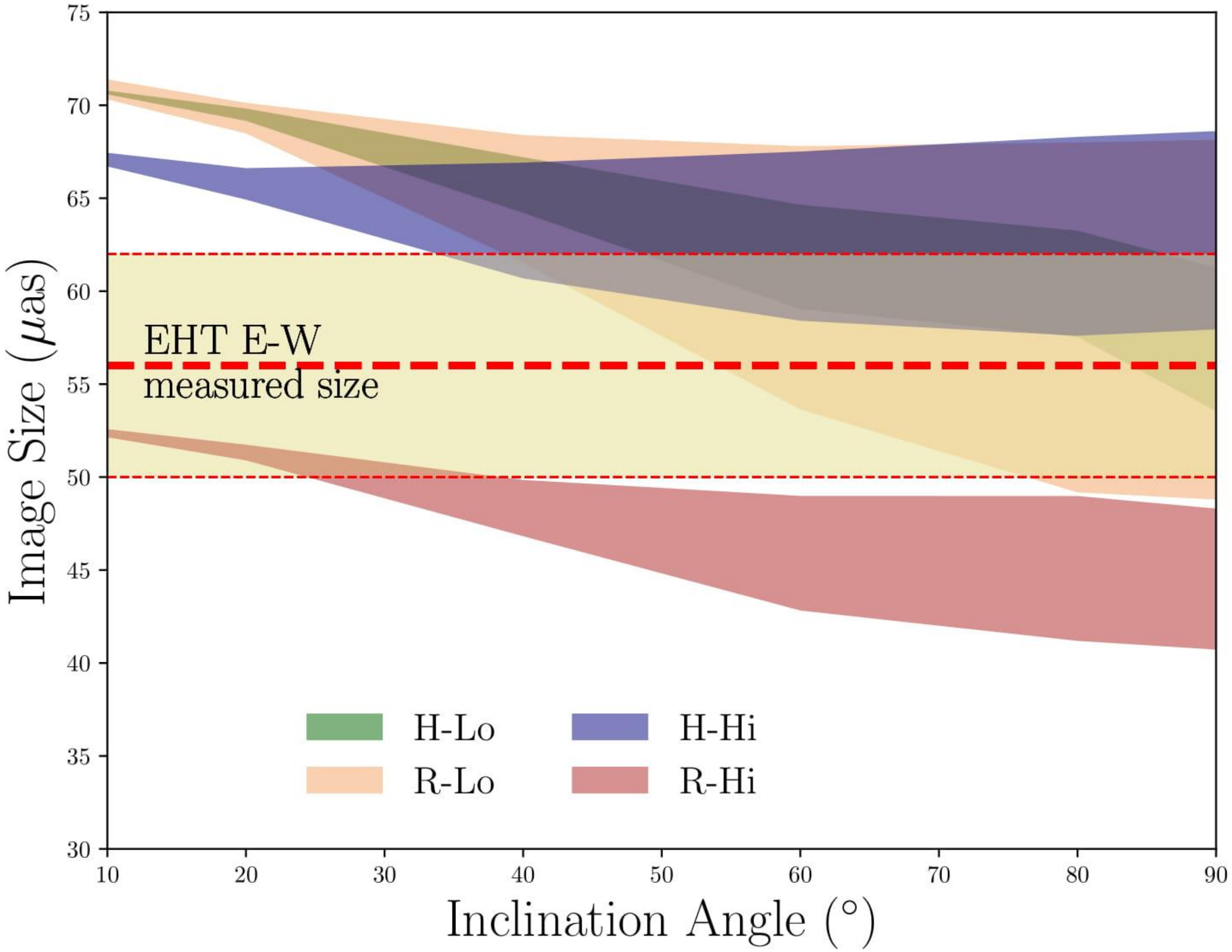
Image Anisotropy with wavelength

- Emergence of jet at low frequencies makes Howes models anisotropic

- See Johnson+2018 (in prep) for new measurements of intrinsic size/anisotropy with wavelength



