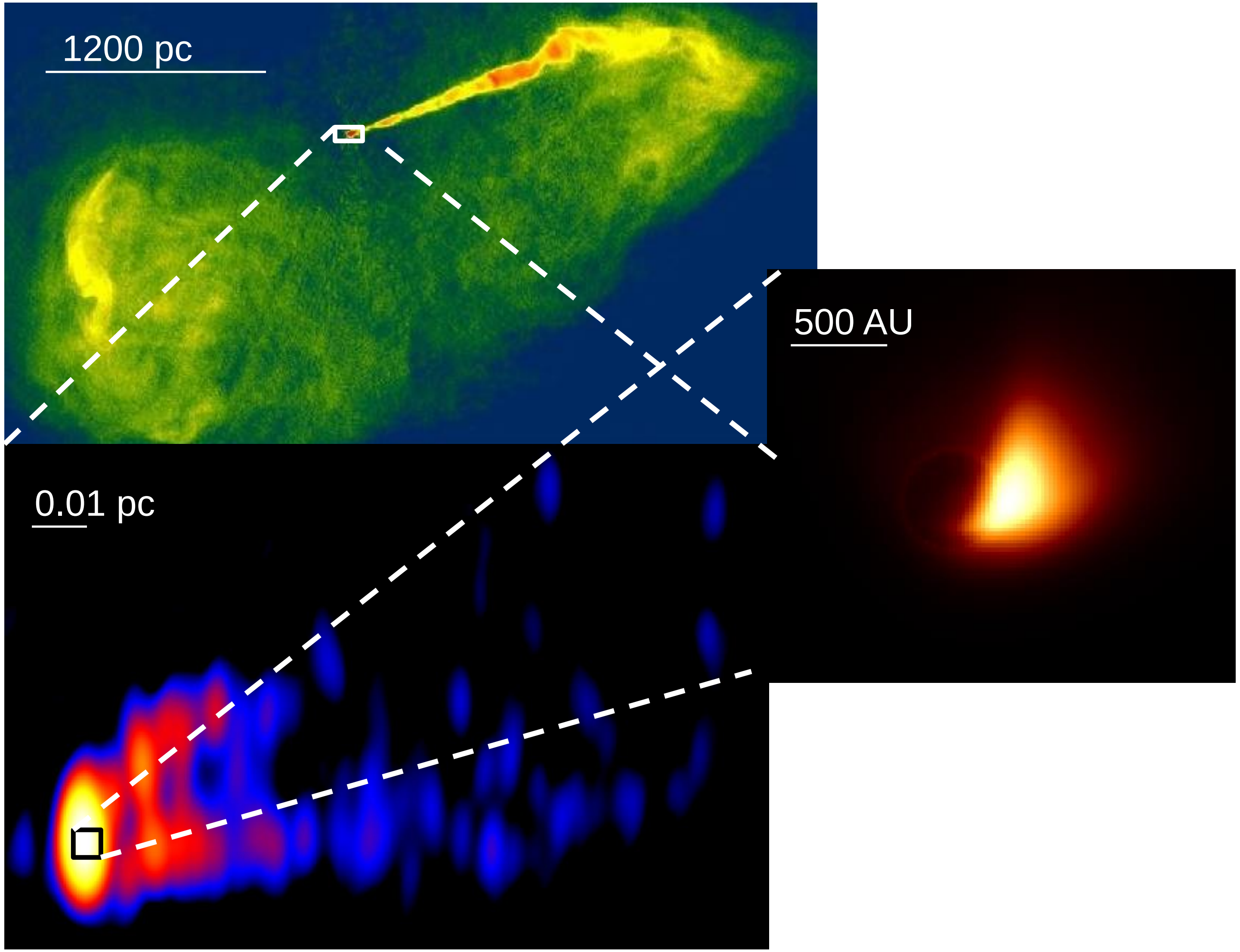
Evolving Nonthermal Electron Distributions in Black Hole Accretion Simulations

Andrew Chael, Harvard Physics & CfA

SOMA 2017, MIPT
July 10, 2017

arXiv:1704.05092
Work with Ramesh Narayan and Aleksander Sądowski

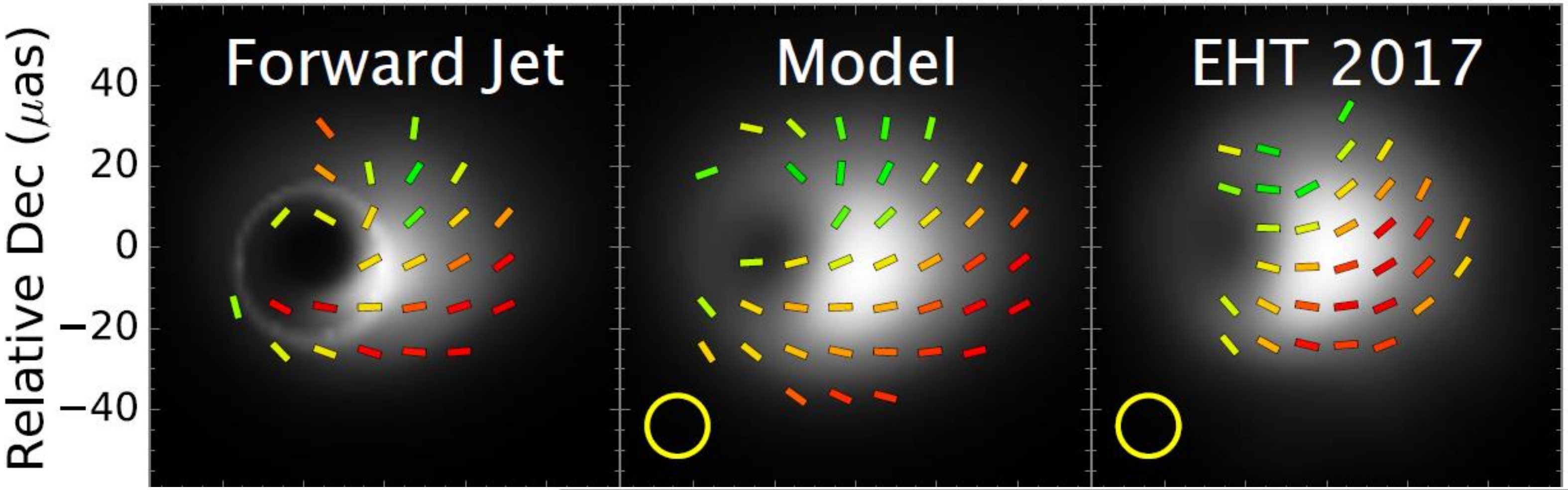
Imaging a Black Hole with the EHT



Left Image Credit: NRAO (Top Left), Hada et al. 2016 (Bottom Left), Avery Broderick & Kazu Akiyama (Right)

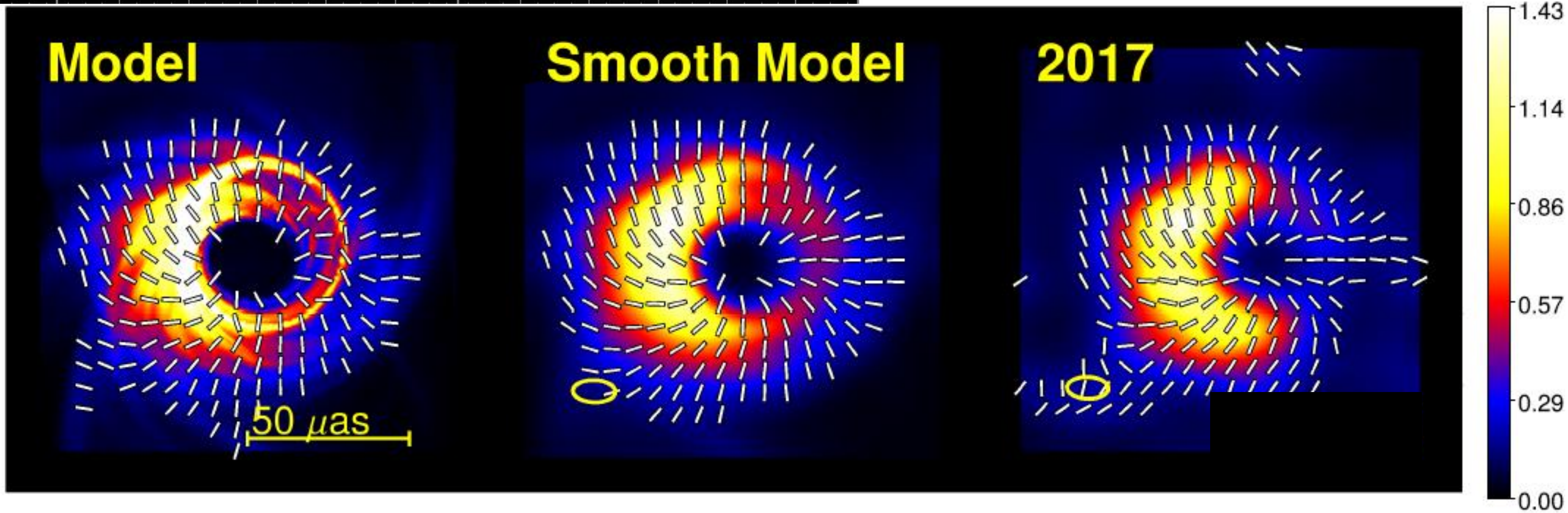
Right Image Credit: Michael Johnson. APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

Other work: Imaging for EHT 2017



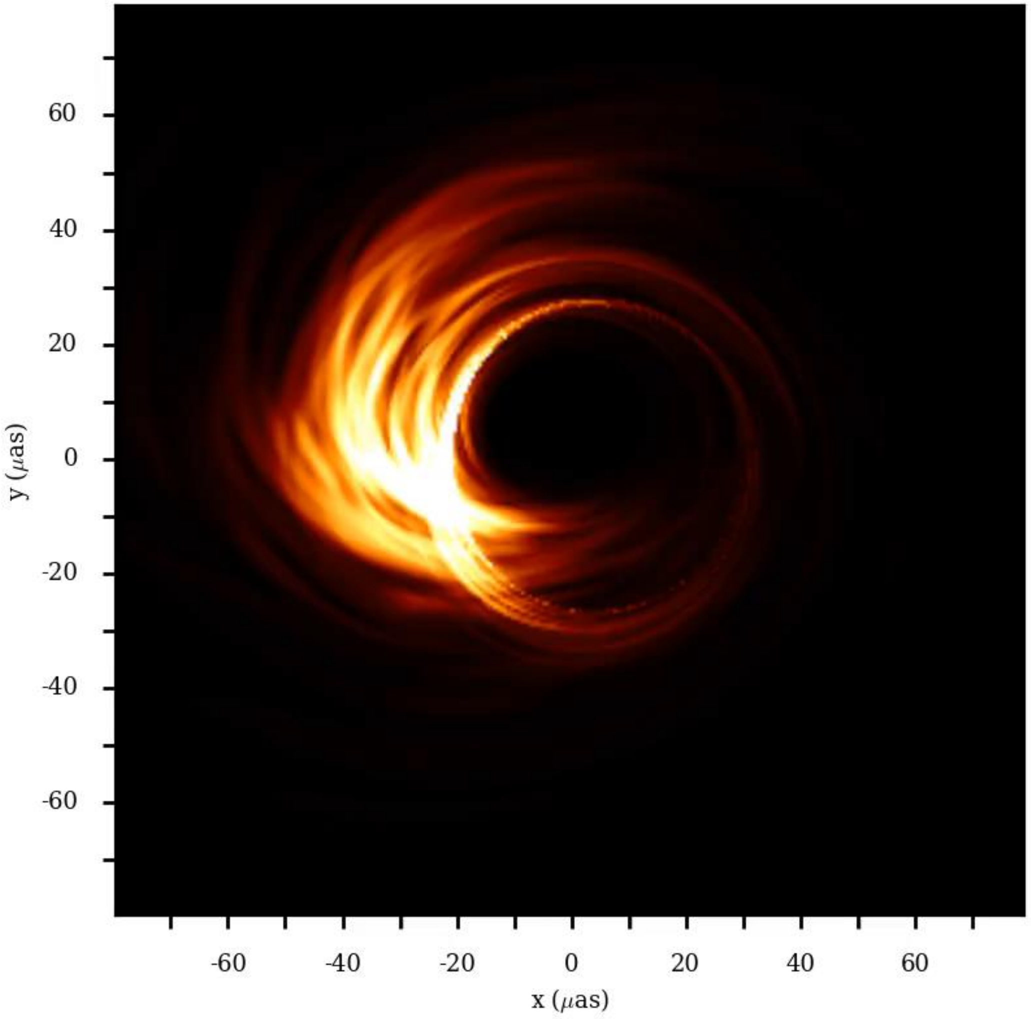
Chael et al. 2016

(arXiv 1704.05092)
VLBI imaging software at
https://github.com/achael/eht-imaging



