Evolving Thermal and Nonthermal Electron Distributions in Simulations of Sgr A*

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MNRAS 466, 705 (arXiv: 1605.03184)
MNRAS 470, 2367 (arXiv: 1704.05092)

Work with Ramesh Narayan and Aleksander Sądowski

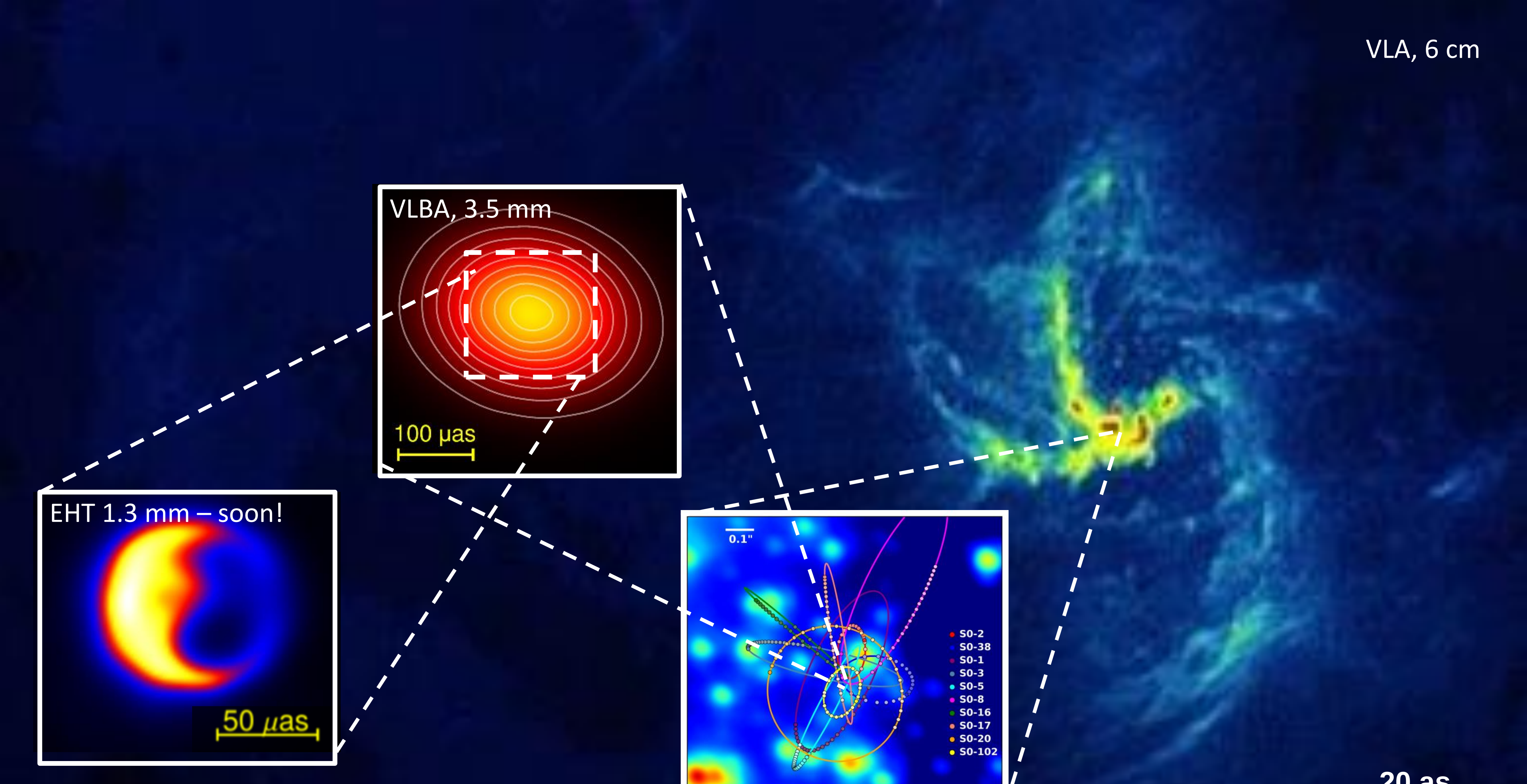


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Gisela Ortiz-Leon (VLBA+LMT model fit), Avery Broderick & Katie Bouman (EHT simulation)

Sgr A* Spectrum

- Hot (Radiatively Inefficient) Accretion Flow ($\dot{M} \sim 10^{-7}\dot{M}_{\rm Edd.}$)
- Hot flows → low densities → inefficient Coulomb coupling → different election and ion temperatures.
- A separate nonthermal electron population can explain low-frequency & NIR spectrum (Özel et al. 2000, Yuan et al. 2003)