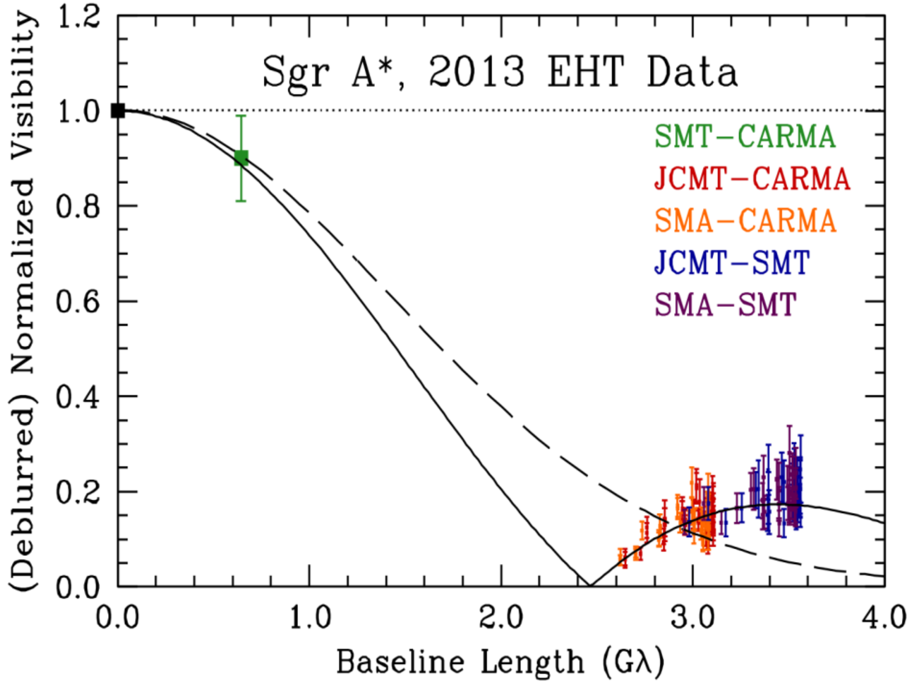
Comparison with EHT 230 GHz measurements



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

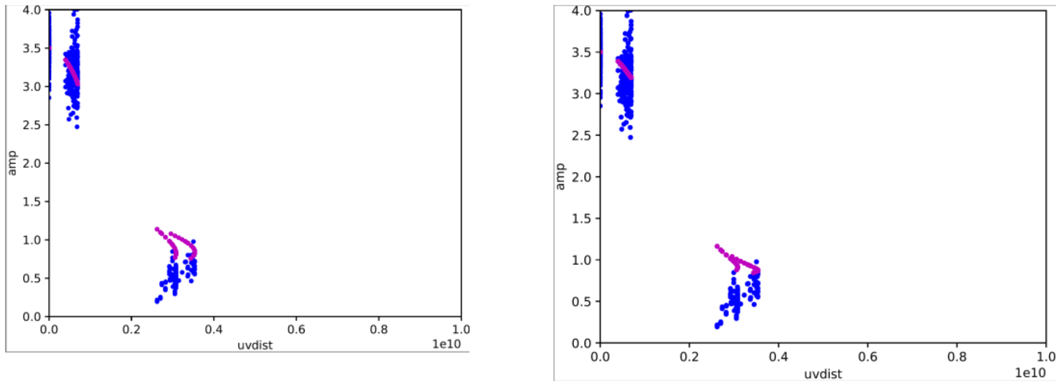
R-Hi is the most compact, so it is only consistent with the measured size near-face on

Comparison with EHT 2013 230 GHz measurements

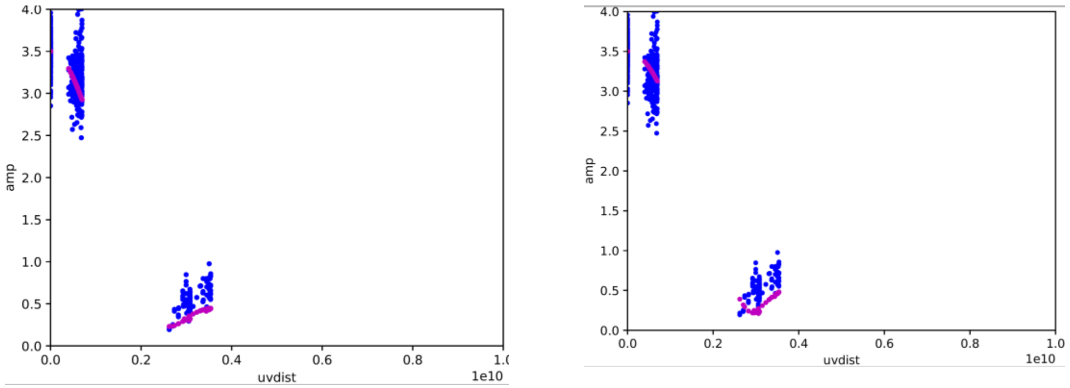


Johnson+ (2015)