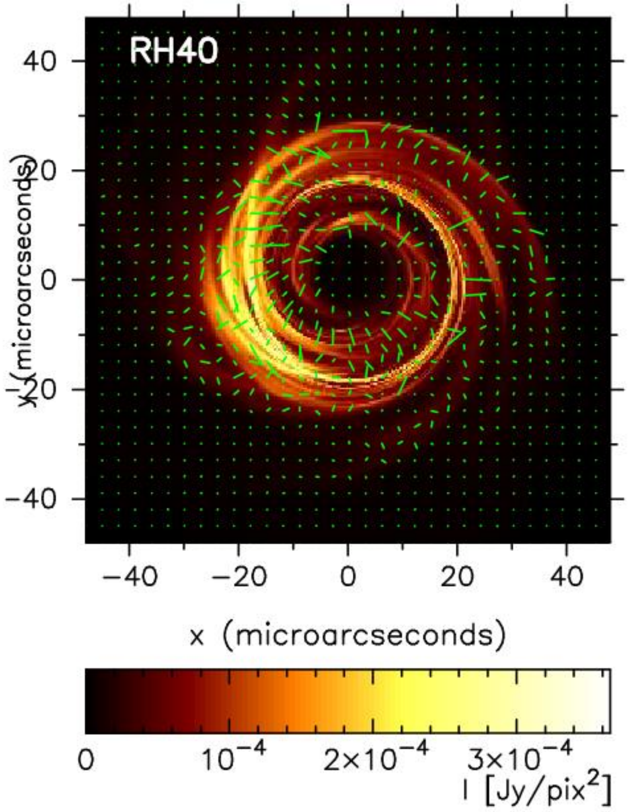
Simulation Credit: Avery Broderick (Top)
Jason Dexter (Bottom)
Top Image Credit: Kazu Akiyama

GRMHD Simulations as models for EHT sources

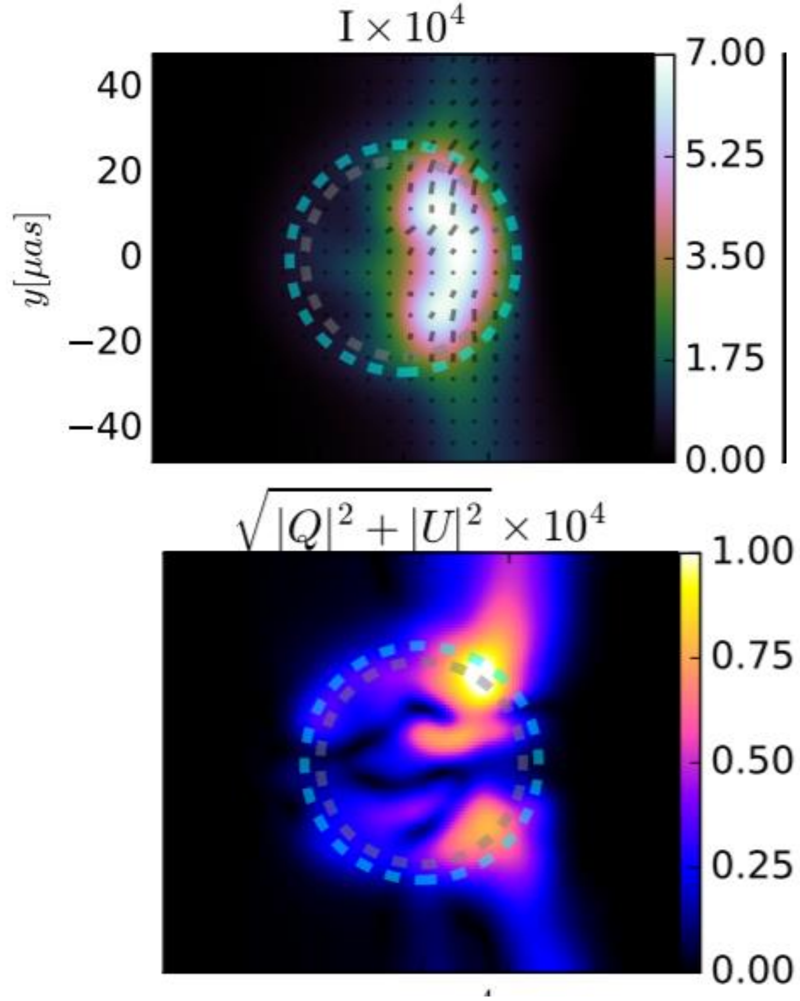


Movie Credit: Hotaka Shiokawa

GRMHD Simulations model EHT sources - Polarization



M87: Moscibrodzka et al. 2017
arXiv 1703.02390



Sgr A*: Gold et al. 2016
arXiv 1601.05550

GRMHD Simulations

- Collisions bring the plasma as a single ideal fluid in local thermodynamic equilibrium.

- **Ideal MHD**: high conductivity cancels electric field in the rest frame – Lorentz force on a particle vanishes.

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

ADAFs

- **A**dvection **D**ominated **A**ccretion **F**low.
- Most viscous energy is advected to smaller radii instead of being radiated.
- Flows are:
  - Hot
  - Low luminosity
  - Low accretion rate
  - Optically thin
  - Geometrically thick

Two-Temperature Simulations

- Low densities in hot flows → inefficient Coulomb coupling between ions and electrons.

- Generally expect ions to be hotter than electrons:
  - Electrons lose energy through radiation much more efficiently than ions.

  - Relativistic electrons store more energy with a smaller increase in temperature than non-relativistic ions.

$$nk_BT = (\Gamma - 1)u$$

Two-Temperature Simulations

Ressler et al. 2015 (arXiv 1509.04717)
2017 (arXiv 1611.09365)

Sadowski et al. 2017 (arXiv 1605.03184)

Electron Thermodynamics in GRMHD Simulations of Low-Luminosity Black Hole Accretion

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[3]Department of Physics, University of Illinois, 1002 West Green Street, Urbana, IL 61801

15 October 2015

ABSTRACT
Simple assumptions made regarding electron thermodynamics often limit the extent to which general relativistic magnetohydrodynar vations of low-luminosity accreting bl that self-consistently evolves an entropy effects of spatially varying electron he along magnetic field lines. We neglect t of the accretion flow. Our model is appr ton accretion rate, so radiative cooling higher accretion rates in the future by in collisions. We present a suite of tests s for electron heating under a range of ci bulence. Our initial applications to axis that (1) physically-motivated electron h strength yield electron temperature distr tron to proton temperature ratios assume concentrated in the coronal region betw tion significantly modifies the electron t flows if the effective electron mean free (at least for the initial conditions and m developed in this work are important f sion from accreting black holes such a explored in future work.

Key words: MHD — general relativity

The Disc-Jet Symbiosis Emerges: Modeling the Emission of Sagittarius A* with Electron Thermodynamics

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9 February 2017

ABSTRACT
We calculate the radiative properties of Sagittarius A* – spectral energy distribution, variability, and radio-infrared images – using the first 3D, physically motivated black hole accretion models that directly evolve the electron thermodynamics in general relativistic MHD simulations. These models reproduce the coupled disc-jet structure for the emission favored by previous phenomenological analytic and numerical works. More specifically, we find that the low frequency radio emission is dominated by emission from a polar outflow while the emission above 100 GHz is dominated by the inner region of the accretion disc. The latter produces time variable near infrared (NIR) and X-ray emission, with frequent flaring events (including IR flares without corresponding X-ray flares and IR flares with weak X-ray flares). The photon ring is clearly visible at 230 GHz and 2 microns, which is encouraging for future horizon-scale observations. We also show that anisotropic electron thermal conduction along magnetic field lines has a negligible effect on the radiative properties of our model. We conclude by noting limitations of our current generation of first-principles models, particularly that the outflow is closer to adiabatic than isothermal and thus underpredicts the low frequency radio emission.

Key words: MHD — galaxy: centre — relativistic processes — accretion — black hole physics

Radiative, two-temperature simulations of low luminosity black hole accretion flows in general relativity

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6 December 2016

ABSTRACT
We present a numerical method which evolves a two-temperature, magnetized, radiative, accretion flow around a black hole, within the framework of general relativistic radiation magnetohydrodynamics. As implemented in the code KORAL, the gas consists of two subcomponents – ions and electrons – which share the same dynamics but experience independent, relativistically consistent, thermodynamical evolution. The electrons and ions are heated independently according to a prescription from the literature for magnetohydrodynamical turbulent dissipation. Energy exchange between the particle species via Coulomb collisions is included. In addition, electrons gain and lose energy and momentum by absorbing and emitting synchrotron and bremsstrahlung radiation, and through Compton scattering. All evolution equations are handled within a fully covariant framework in the relativistic fixed-metric spacetime of the black hole. Numerical results are presented for five models of low luminosity black hole accretion. In the case of a model with a mass accretion rate $\dot{M} \sim 4 \times 10^{-8} \dot{M}_{\rm Edd}$, we find that radiation has a negligible effect on either the dynamics or the thermodynamics of the accreting gas. In contrast, a model with a larger $\dot{M} \sim 4 \times 10^{-4} \dot{M}_{\rm Edd}$ behaves very differently. The accreting gas is much cooler and the flow is geometrically less thick, though it is not quite a thin accretion disk.

Key words: accretion, accretion discs – black hole physics – relativistic processes – methods: numerical

Two-Temperature Simulations

- Low densities in hot flows → inefficient Coulomb coupling between ions and electrons.

- Generally expect ions to be hotter than electrons:
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  - Relativistic electrons store more energy with a smaller increase in temperature than non-relativistic ions.

$$nk_BT = (\Gamma - 1)u$$

- But the heating prescription can make a big difference.
  - Howes (2010) puts almost all energy into electrons in high magnetization regions

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$$nk_BT = (\Gamma - 1)u$$

Adjust from 5/3 -> 4/3 self consistently with T

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Two-Temperature GRRMHD Simulations

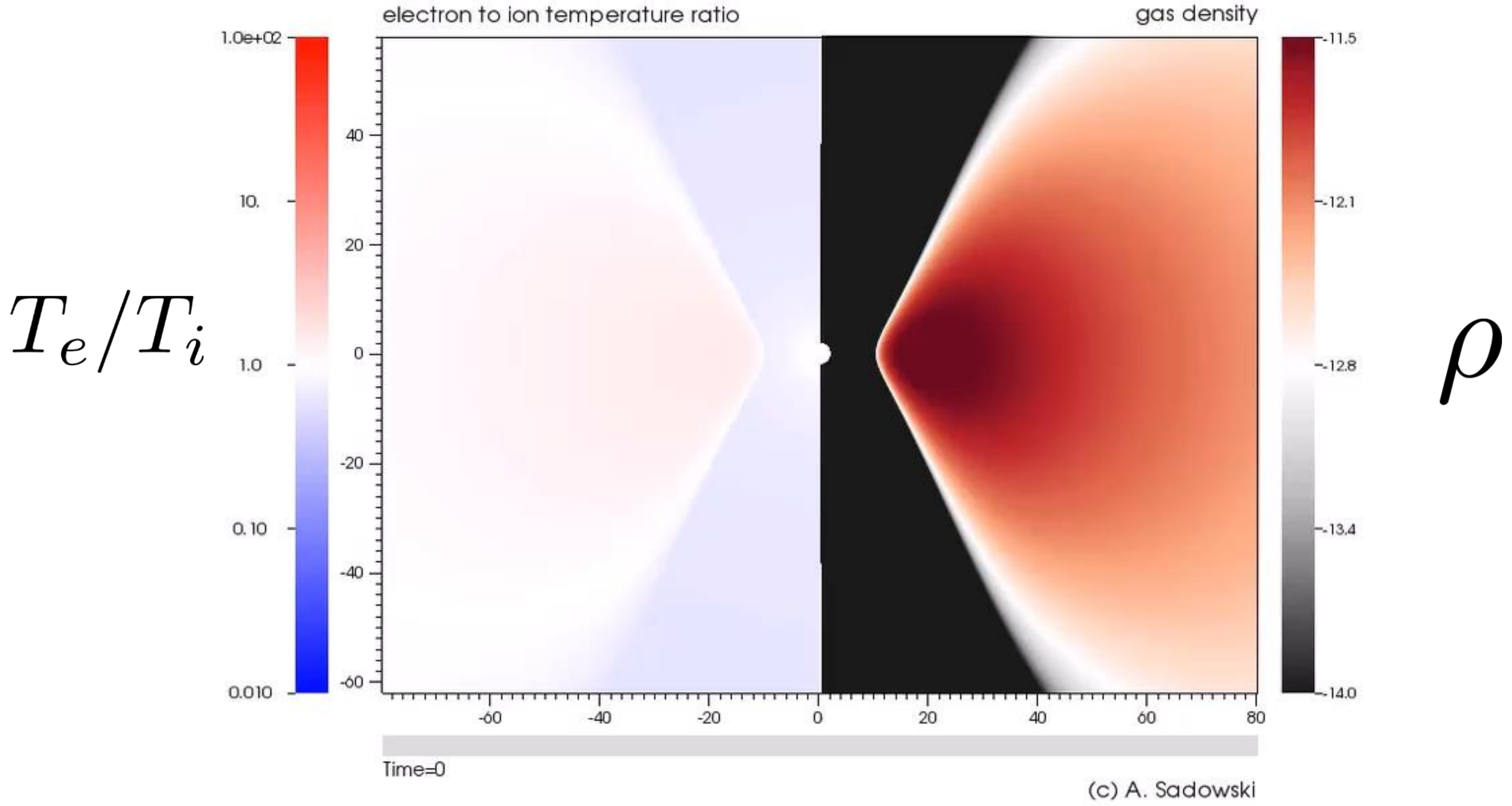
- Total fluid quantities are evolved as in single-temperature GRRMHD
- Electron and ion energy densities are evolved via the 1st law of thermodynamics:

$$T_e(n_e s_e u^\mu)_{;\mu} = \delta_\mathrm{e} q^v + q^C + \hat{G}^0$$
$$T_i(n_i s_i u^\mu)_{;\mu} = (1-\delta_\mathrm{e}) q^v - q^C$$

entropy per particle

dissipative processes

Two-Temperature ADAF simulation (Sądowski et al. 16)



Sgr A* SED: Nonthermal Electrons are important!