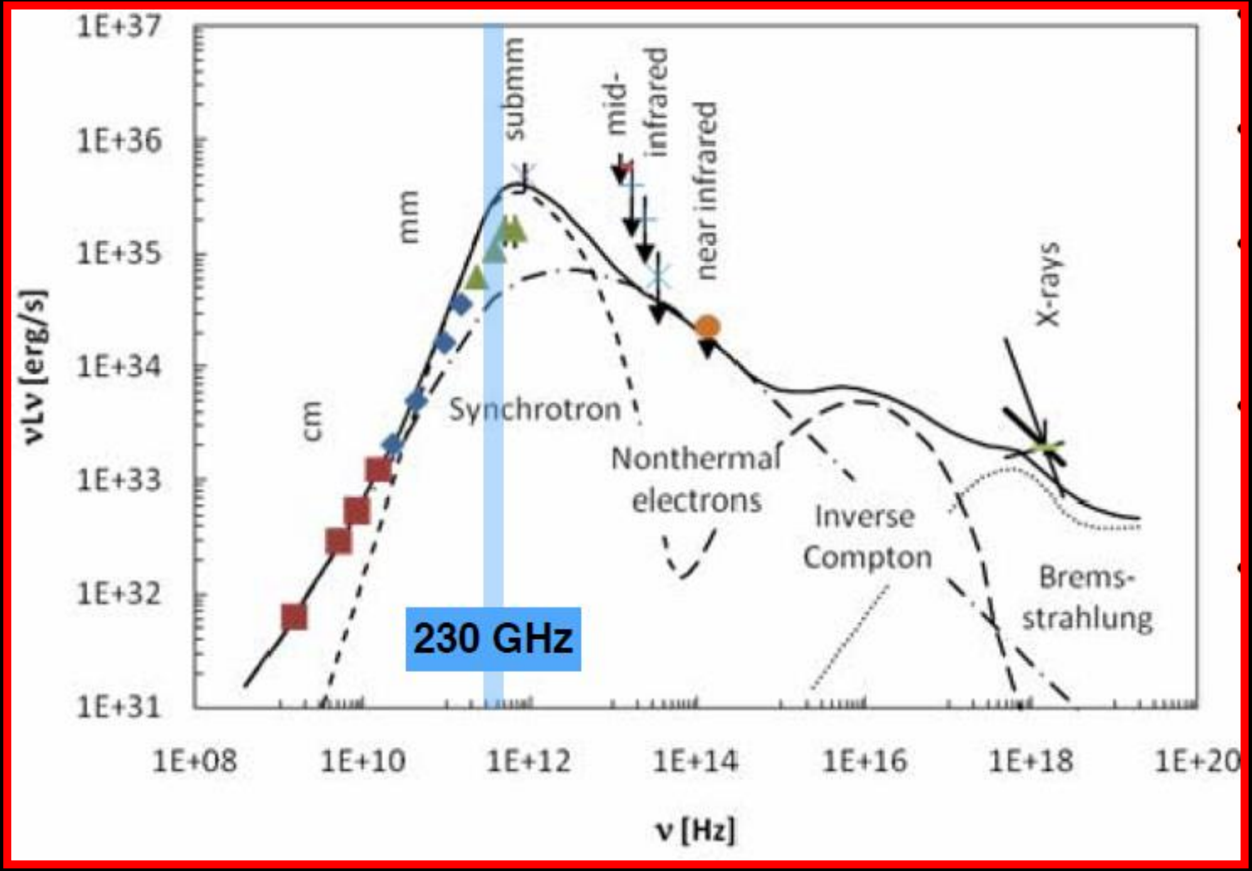
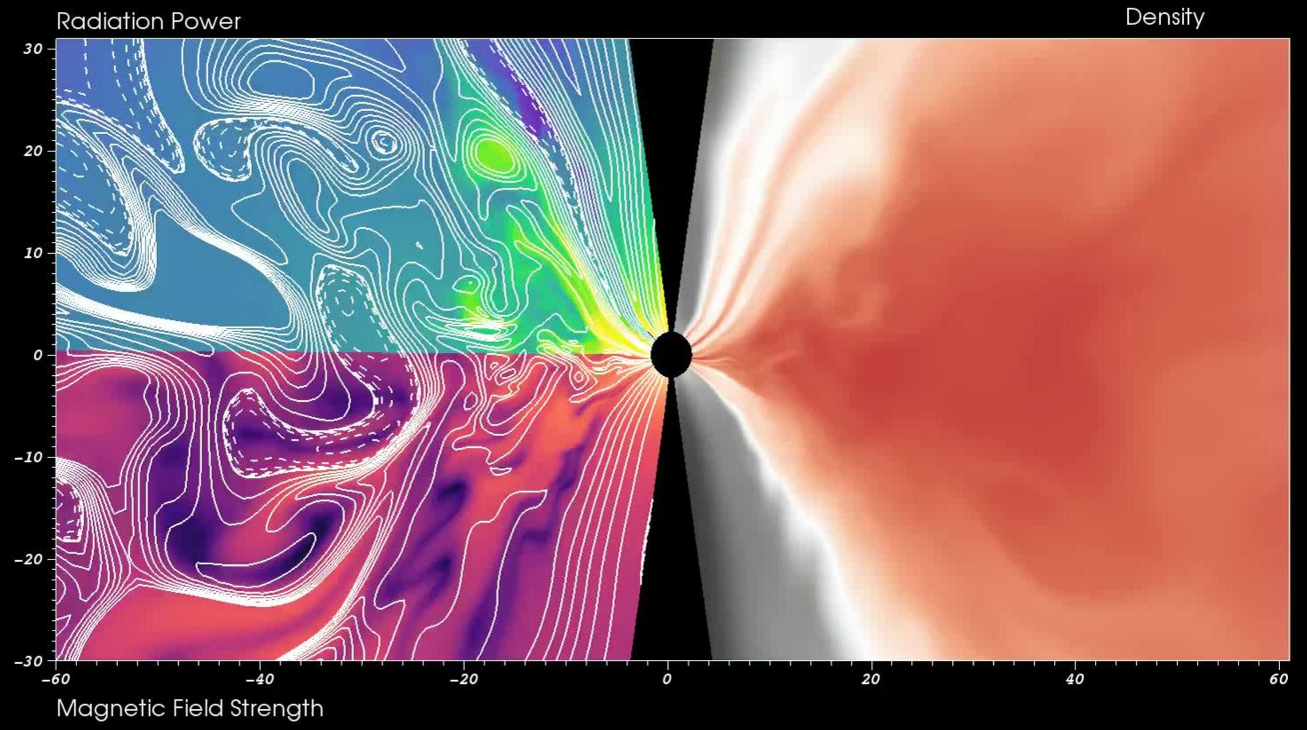


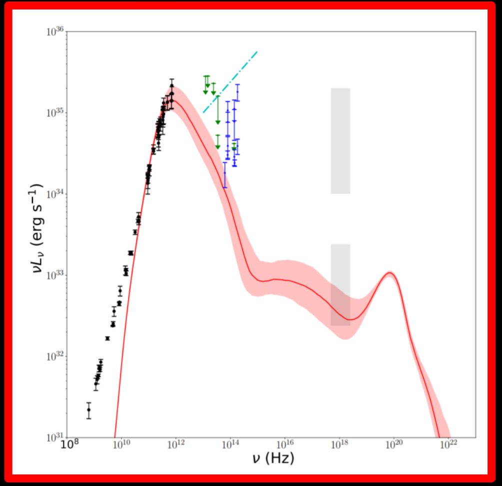
Image Credit: Genzel et al. (2010), Yuan et al. (2003).