60 degree inclination – no visibility null



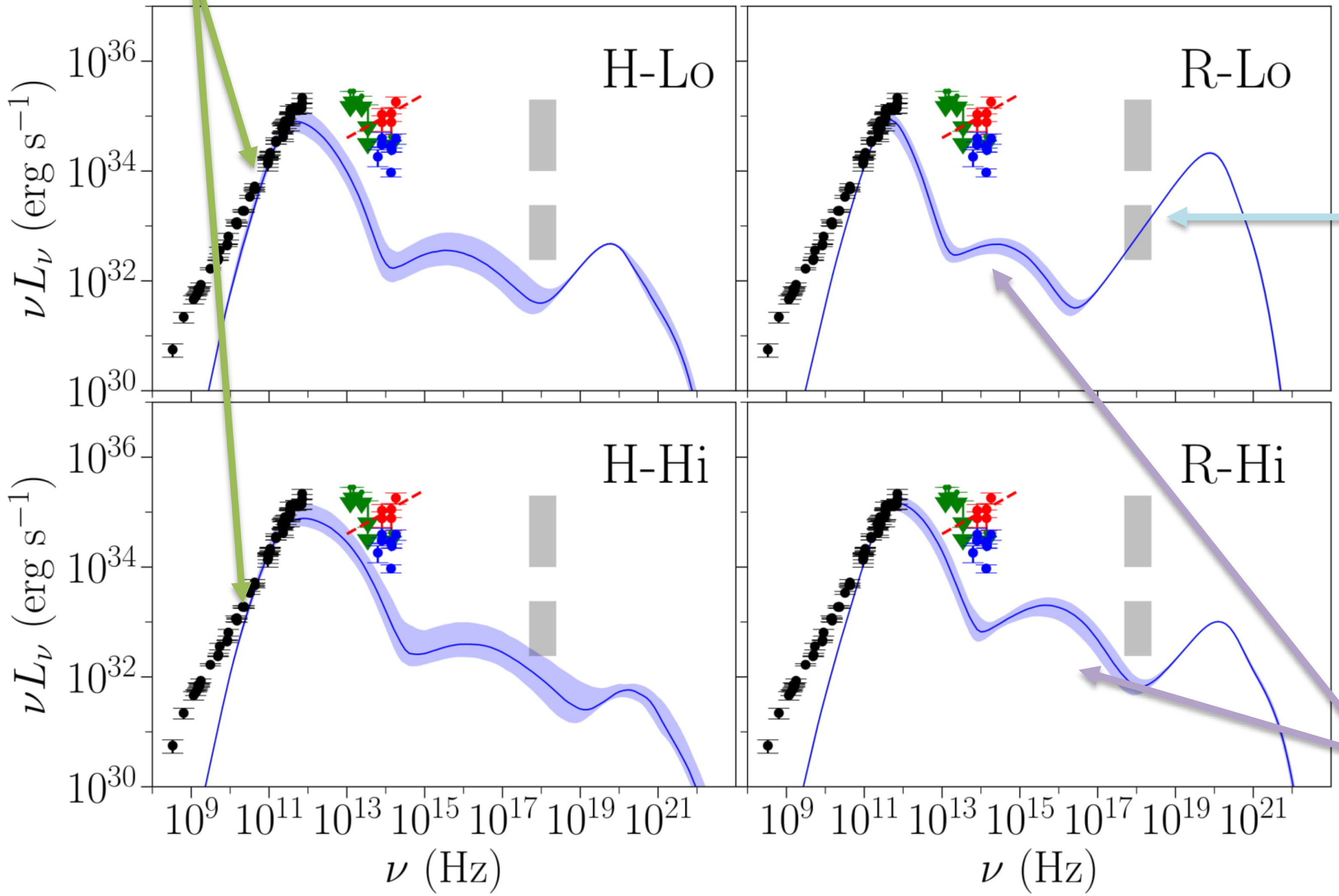
10 degree inclination – visibility null from symmetric ring