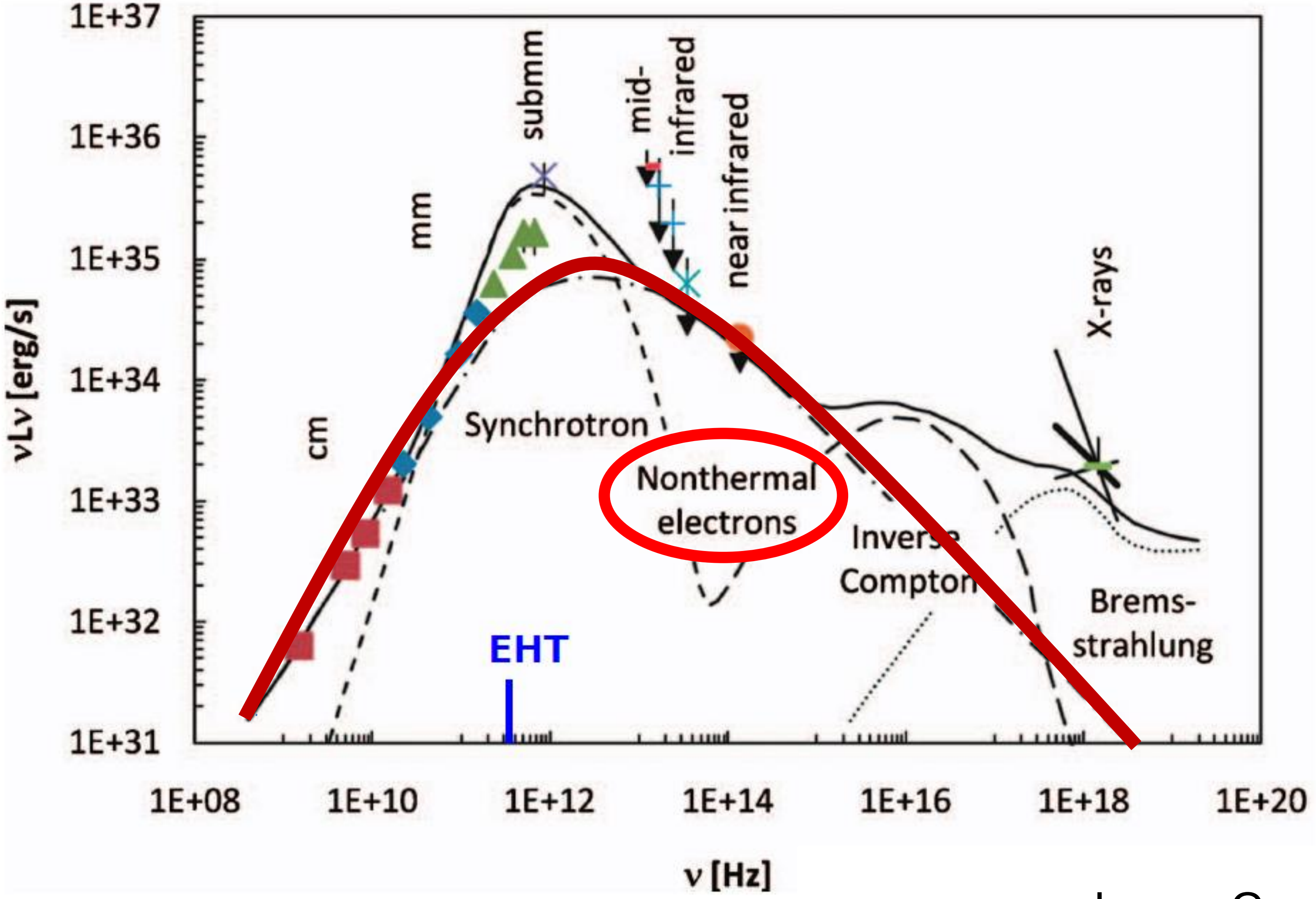
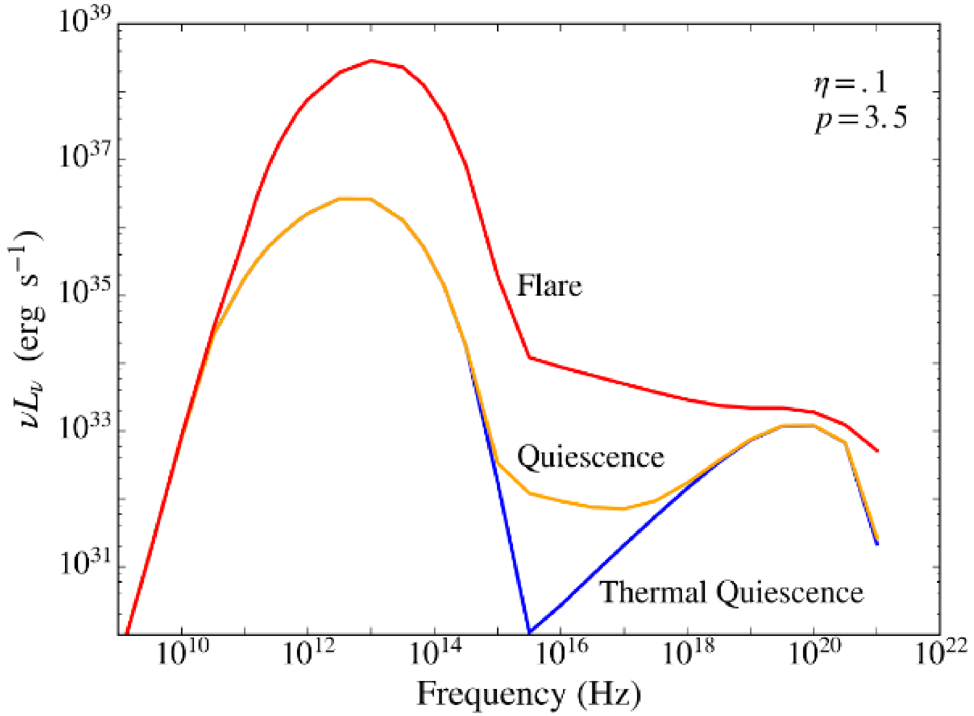
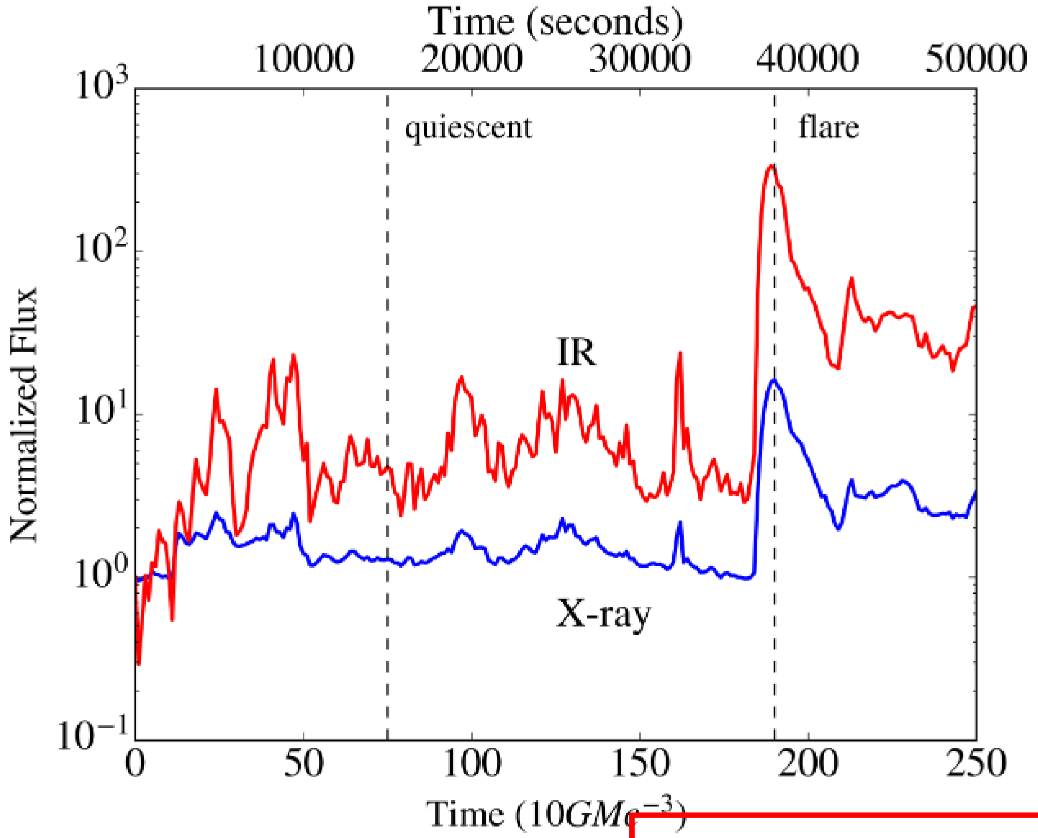


Image Credit: Genzel et al. (2010)
Yuan et al. (2003)

Nonthermal distributions contribute to Sgr A* variability!





Ball et al. 2016 arXiv 1602.05968

Goals:

1. 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 . . .)

2. Include the resulting nonthermal population in radiative transfer to produce images & spectra.

3. Compare to data and constrain the bulk properties and microphysics of the accretion flow.

Non-Thermal Population: Assumptions

- Track the spectrum $n(\gamma)$ sampled in different “bins” in Lorentz factor space.
- We assume the non-thermal distribution is **isotropic in the fluid frame.**
- We also assume the non-thermal population is **highly relativistic** and **optically thin** (neglect absorption).

Evolution Equation

$$\underbrace{\frac{\partial n(\gamma)}{\partial t} - \vec{\nabla} \cdot (\vec{v}\, n(\gamma))}_{\text{Advection}} =$$

Advection

Evolution Equation

$$\frac{\partial n(\gamma)}{\partial t} - \vec{\nabla} \cdot (\vec{v}\, n(\gamma)) = -\frac{\partial}{\partial \gamma} \left(\dot{\gamma}_{\mathrm{adiab}} n(\gamma) \right)$$

Advection **Adiabatic Compression/Expansion**

Evolution Equation

Radiative Cooling

$$\frac{\partial n(\gamma)}{\partial t} - \vec{\nabla} \cdot (\vec{v}\, n(\gamma)) = -\frac{\partial}{\partial \gamma}\left(\dot{\gamma}_{\mathrm{adiab}} n(\gamma)\right) - \frac{\partial}{\partial \gamma}\left(\dot{\gamma}_{\mathrm{rad}} n(\gamma)\right)$$

Advection

Adiabatic Compression/Expansion

Evolution Equation

$$\frac{\partial n(\gamma)}{\partial t} - \vec{\nabla} \cdot (\vec{v}\, n(\gamma)) = -\frac{\partial}{\partial \gamma}\left(\dot{\gamma}_{\rm adiab} n(\gamma)\right) - \frac{\partial}{\partial \gamma}\left(\dot{\gamma}_{\rm rad} n(\gamma)\right) + Q(\gamma)$$

Radiative Cooling

Advection

Adiabatic Compression/Expansion

Injection/Particle Acceleration

Evolution Equation

$$(n(\gamma)u^{\alpha})_{;\alpha} = \frac{\partial}{\partial\gamma}\left[\frac{1}{3}u^{\alpha}_{;\alpha}(\gamma - \gamma^{-1})n(\gamma)\right] - \frac{\partial}{\partial\gamma}\left(\dot{\gamma}_{\rm tot}n(\gamma)\right) + Q^{I}(\gamma).$$