GRMHD Simulations of Sgr A*



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

$T_e?$



Raytraced Movie Credit: Hotaka Shiokawa

Two-Temperature GRMHD Simulations

Independently evolve two particle species with magnetic field & radiation

- using **KORAL** (Sądowski et al. 2013)

Because electrons radiate efficiently, ions should be hotter:

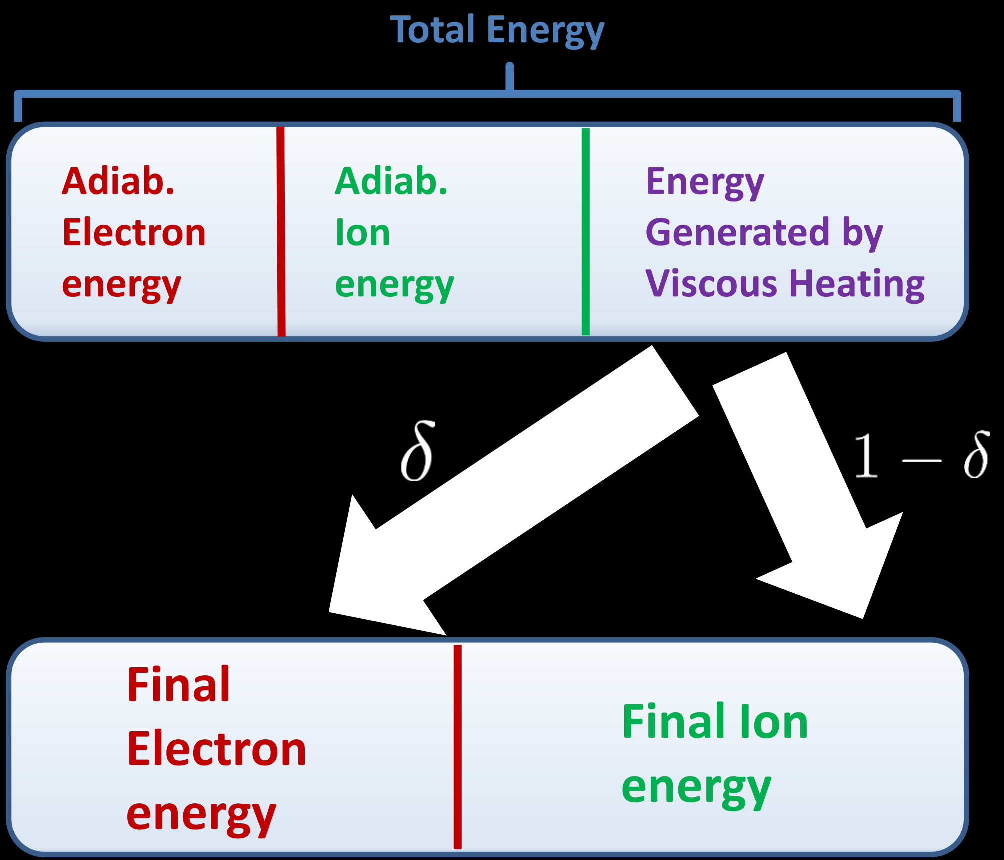
- but the **subgrid heating prescription** can make a big difference.

Previous work:

- Ressler et al. 2015 (*MNRAS* 454, 1848)
- Sądowski et al. 2017 (*MNRAS* 466, 705)
- Ressler et al. 2017 (*MNRAS* 467, 3604)

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 δ goes directly into the electrons.

Subgrid Heating Prescriptions

Landau-Damped Cascade (Howes 2010)

- Based on solar wind physics – very different environment from Sgr A*.
- Predominantly heats electrons when plasma highly magnetized.
- Used in all previous work (Sadowski 2016, Ressler 2016,2017)

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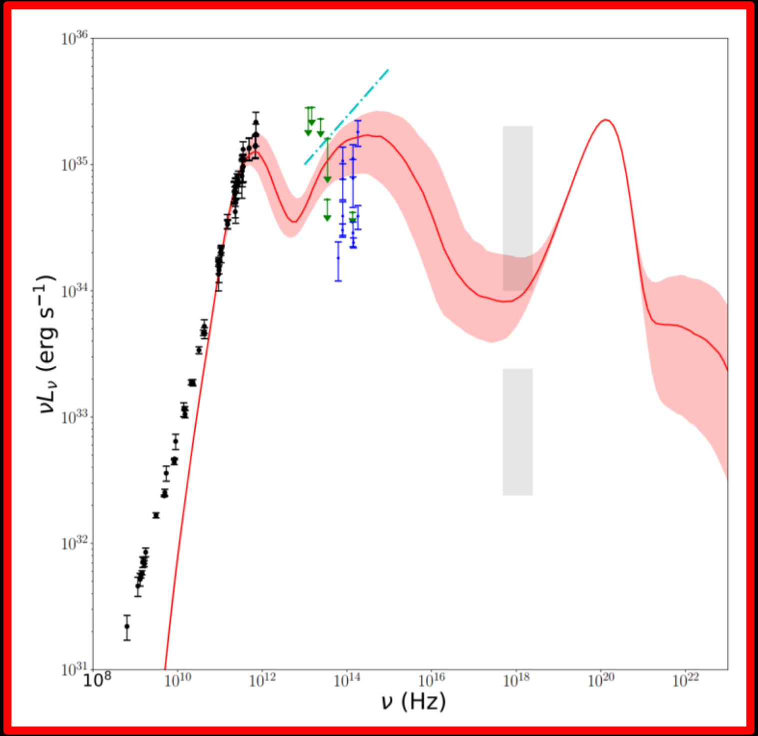
Magnetic Reconnection (Rowan 2017)

- Fit to Particle-in-Cell simulation results at appropriate Sgr A* ranges of temperature, magnetization
- Always heats ions more effectively: but at low magnetizations/high temperatures, $\delta \rightarrow 0.5$