Results: *Spectra*

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

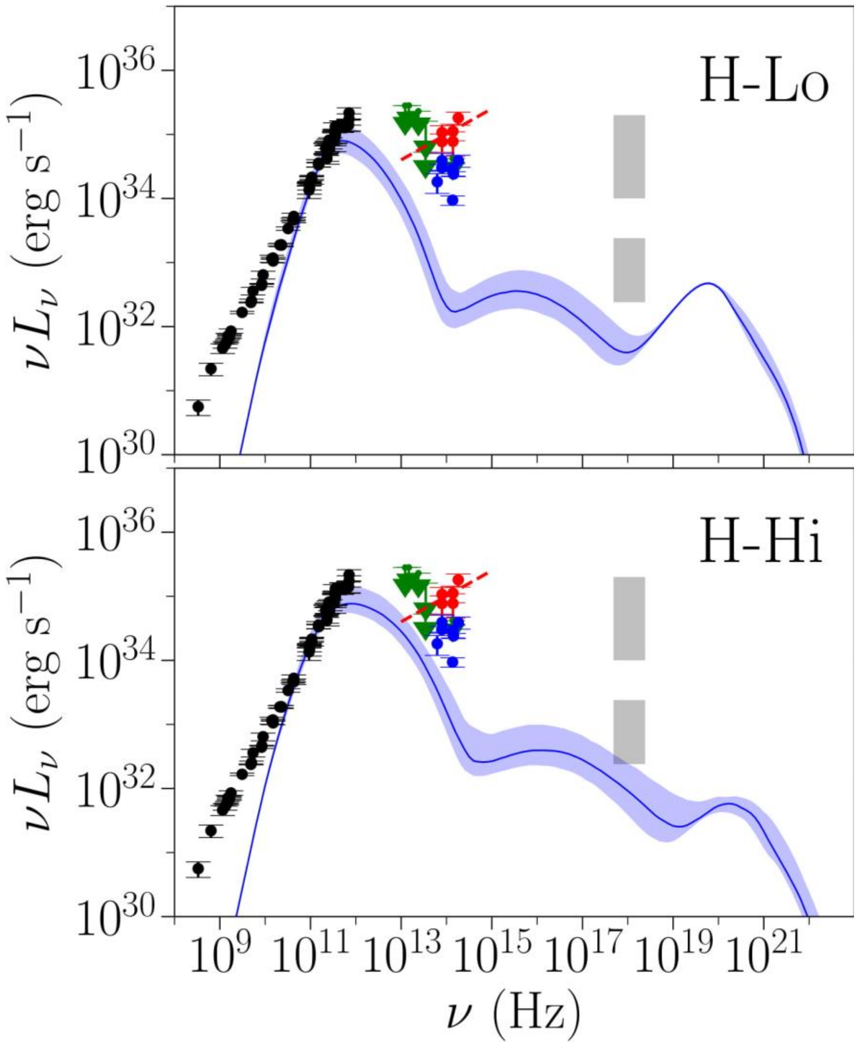
Howes models with funnel emission do slightly better at low frequencies



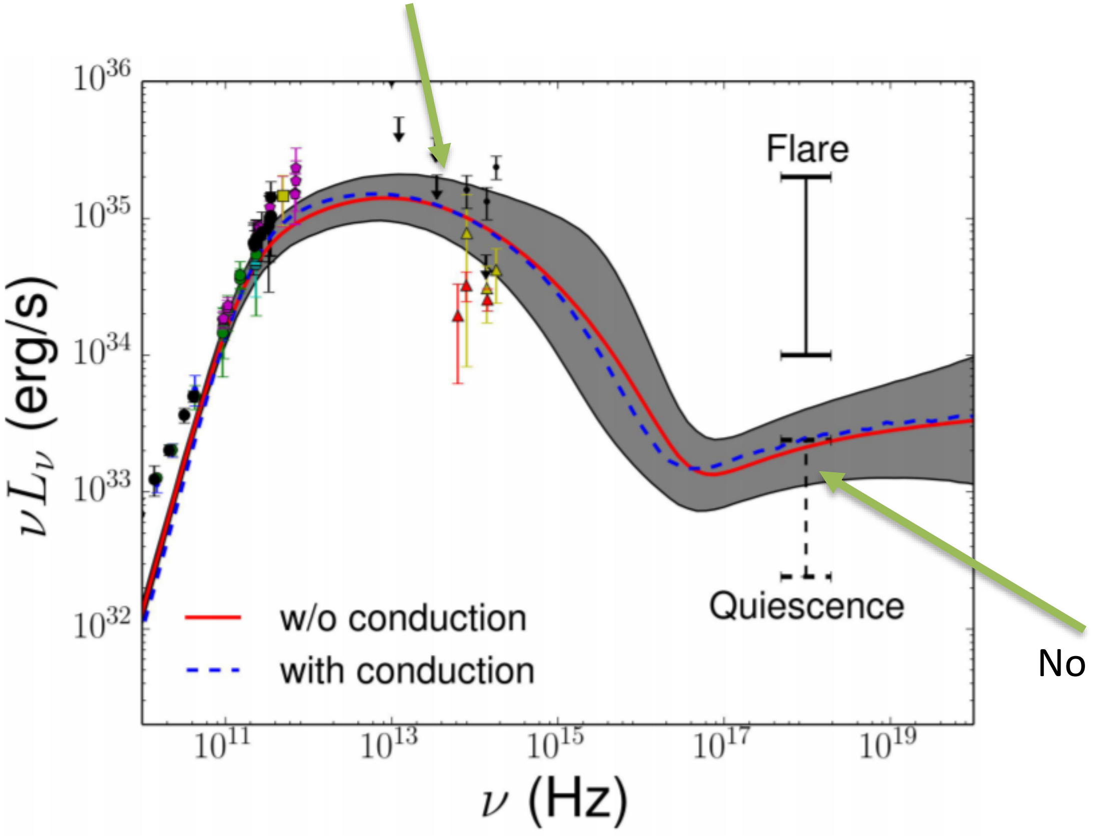
Free-free X-ray emission set by density scaling needed to match sub-mm peak.