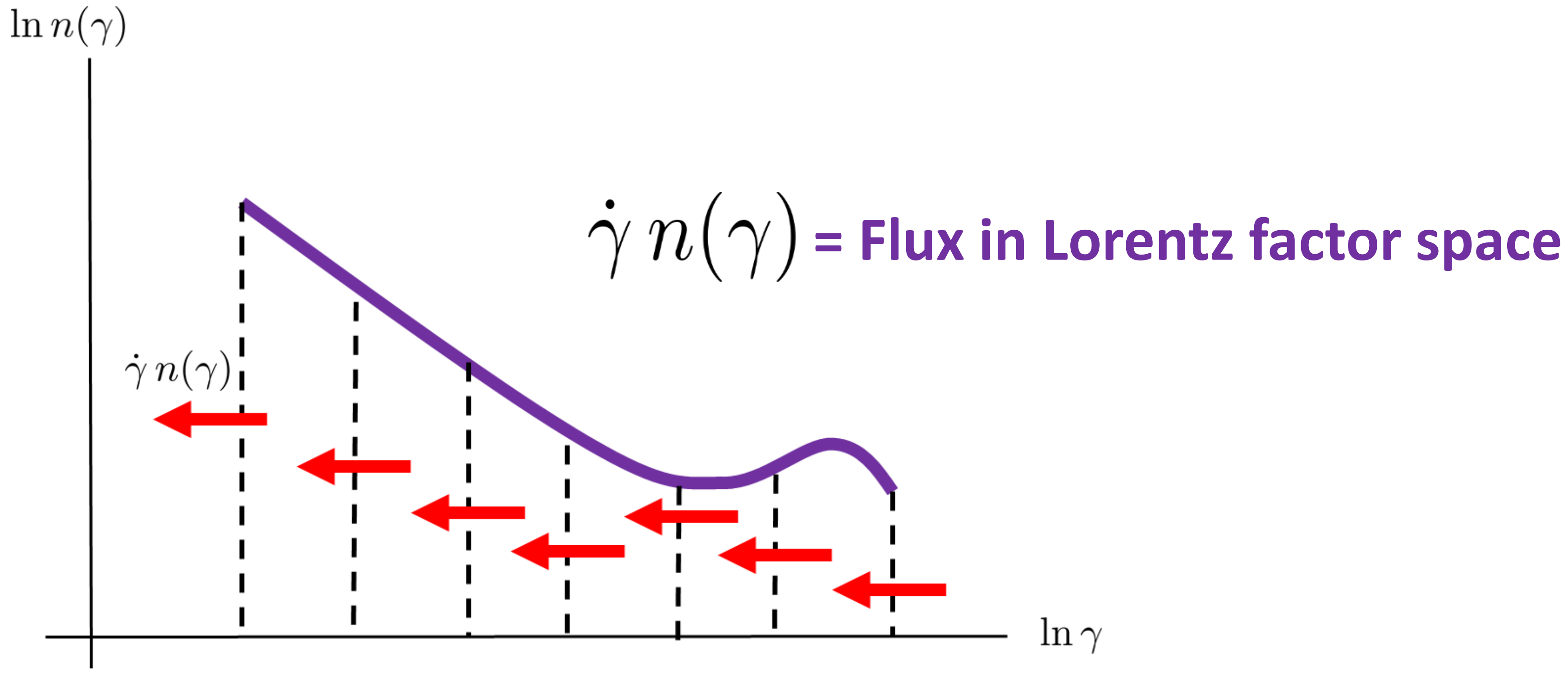
Advection — $(n(\gamma)u^{\alpha})_{;\alpha}$

Adiabatic Compression/Expansion — $\frac{\partial}{\partial\gamma}\left[\frac{1}{3}u^{\alpha}_{;\alpha}(\gamma - \gamma^{-1})n(\gamma)\right]$

Radiative Cooling — $\left(\dot{\gamma}_{\rm tot}n(\gamma)\right)$

Injection/Particle Acceleration — $Q^{I}(\gamma)$

Evolution Equation



Solved with implicit upwind finite differencing.
Maybe spectral method in future?

Radiative Cooling

- Synchrotron:

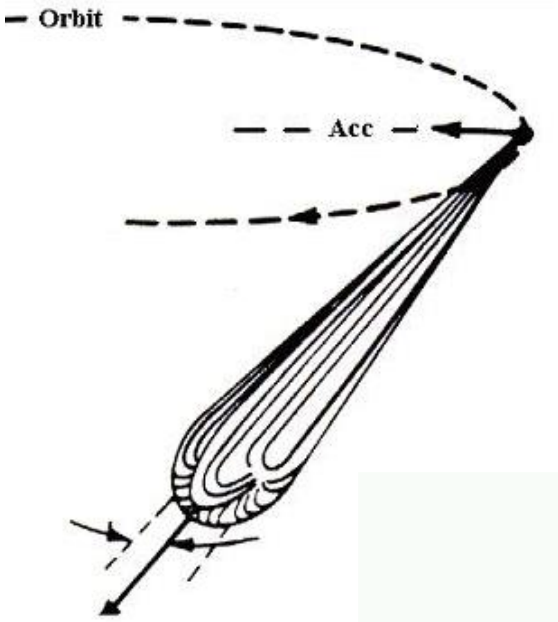
$$\dot{\gamma}_{\rm syn} \sim B^2 \gamma^2$$

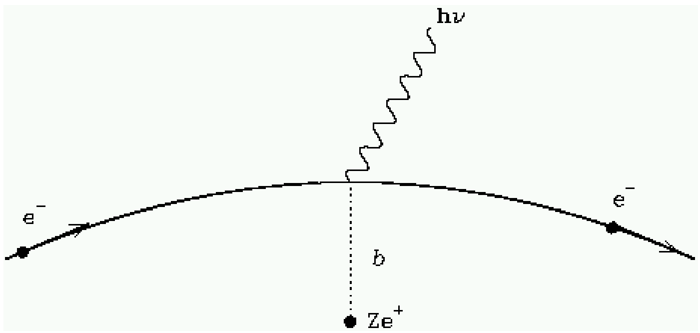
- Free-Free:

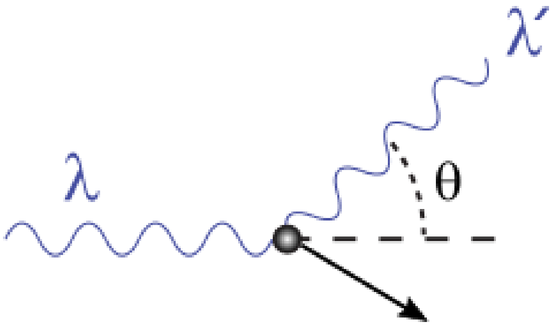
$$\dot{\gamma}_{ff} \sim -n_i\, \gamma\, \log \gamma$$

- Inverse Compton:

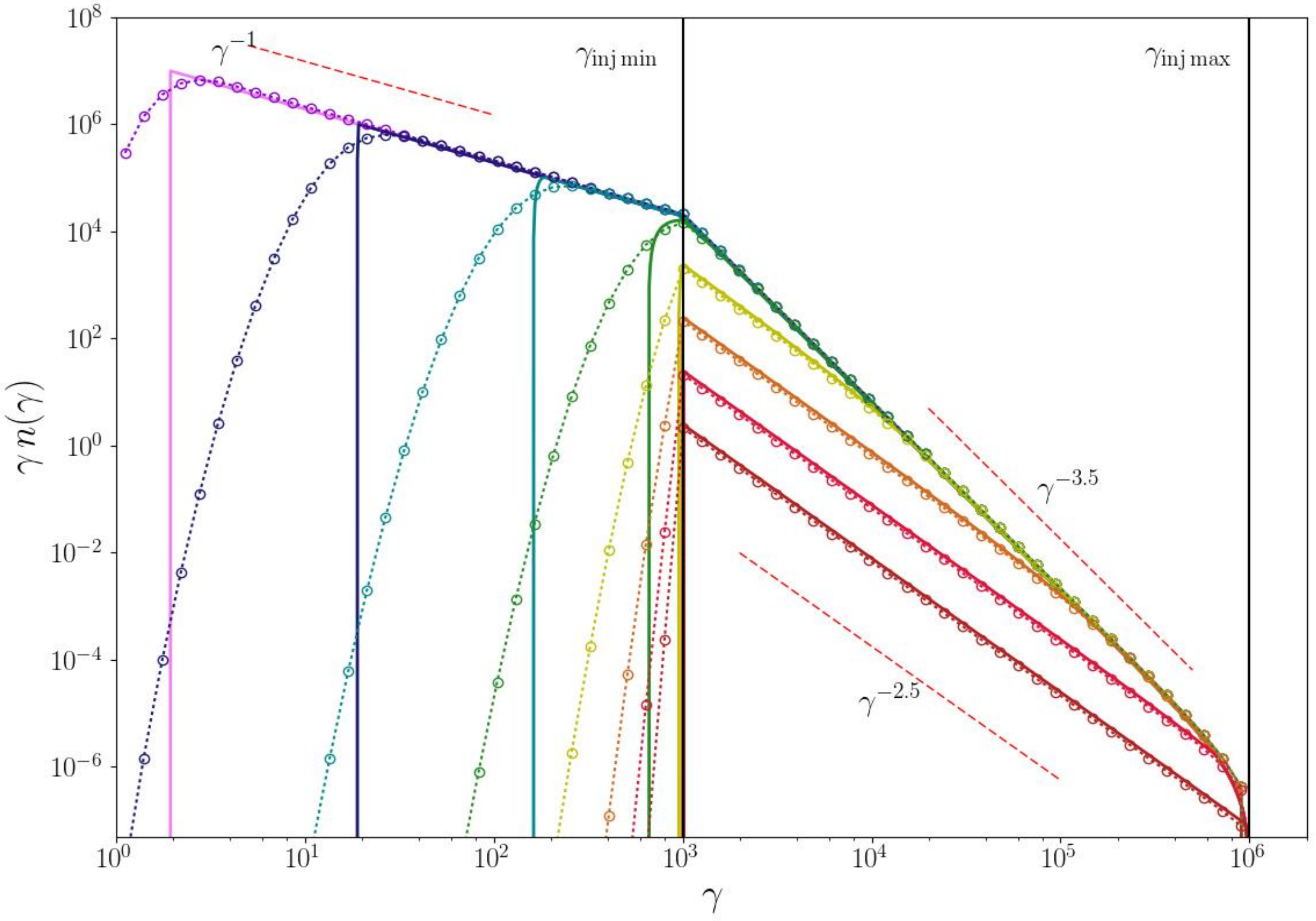
$$\dot{\gamma}_{\rm IC} \sim -\hat{E}_r\, \gamma^2 F_{KN}(\gamma)$$







Synchrotron Cooling + Particle Injection



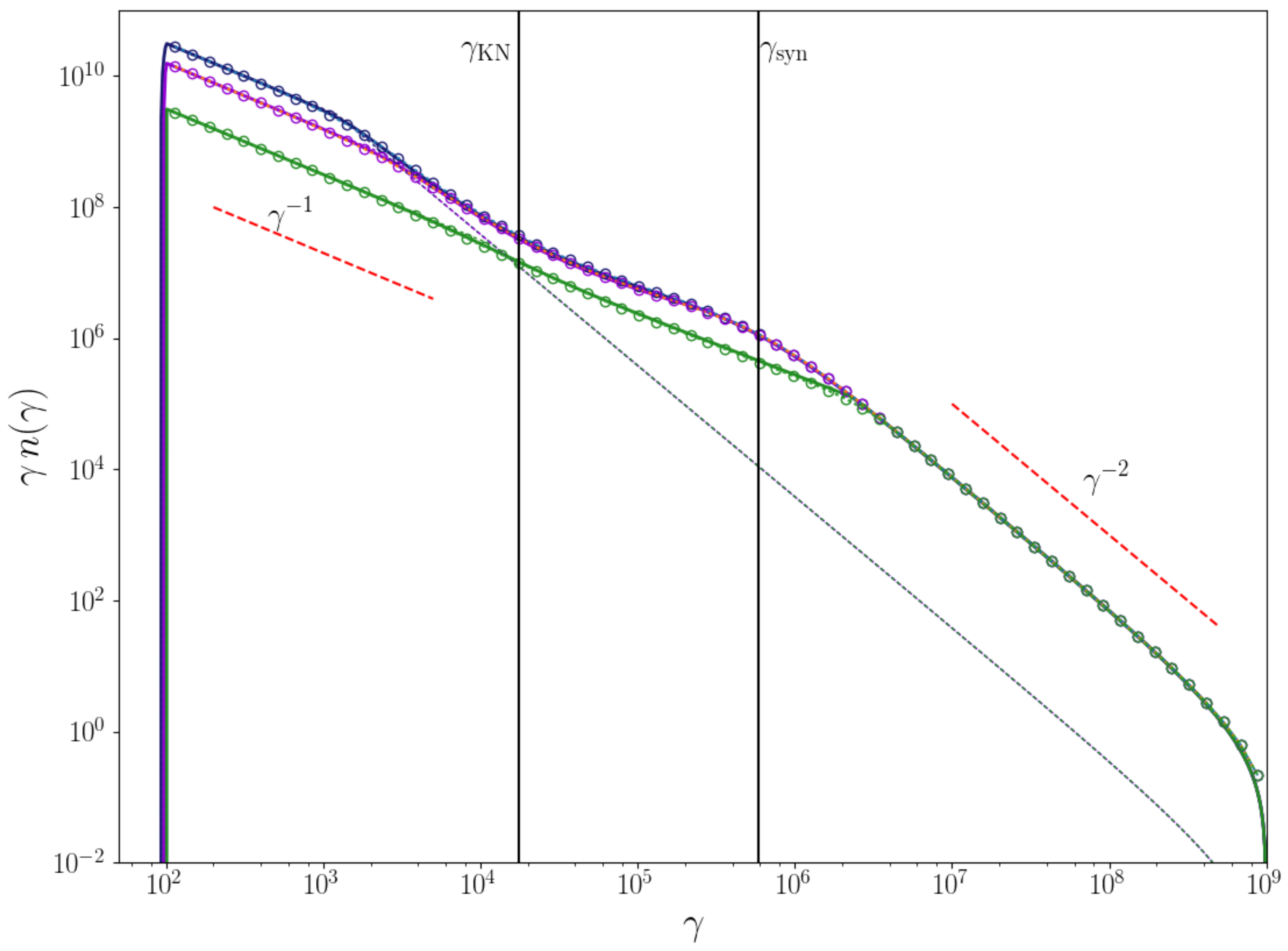
- Constant background B-field and particle injection spectrum.

$$\dot{\gamma}_{\rm syn} \sim B^2\gamma^2$$

- Synchrotron cooling break between injection index p and p+1 propagates to lower Lorentz factor:

- Below minimum injection Lorentz factor, spectrum has universal power law of -2

Test: Inverse Compton Cooling (with Klein-Nishina)



- Based on result from Manolakou et al 2007
- 30,000 K photon background modifies IC cooling.