Two Heating Prescriptions

Spectra

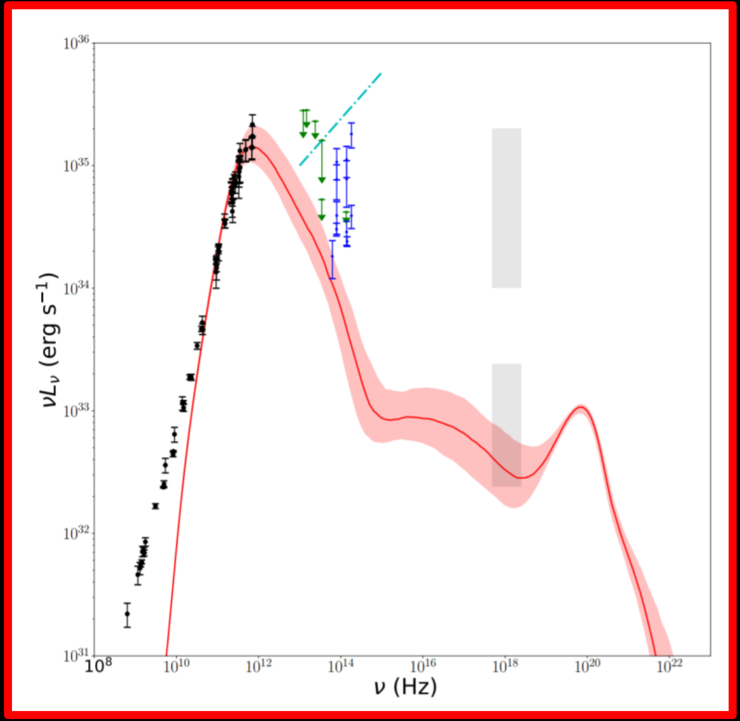
Magnetic Reconnection



IC bump at near IR frequencies produces approx. correct **spectral slope** (Witzel et al. 2013), but with too much luminosity

Overpredicts free-free X-rays from hot gas at large radii

Landau Damped Cascade



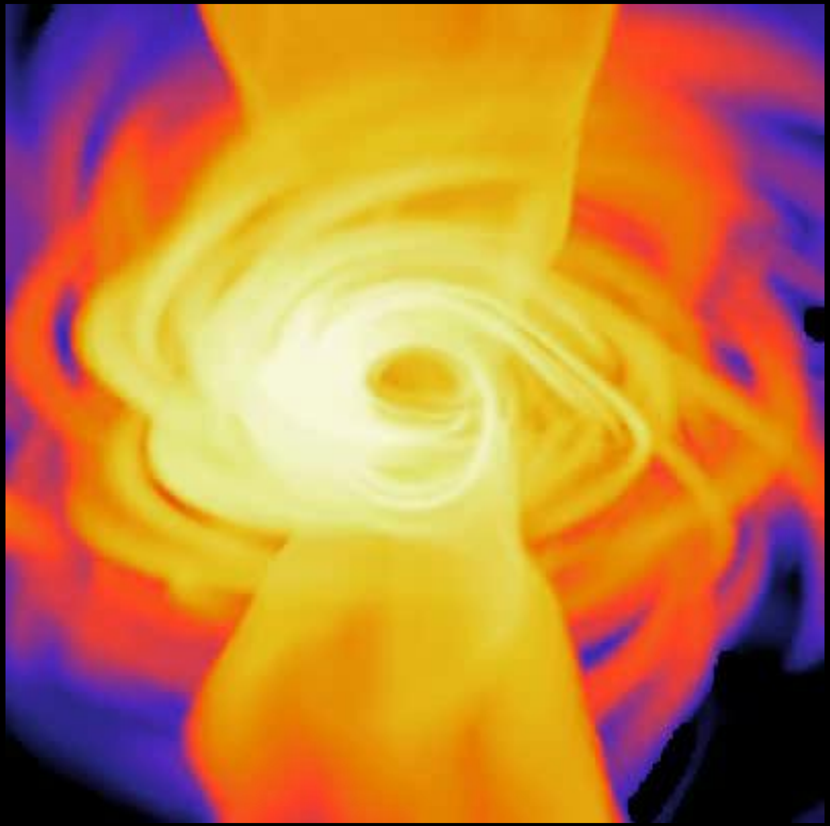
Underpredicts NIR flux and spectral slope.

Large-radii X-rays in the right range, though **no large flares**.

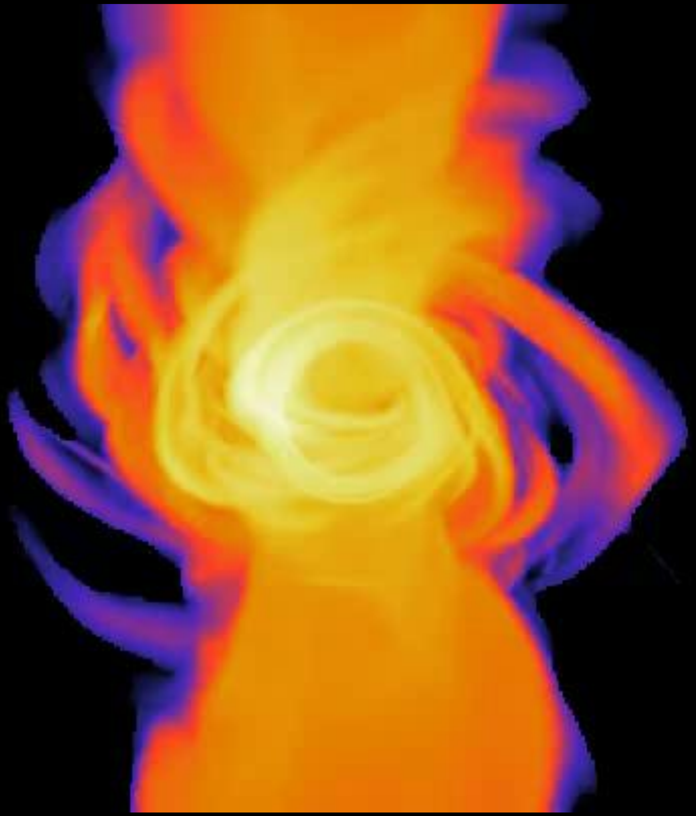
Two Heating Prescriptions

1.3 mm movies (log scale)