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

Results: *Spectra – comparison to Ressler+ 2017*



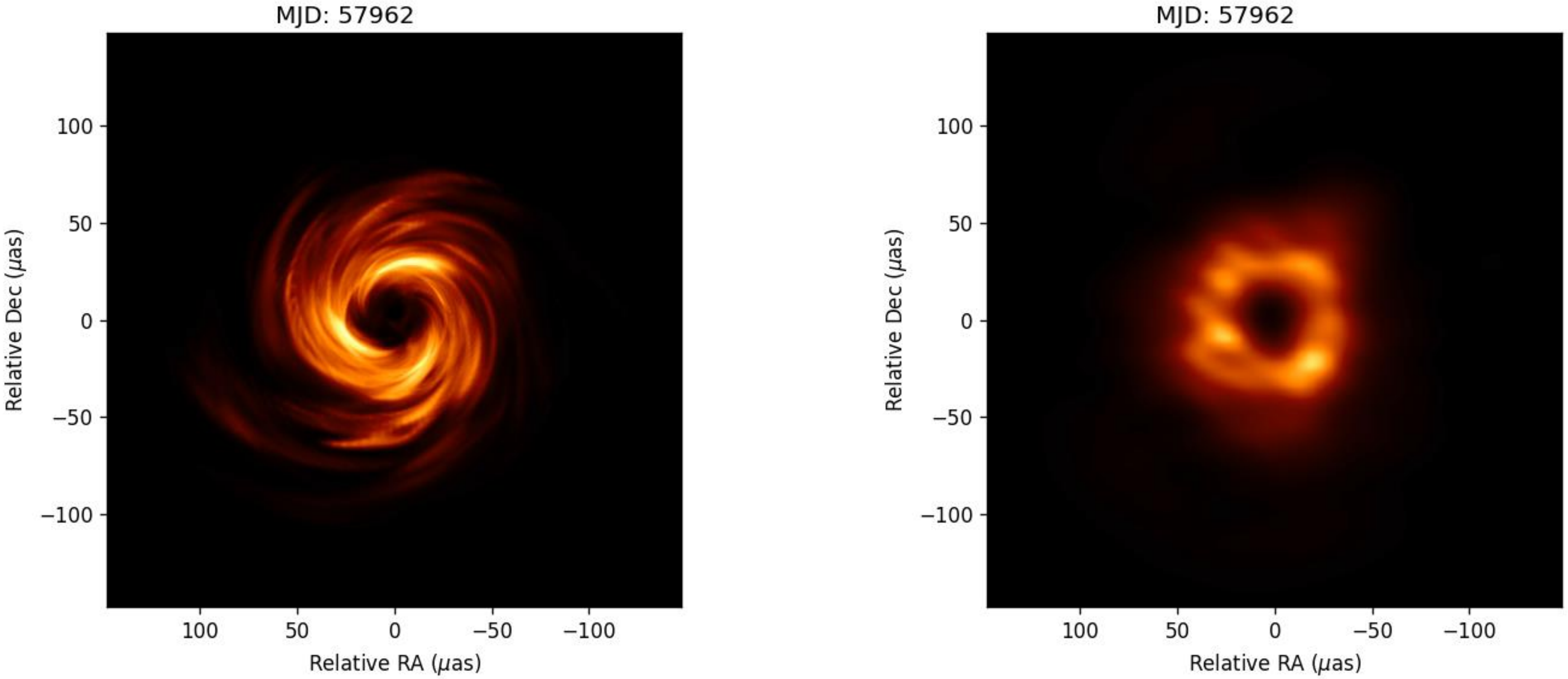
With much more magnetization (MAD parameter ~40), Ressler+17 are able to hit/exceed quiescent IR points but do not match the measured spectral index



No free-free included

Video Reconstruction:

Using Dynamical Imaging (Johnson+ 2018) and EHT-Satellite Baselines



Movie credit: Daniel Palumbo