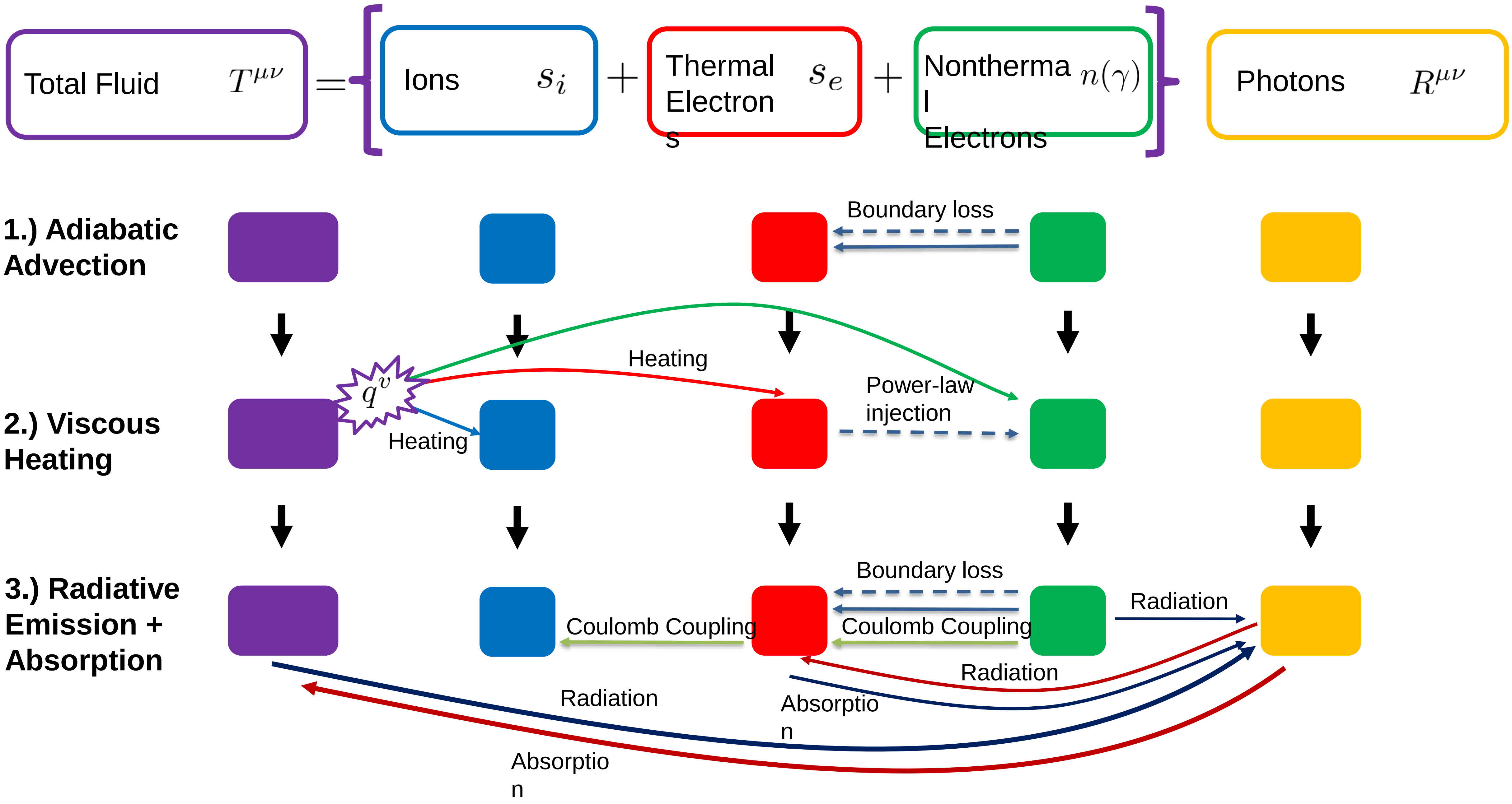
$$\dot{\gamma}_{\rm IC} \sim -\hat{E}_r\, \gamma^2 F_{KN}(\gamma)$$

$$F_{KN}(\gamma) = \left(1 + 11.2\gamma \frac{kT_r}{m_e c^2}\right)^{-3/2}$$

- At the highest Lorentz factors, Synchrotron dominates, and the spectrum is broken.
- At the lowest Lorentz factors, the KN correction is unimportant and the IC break develops normally.

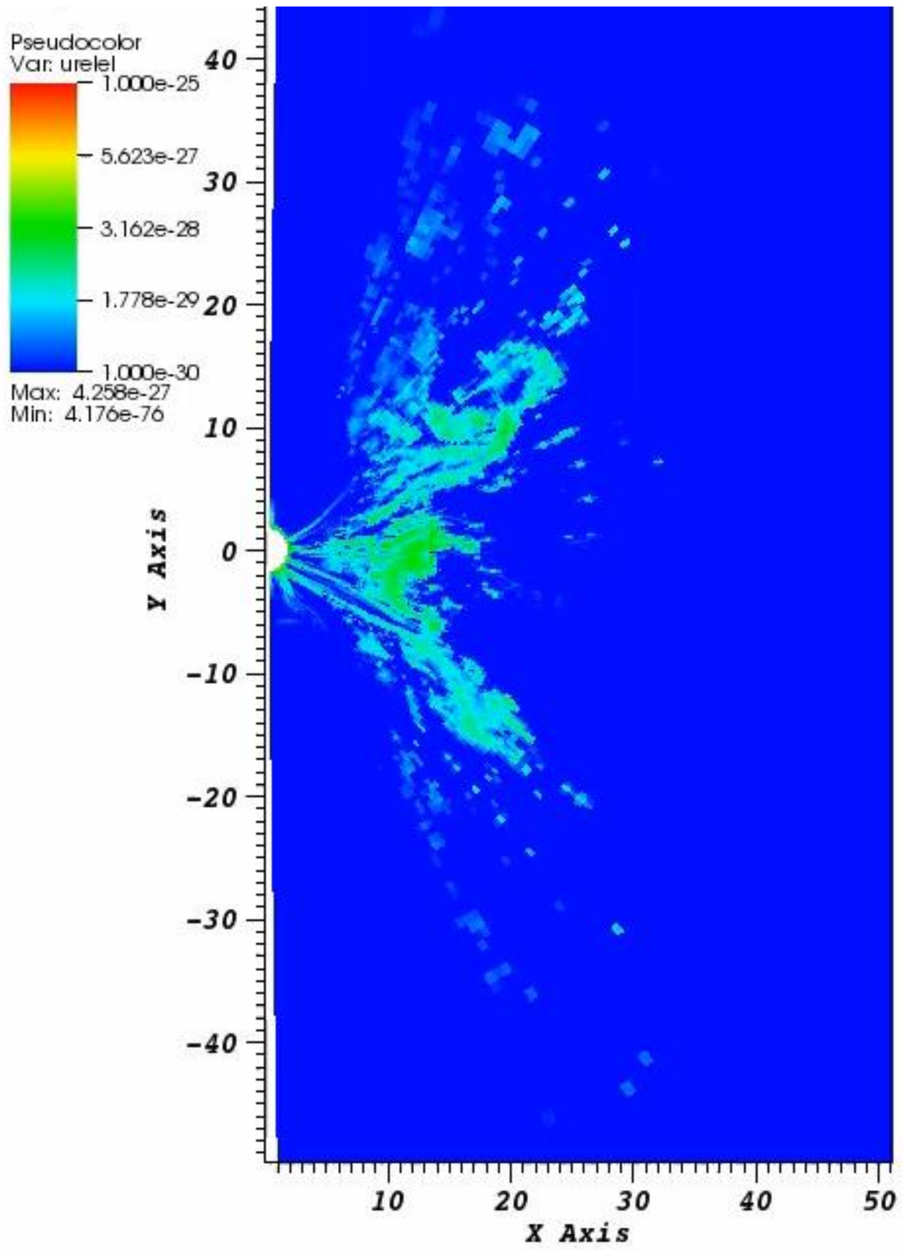
Viscous Heating & Injection

- We compare the internal energy of the total fluid to the internal energy of the components **evolved adiabatically**.
- A fraction δ_e goes directly into both electron populations: δ_{nth} of that goes into non-thermal electrons.
- We must also specify an injection **power law index** and **minimum Lorentz factor**
- What physics determines the heating/injection rate? MHD turbulence, shocks, reconnection….

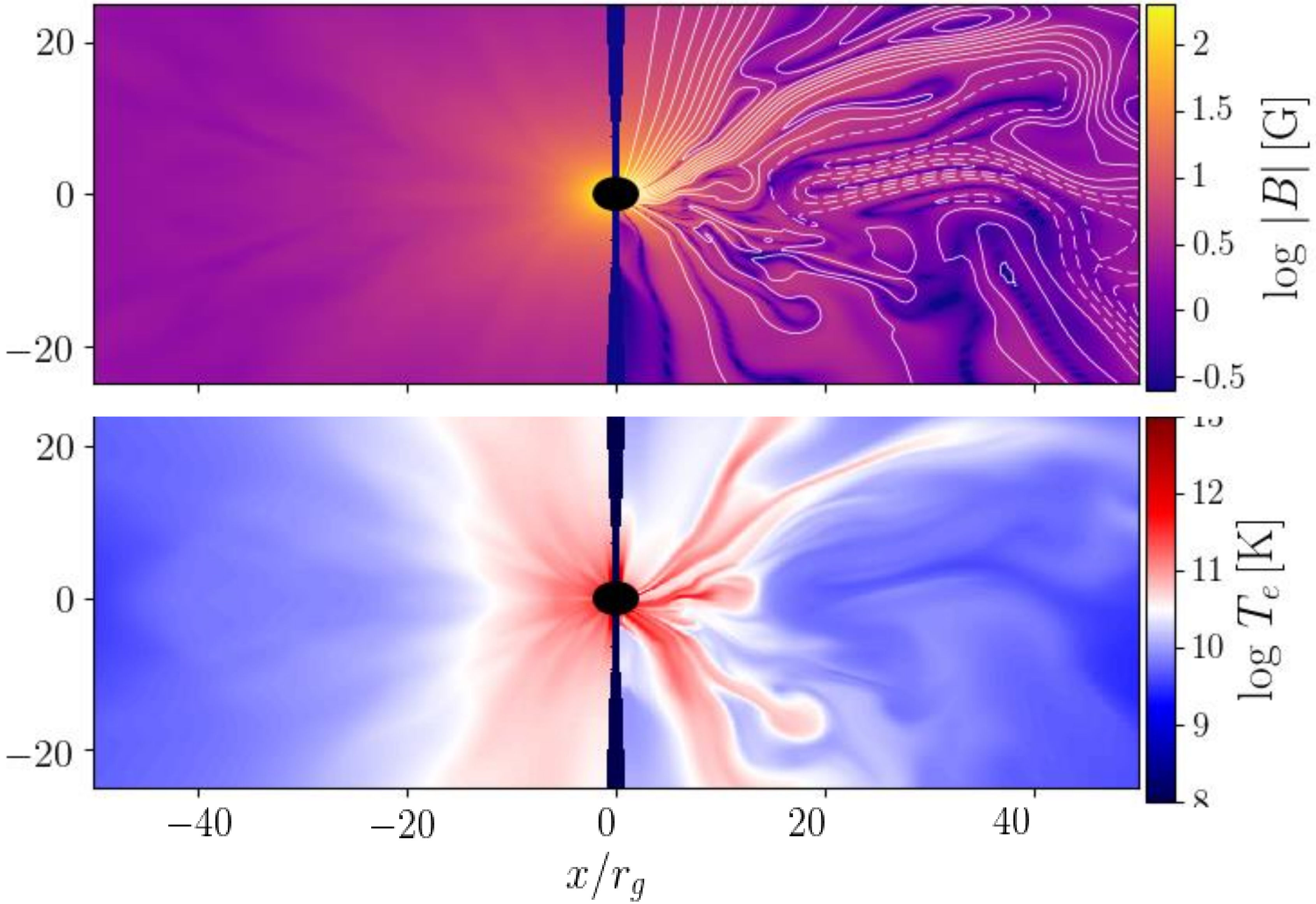

Total Fluid $T^{\mu\nu}$
=
Ions s_i
+
Thermal Electrons s_e
+
Nonthermal Electrons $n(\gamma)$
Photons $R^{\mu\nu}$
1.) Adiabatic Advection
Boundary loss
2.) Viscous Heating
q^v
Heating
Heating
Power-law injection
3.) Radiative Emission + Absorption
Boundary loss
Coulomb Coupling
Coulomb Coupling
Radiation
Radiation
Radiation
Absorption
Absorption