Magnetic Reconnection

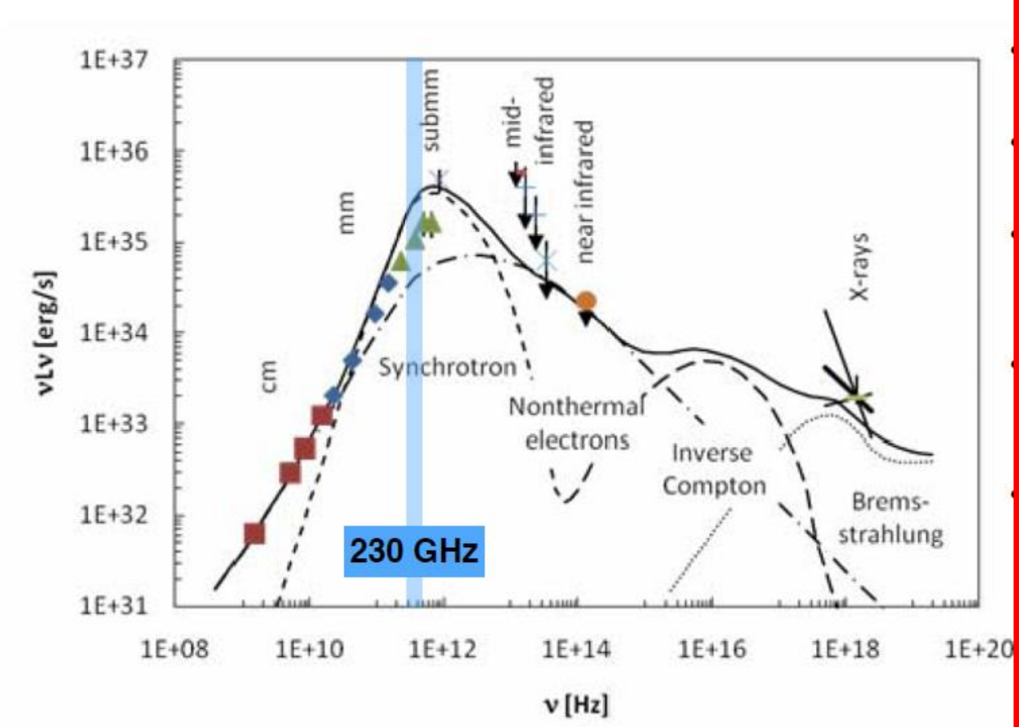


Landau Damped Cascade

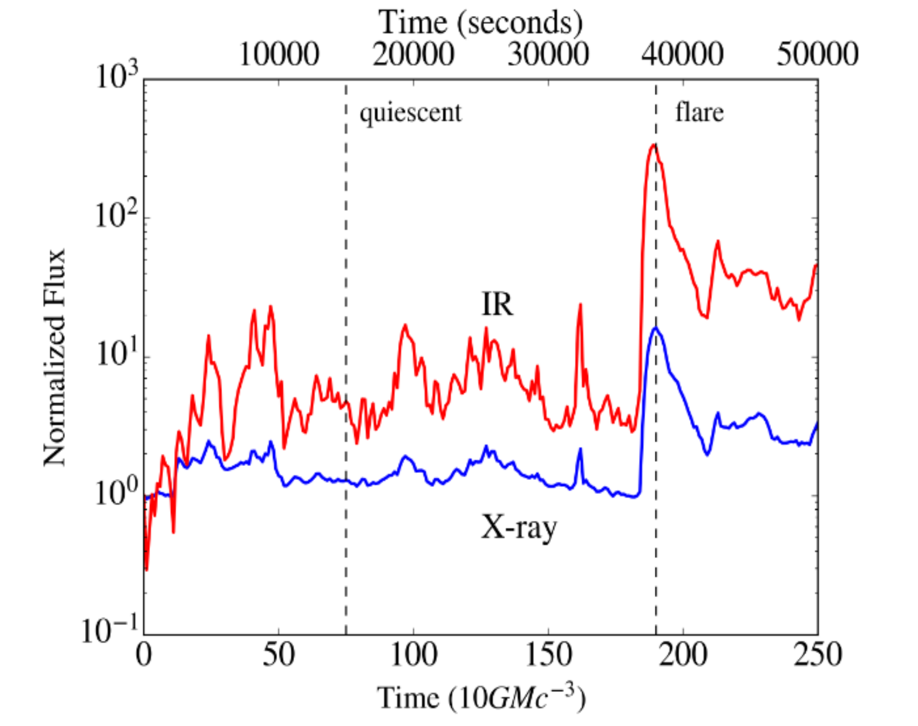


Why do we need a Nonthermal Population?

1. Low-frequency spectrum



2. Flares



Ball et al. 2016
arXiv 1602.05968

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

Simulating a Non-Thermal Population

Self-consistently evolve a spectrum $n(\gamma)$ of nonthermal electrons in global GRRMHD simulations **including interactions** with all other quantities (thermal gas, radiation, magnetic field . . .)

$$\underbrace{\frac{\partial n(\gamma)}{\partial t} + \vec{\nabla} \cdot (\vec{v}\, n(\gamma))}_{\text{Advection}} = \underbrace{-\frac{\partial}{\partial \gamma}\left(\dot{\gamma}_{\rm adiab} n(\gamma)\right)}_{\text{Adiabatic Compression/Expansion}} \overbrace{- \frac{\partial}{\partial \gamma}\left(\dot{\gamma}_{\rm rad} n(\gamma)\right)}^{\text{Radiative Cooling}} + \underbrace{Q(\gamma)}_{\text{Injection/Particle Acceleration}}$$

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First Nonthermal Sgr A* Simulation

Simple test case:

Constant 1.5% nonthermal energy injection fraction

Constant p=3.5 power law.

Fixed injection minimum and maximum

Current work: incorporating spatial variation in energy injection fraction and in power law index based on local conditions