Sgr A* Simulation

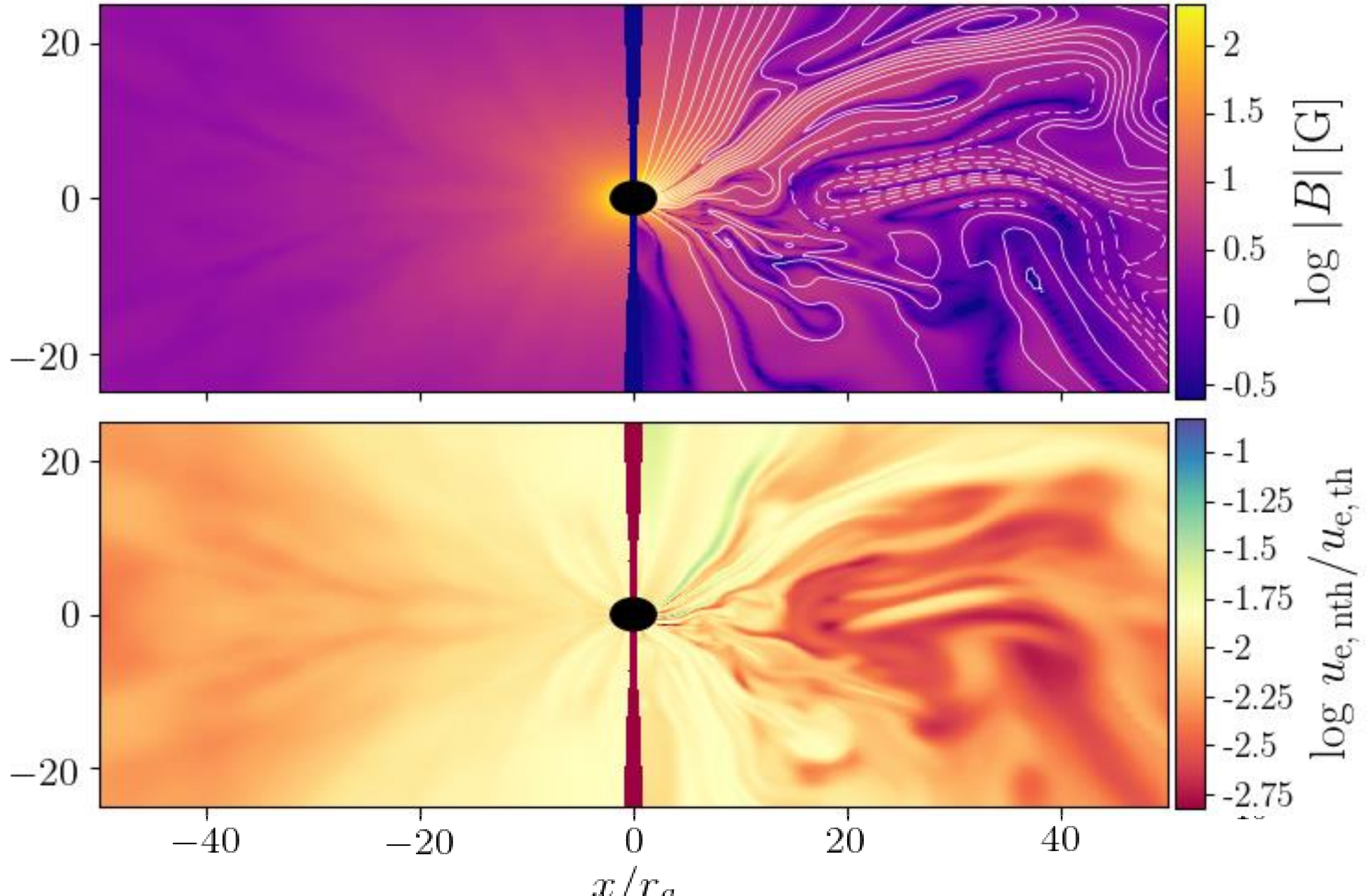
- Initial conditions: evolved two-temperature disk with **no** nonthermal electrons.
- **Constant** 1.5% nonthermal energy injection fraction
- **Constant** p=3.5 power law.
- **Fixed** injection minimum and maximum → chosen to be above hottest thermal peak.



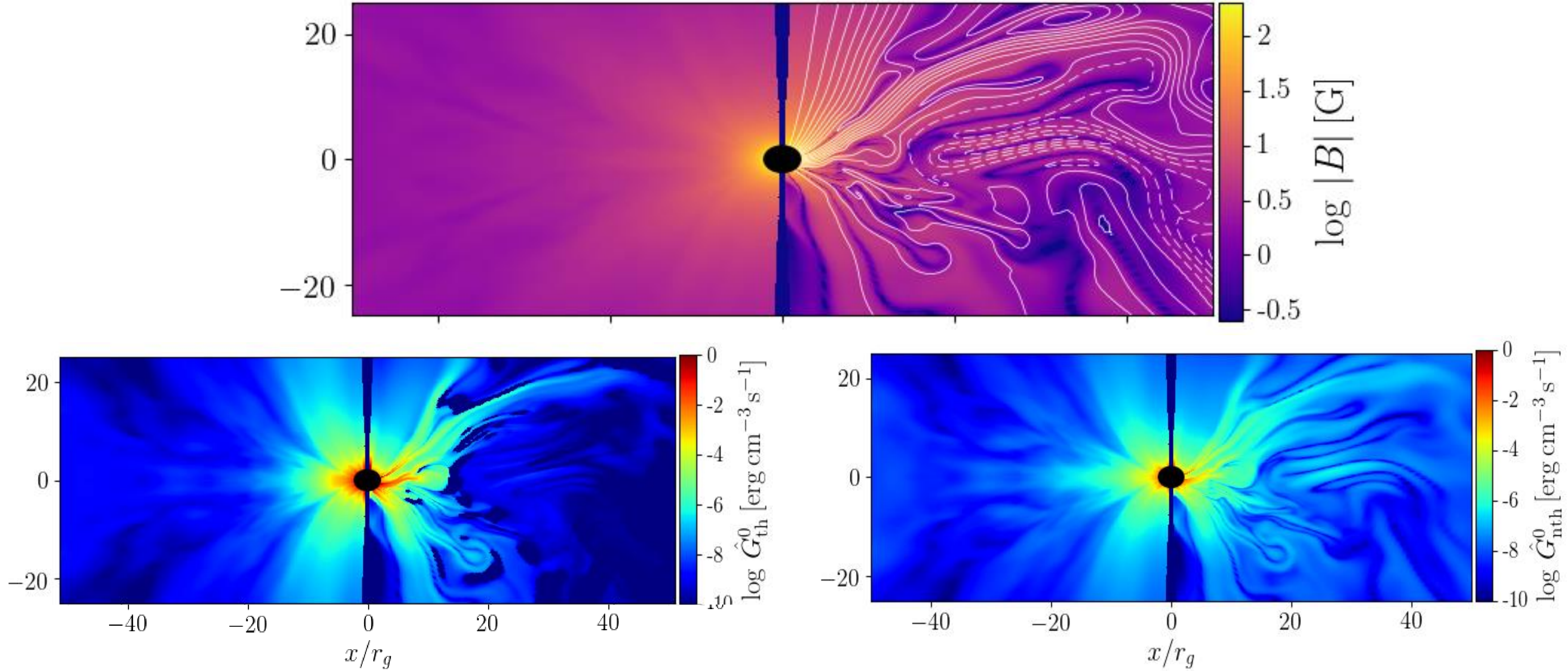
Magnetic Field and Electron Temperature



Nonthermal Energy Density



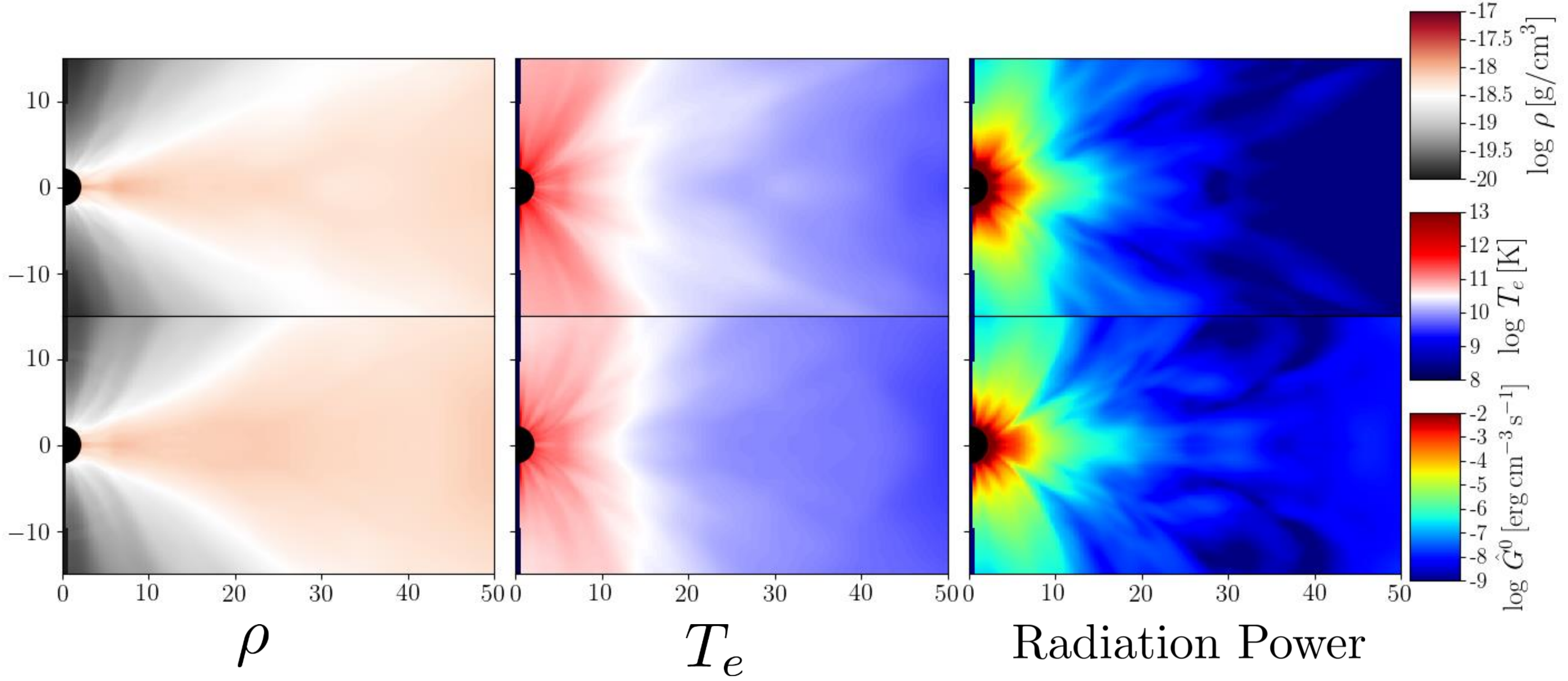
Thermal vs Nonthermal Radiation Power



Thermal Rad. power

Nonthermal Rad. Power

Comparison to simulation without nonthermal electrons



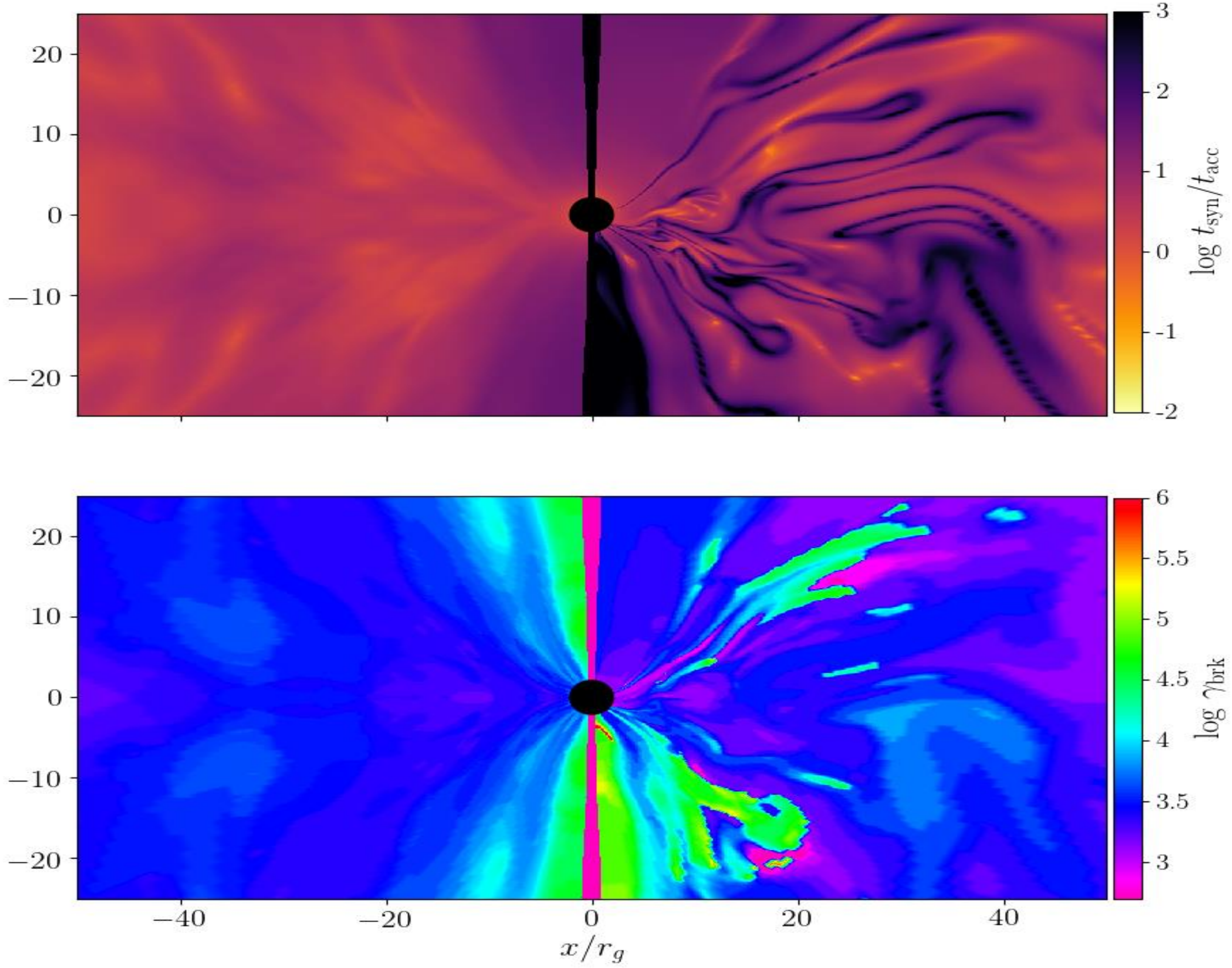
Timescales and Cooling Break

- Cooling time: time for entire injected spectrum to break assuming constant injection.