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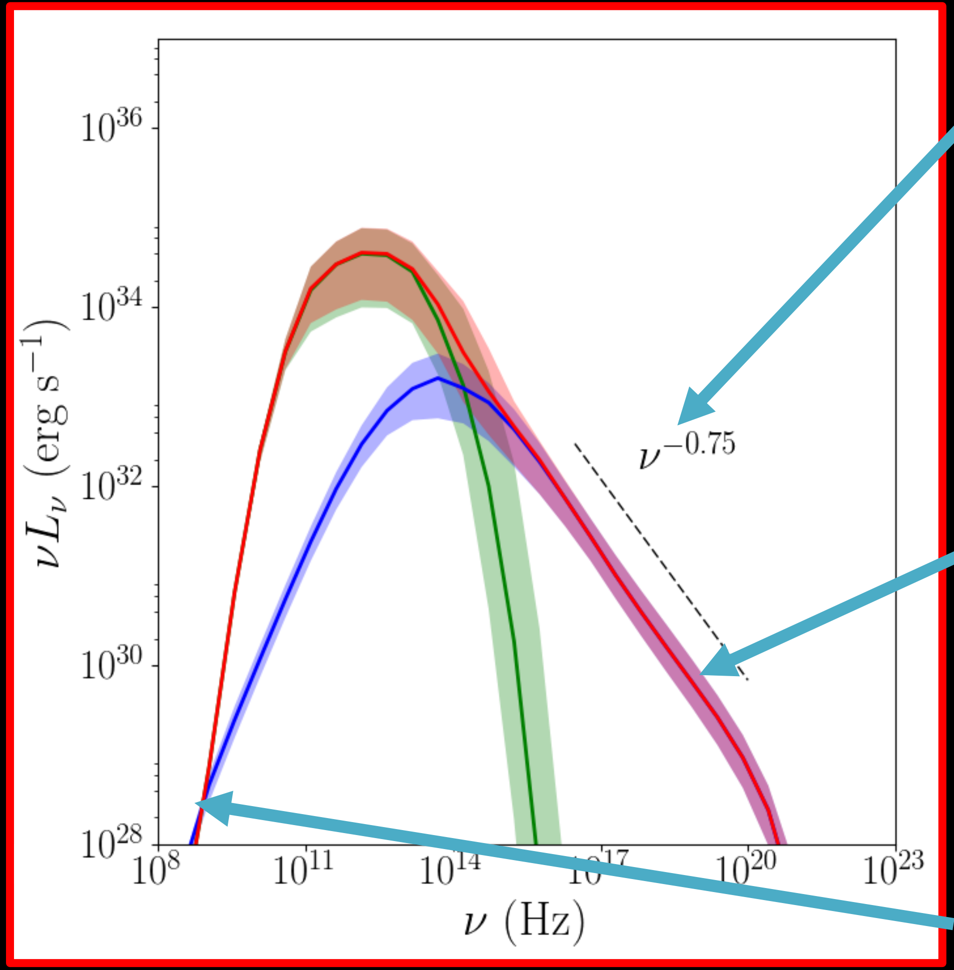
First Nonthermal Sgr A* Simulation

Synchrotron Spectra



Spectrum has broken (due to synchrotron cooling) nearly everywhere (with variation based on local conditions)

Need to add localized injection to produce x-ray flares

Need to lower minimum γ to produce low-frequency nonthermal emission

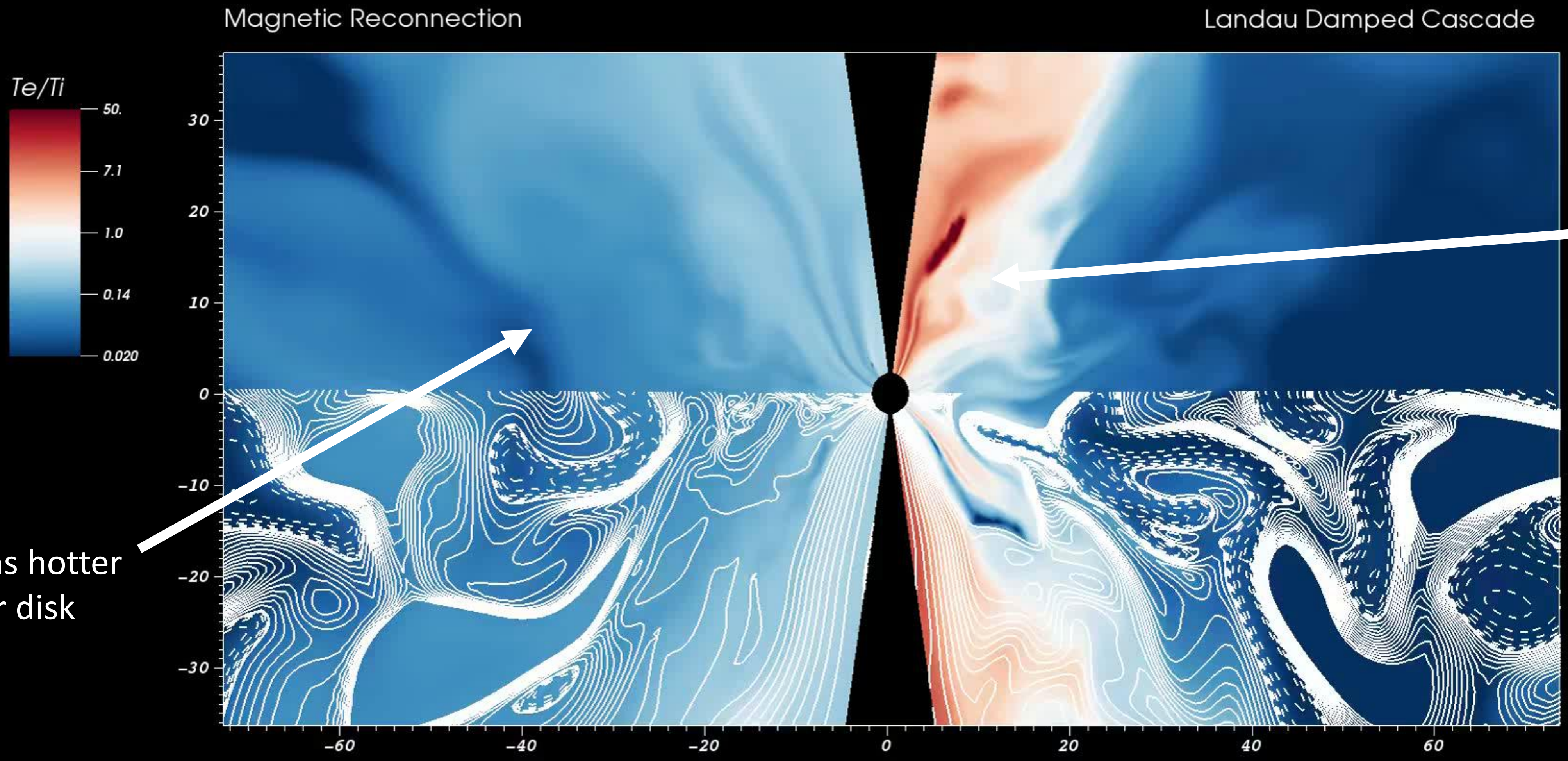
MNRAS 470, 2367 (arXiv: 1704.05092)

Takeaways

- Flows around Sgr A* and M87 should be modeled with consistent electron & ion thermodynamics.
- Different physical plasma heating mechanisms produce qualitiatively different spectra and images can be tested using two-temperature GRMHD
- We now have a method to simulate the evolution of non-thermal electron distributions in global GRMHD simulations → start to explore the origins of extreme NIR and X-ray flares.

Two Heating Prescriptions

Temperature ratio: T_e / T_i

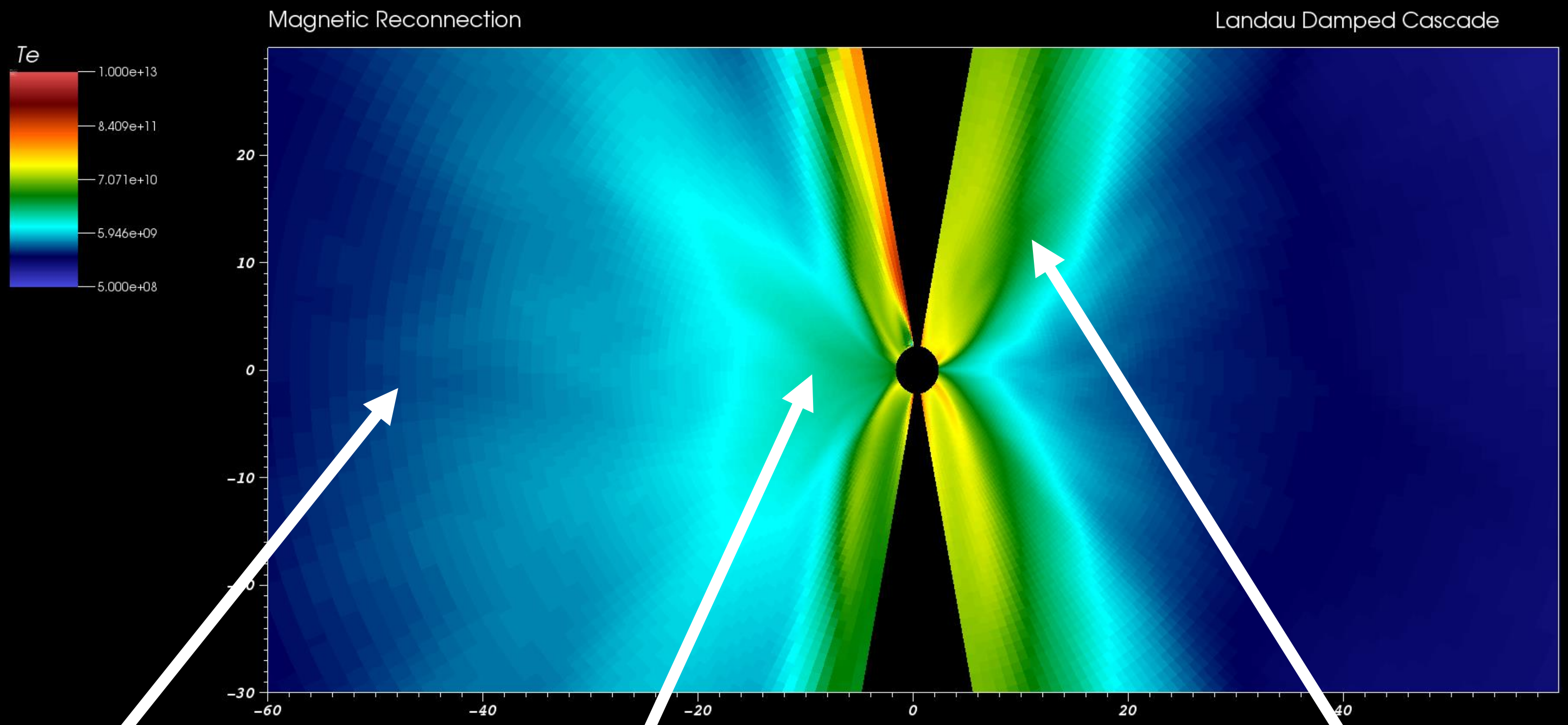


Electrons exceed proton temperature in jet sheath

Electrons hotter in outer disk

Two Heating Prescriptions

Electron Temperature T_e



Hot disk at large radii overproduces free-free

IC from inner disk produces IC bump for NIR, matching data spectral slope

IC from hot jet sheath produces IC at higher frequencies

Two Heating Prescriptions