$$t_{\rm syn} \propto \frac{1}{B^2}\left(\frac{1}{\gamma_{\rm min}} - \frac{1}{\gamma_{\rm max}}\right)$$

- Accretion time:

$$t_{\rm acc} \equiv \frac{r}{\sqrt{v_r^2 + r^2 v_\theta^2}}.$$

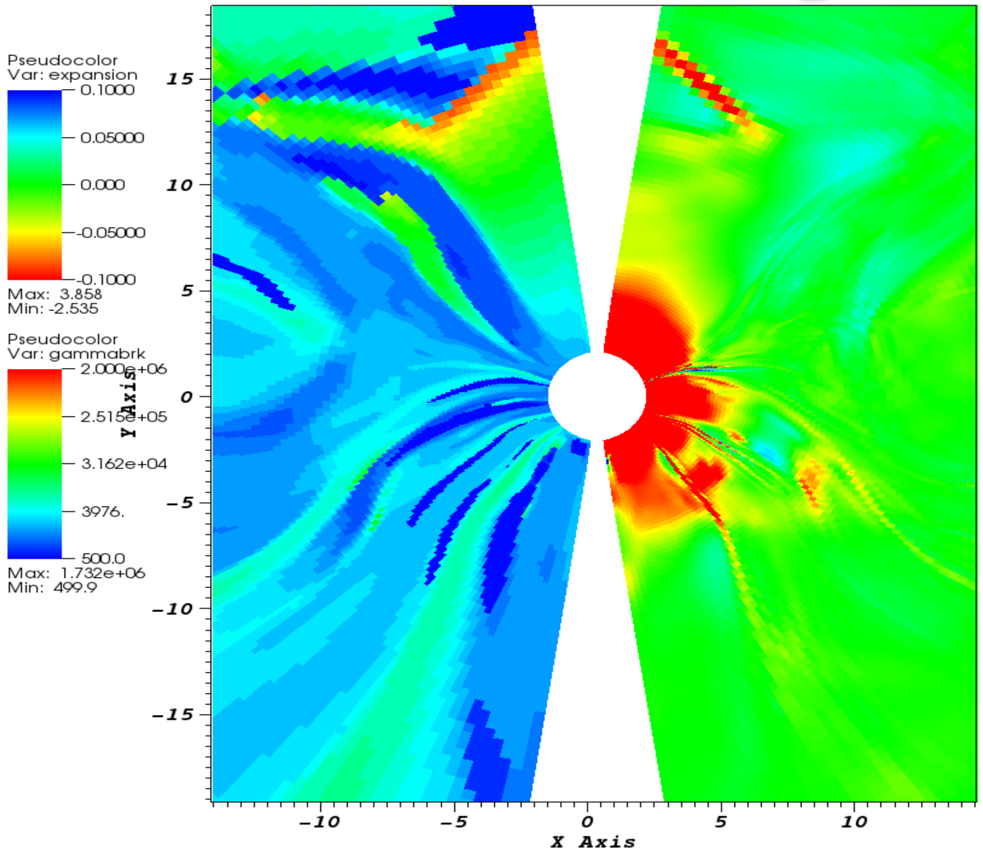


Spectral breaks trace shocks?

Synchrotron break

Gas Expansion

$\sim \vec{\nabla} \cdot \vec{v}$



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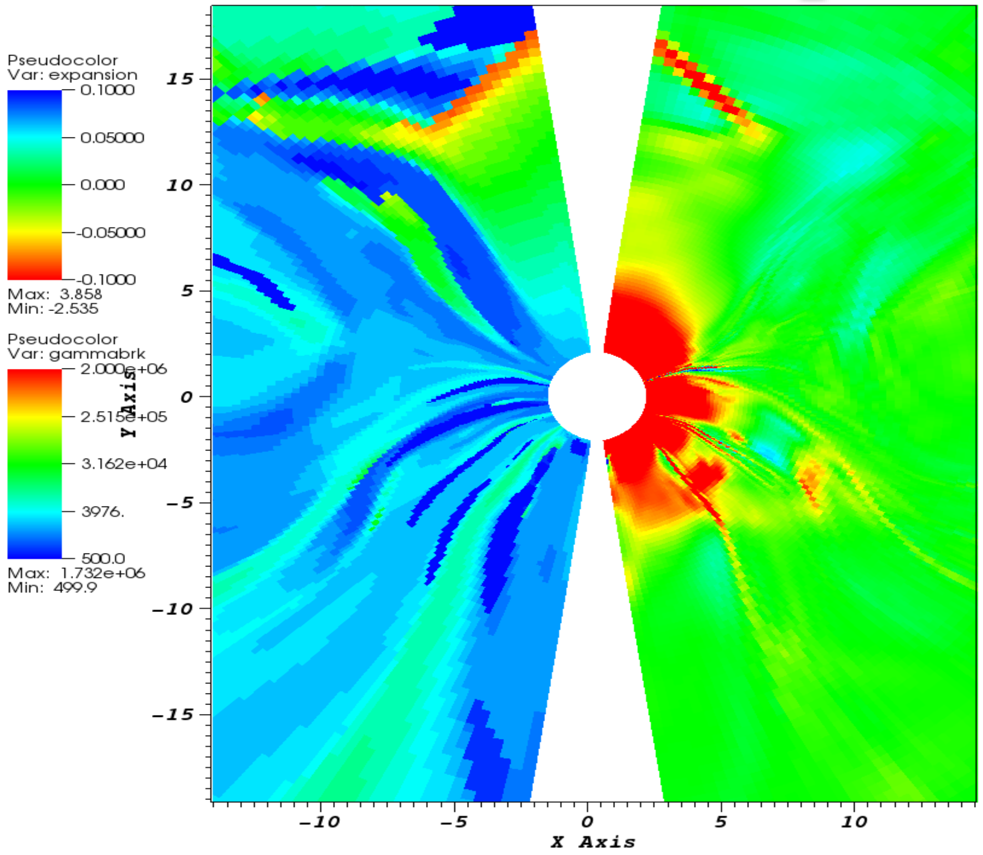
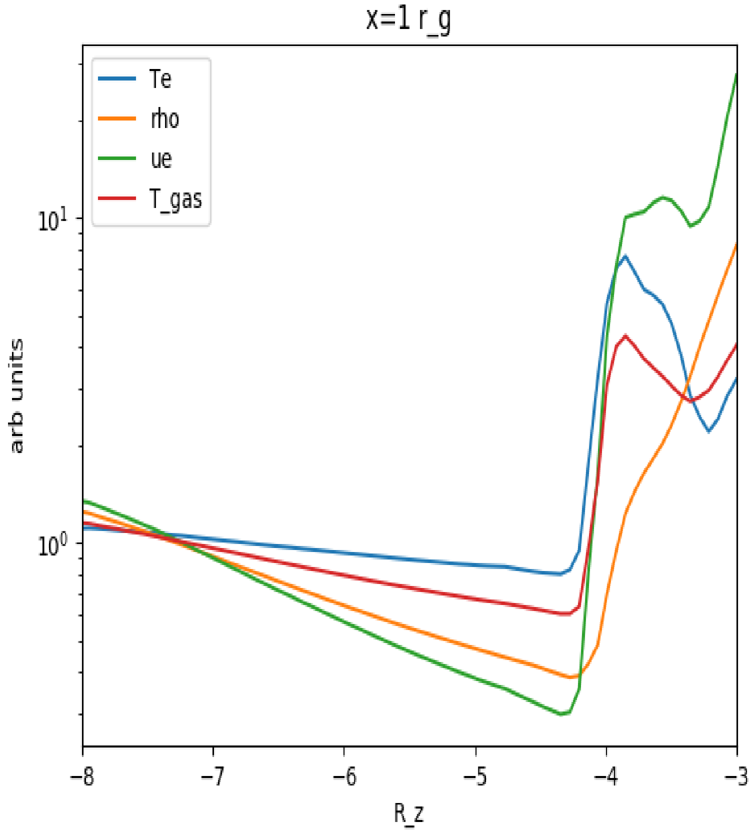
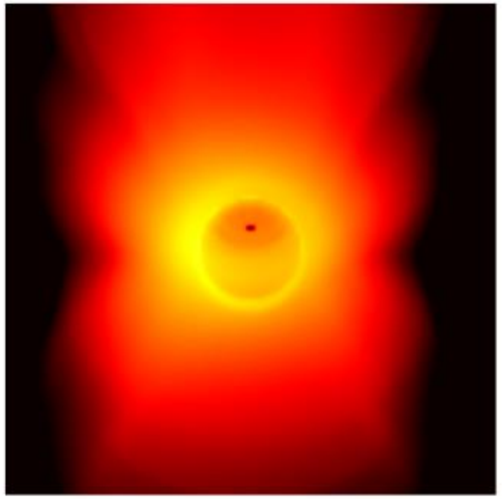




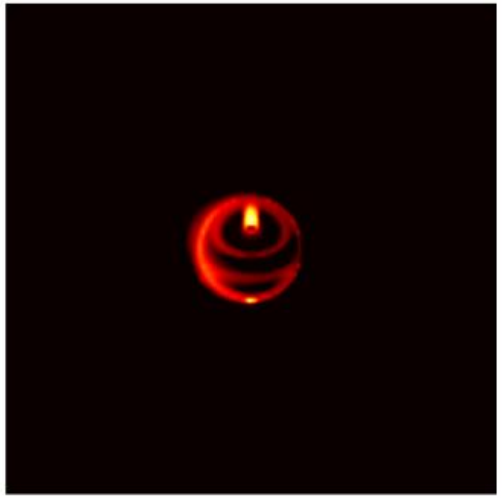
Raytraced Images

Thermal Only

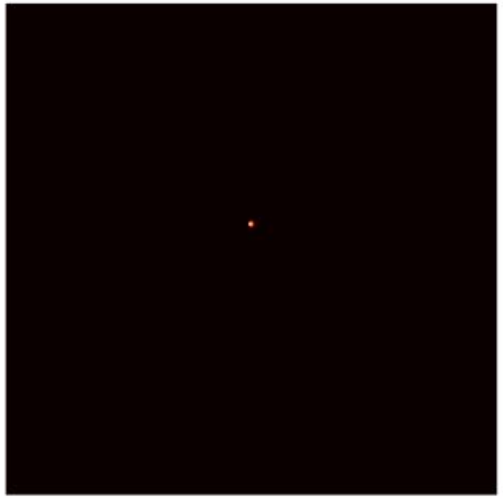
230 GHz



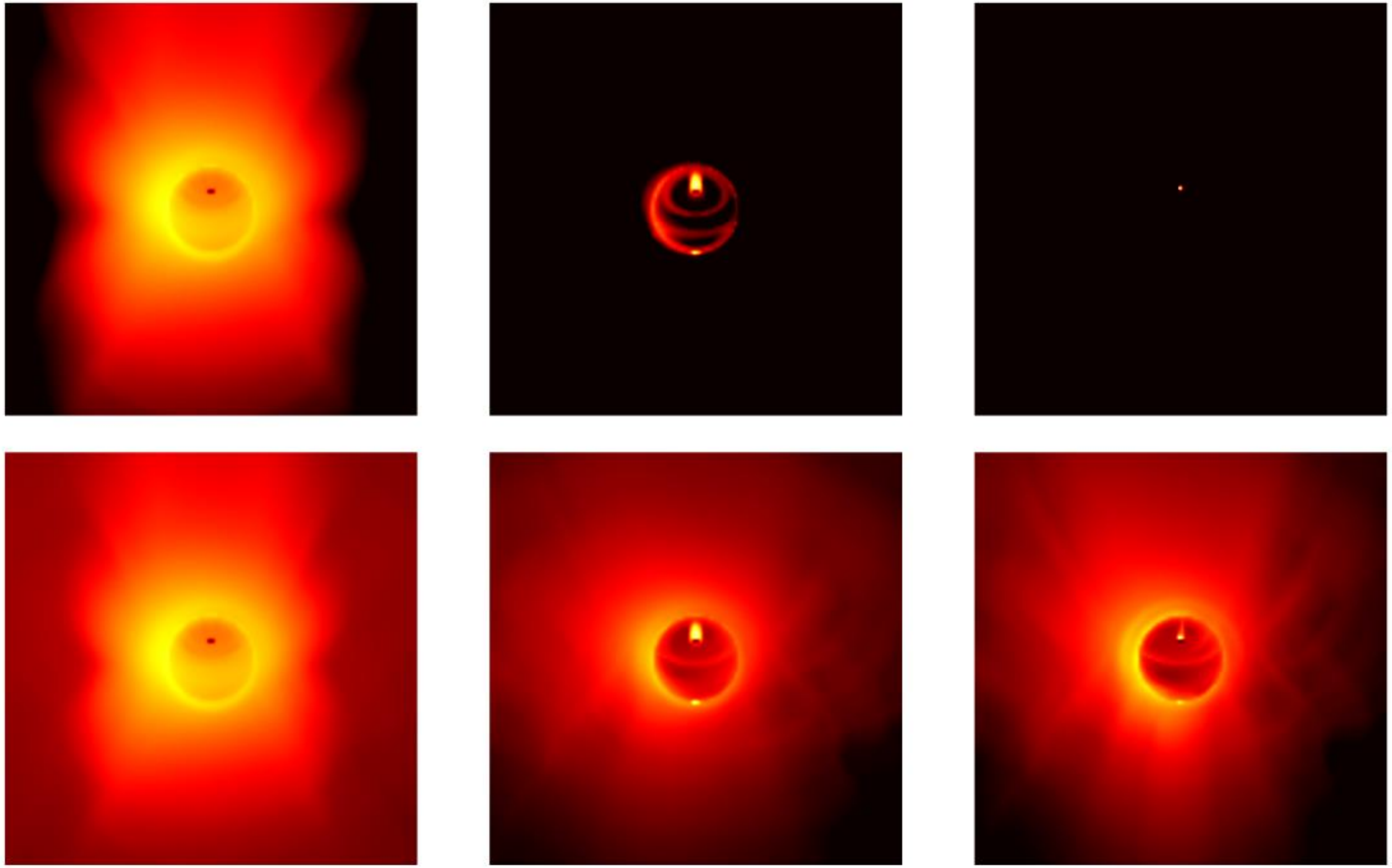
136 THz infrared



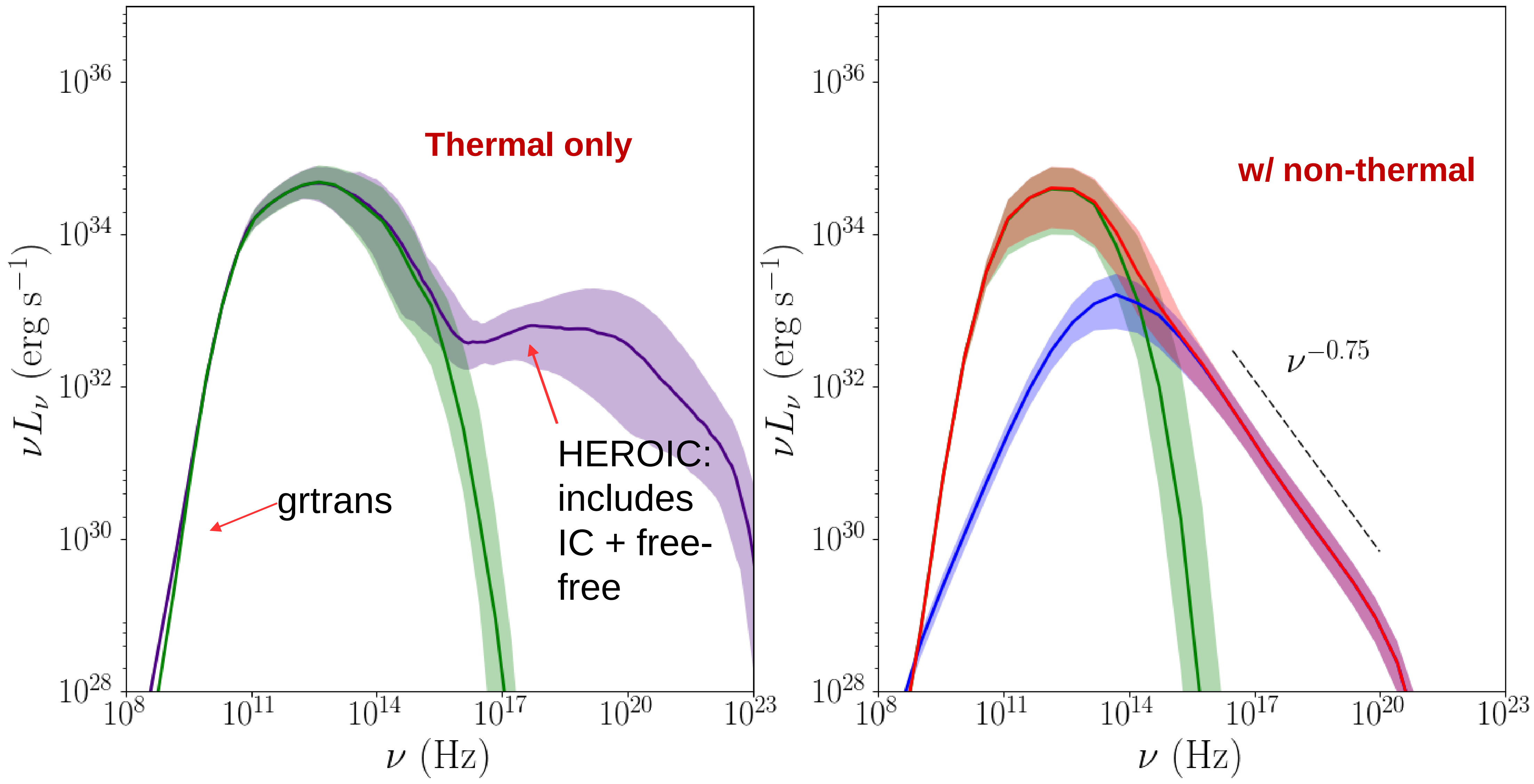
2 keV X-ray



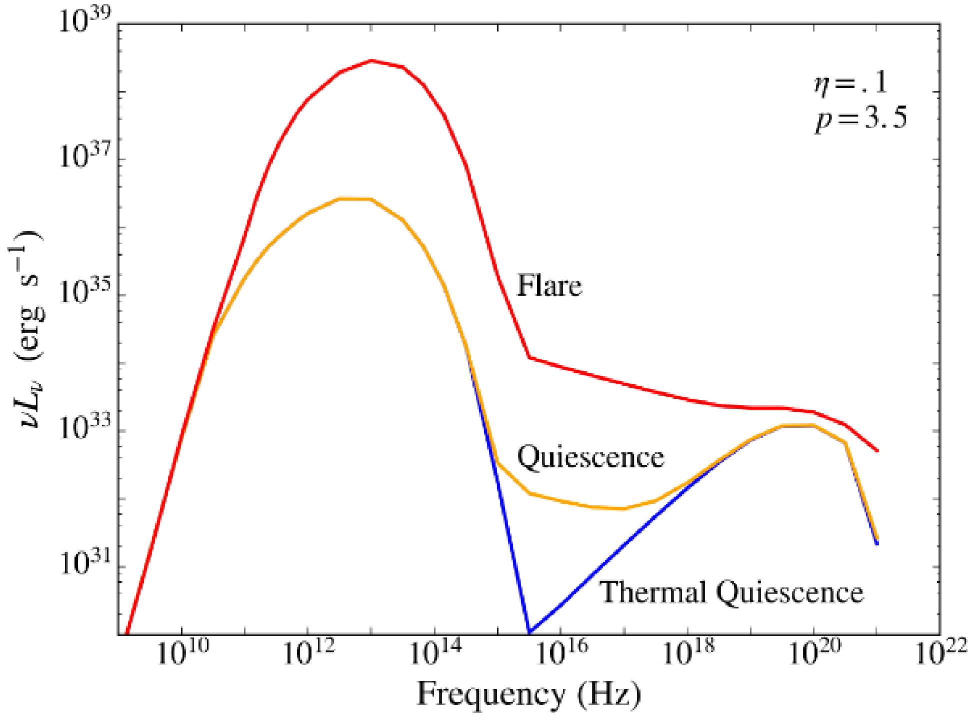
Raytraced Images

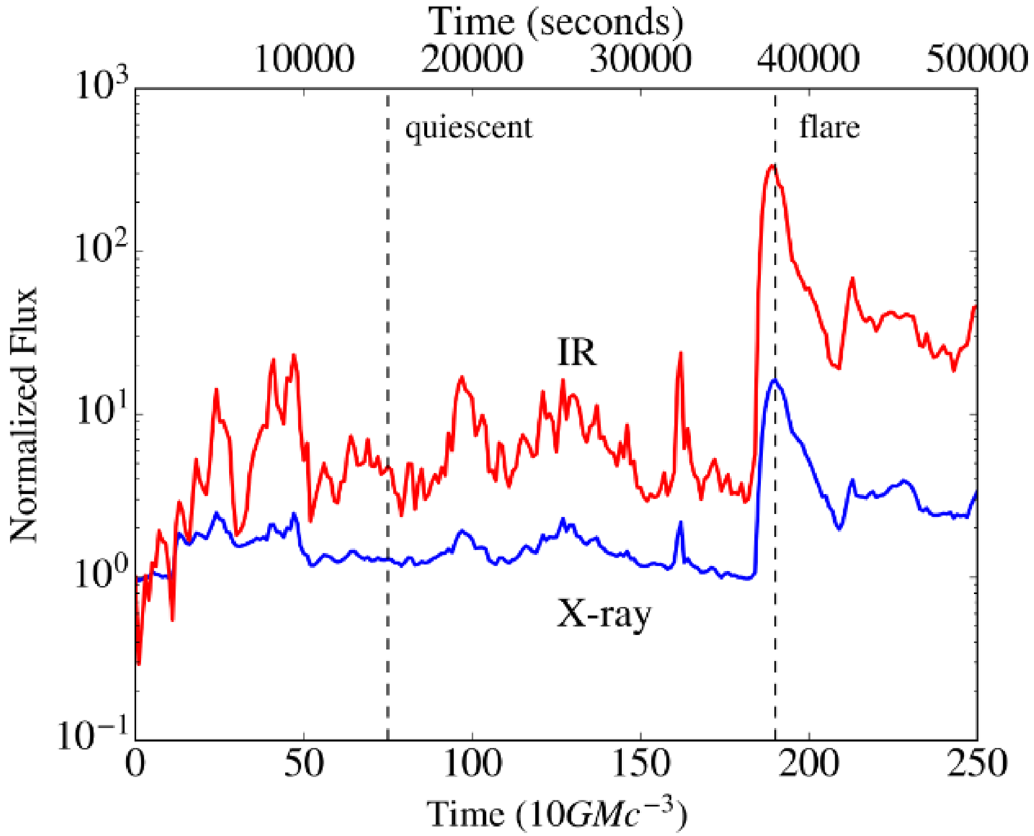


Synchrotron Spectra



Nonthermal effects on Sgr A* variability





Ball et al. 2016

Takeaway Points

Flows around Sgr A* and M87 should be 2 temperature and have an additional non-thermal electron population.

We now have a method to simulate the evolution of non-thermal electron distributions in global GRMHD simulations.

The electron heating/injection prescription is still very uncertain.

Next Steps

- Investigate different injection prescriptions to better capture physics of injection and reproduce variability.
  - In progress: dissipation fraction based on PIC simulations of reconnection (instead of Landau damping)
  - spectral changes in flares: varying injection slopes, varying minimum Lorentz factor.
  - To reproduce flaring activity: Localized nonthermal injection

Next Steps

- Investigate different injection prescriptions to better capture physics of injection and reproduce variability.
  - In progress: dissipation fraction based on PIC simulations of reconnection (instead of Landau damping)
  - spectral changes in flares: varying injection slopes, varying minimum Lorentz factor.
  - To reproduce flaring activity: **Localized** nonthermal injection
- Full 3D simulations & **polarized** radiative transfer
- Investigate different accretion regimes – where IC / free-free / feedback important.

Questions?

What about absorption?

- For $\gamma >> 1$, to **2nd order** in $h\nu/mc^2$, the evolution equation is:

$$\left(\frac{\partial n}{\partial t}\right) = -\frac{\partial}{\partial \gamma}\left[\dot{\gamma}\, n(\gamma)\right] + \frac{\partial}{\partial \gamma}\left[\gamma^2 C(\gamma)\frac{\partial}{\partial \gamma}\left(\frac{n(\gamma)}{\gamma^2}\right)\right]$$

Emission: 1st order

Absorption: 2nd order

- Where:

$$\dot{\gamma} = -\int \frac{\epsilon(\nu,\gamma)}{mc^2} d\nu \propto \left(\frac{h\nu}{mc^2}\right)$$

$$C(\gamma) = \int \frac{I_\nu\, \epsilon(\nu,\gamma)}{2\nu^2 m^2 c^4}\, d\nu \propto \left(\frac{h\nu}{mc^2}\right)^2$$

Requires radiation spectrum and emissivity spectrum!

Thermal and Nonthermal Power