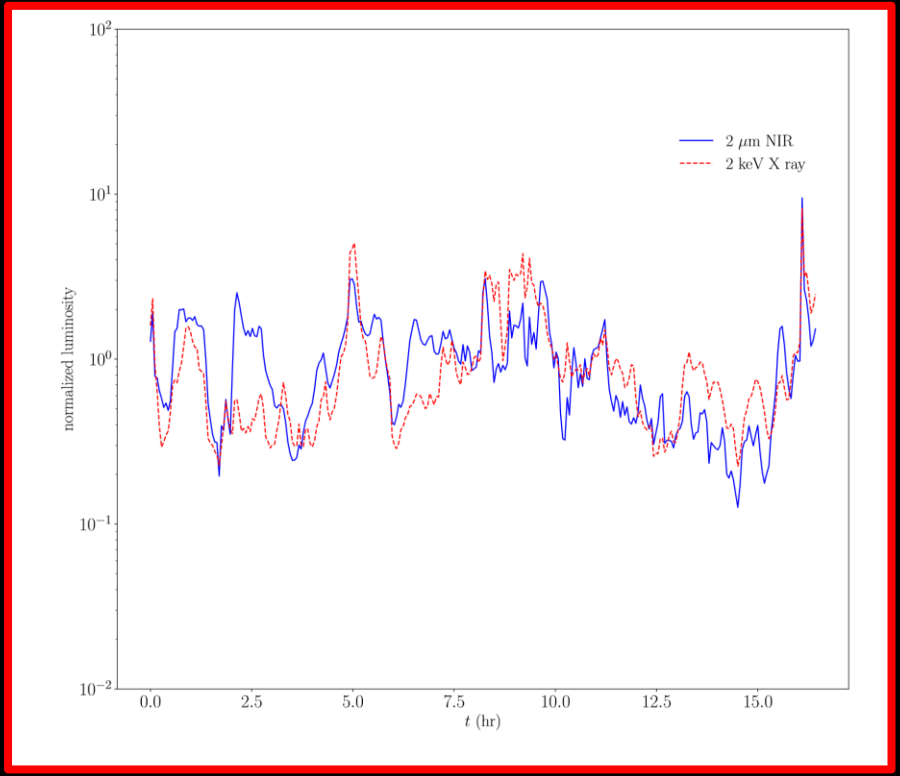
1.3 mm movies

Magnetic Reconnection

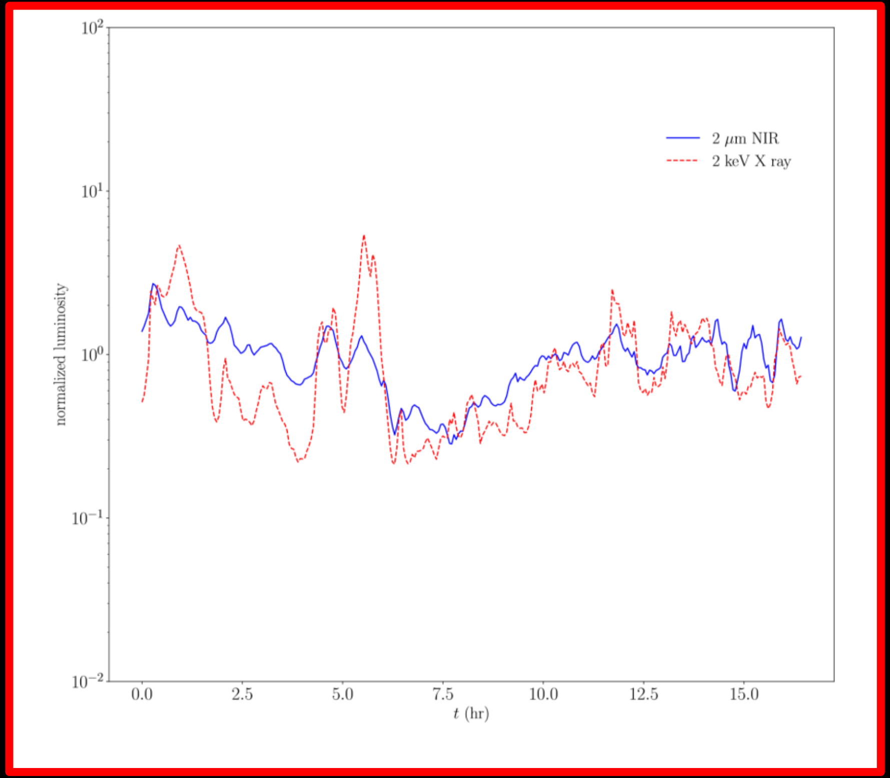
Landau Damped Cascade

Two Heating Prescriptions
Variability

Magnetic Reconnection



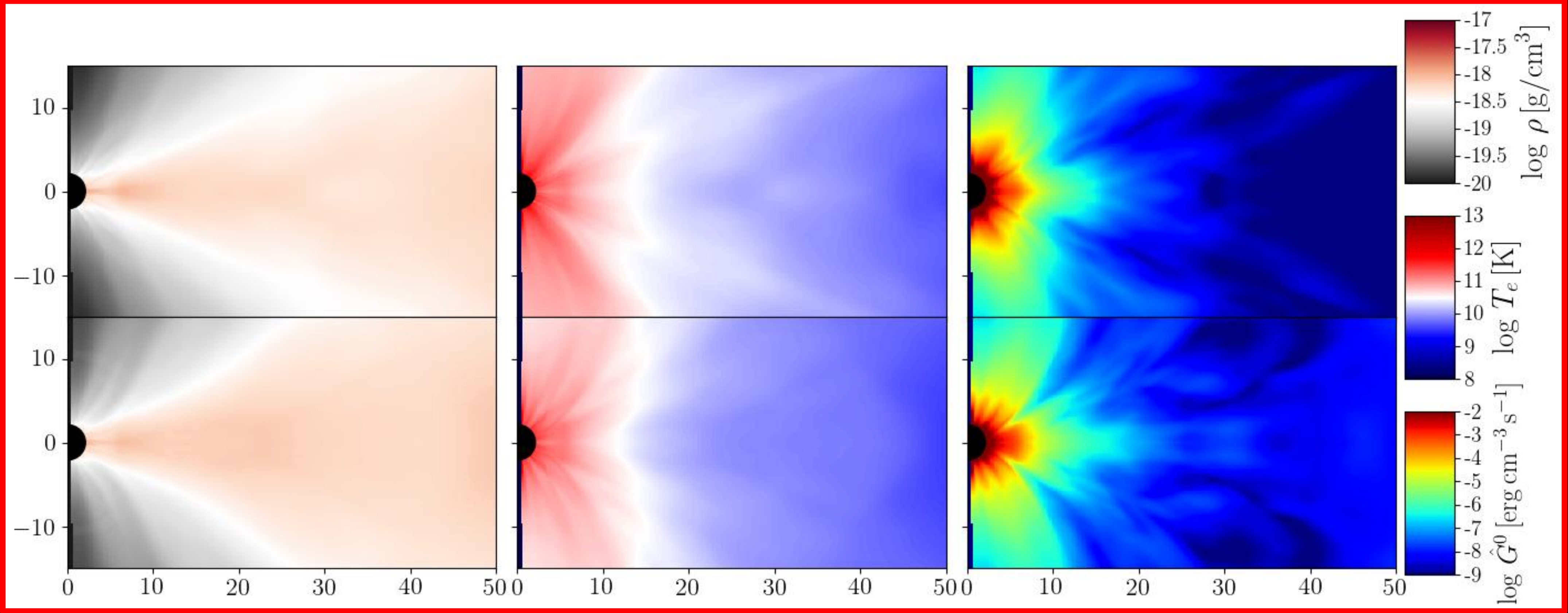
Landau Damped Cascade



First Nonthermal Sgr A* Simulation

Thermal populations only

Nonthermal population included



ρ T_e Radiation Power

Nonthermal – spatial variation in location of power-law break