Evolving Non-Thermal Electron Distributions in Black Hole Accretion Disk Simulations

Andrew Chael

EHT2016

December 2, 2016

Work with Ramesh Narayan and Aleksander Sądowski

Sgr A* SED

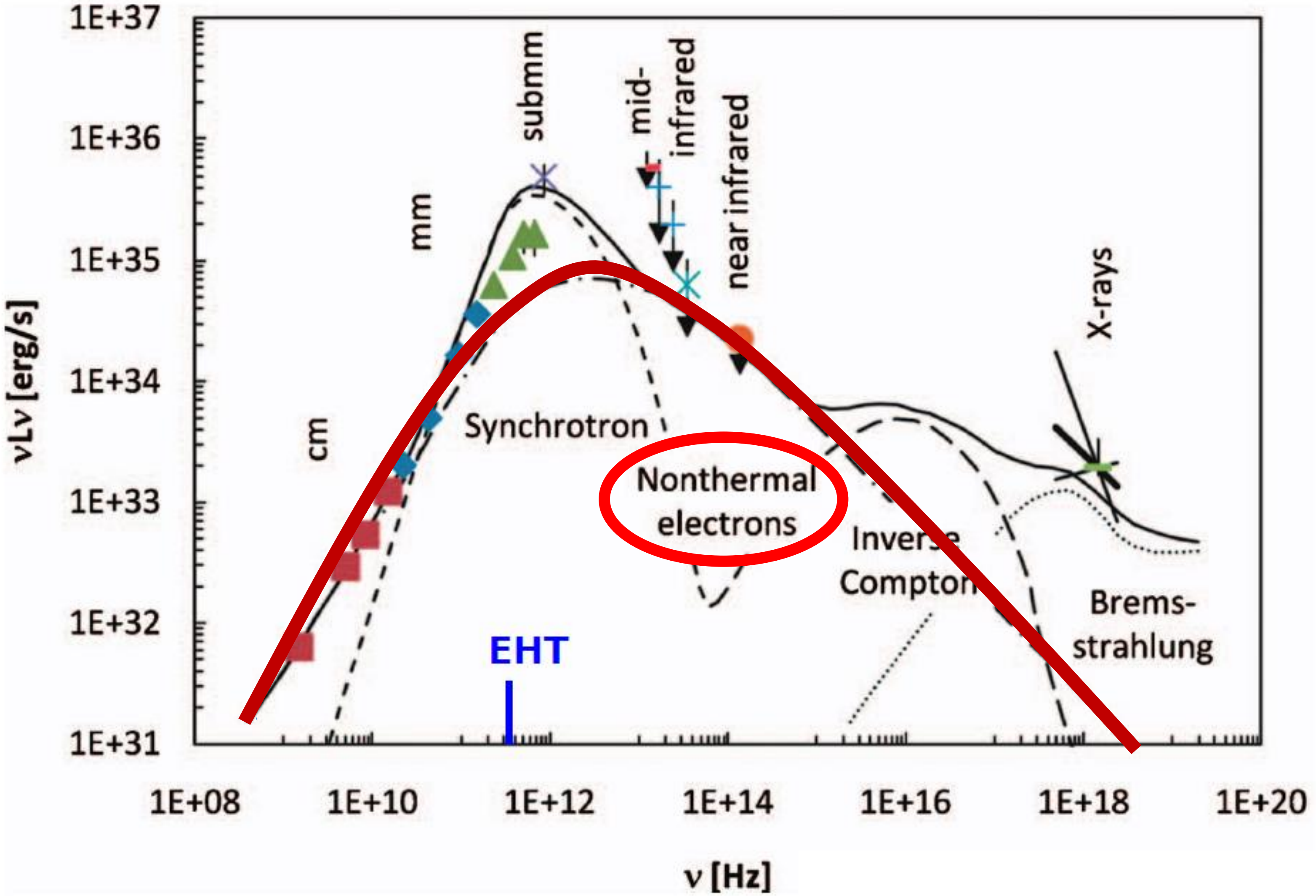


Image Credit: Genzel et al. (2010)

Nonthermal effects on EHT image

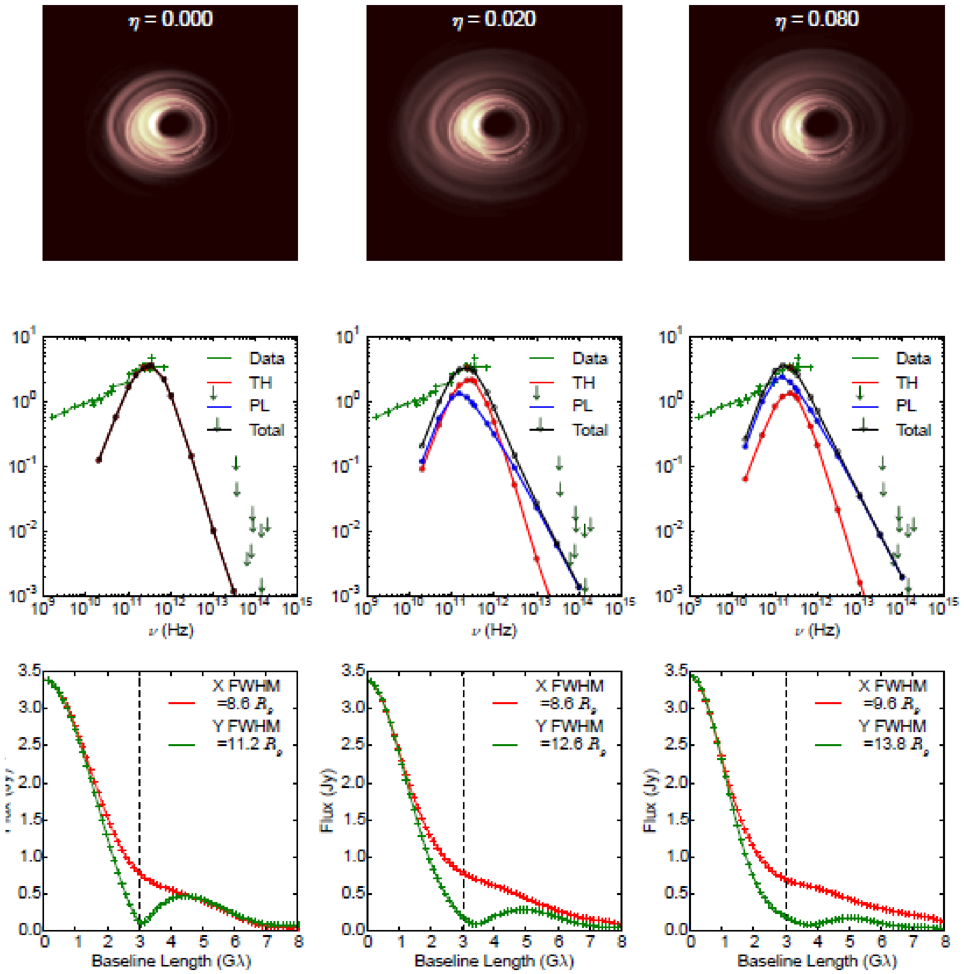


Image Credit: Mao et al. 2016

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.

Background: Two-Temperature Simulations

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

- Electrons lose energy through radiation much more efficiently than ions.

- Electrons can be relativistic ($\Gamma = 4/3$) while ions are not ($\Gamma = 5/3$). Relativistic species store more energy with a smaller increase in temperature.

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

Background: Two-Temperature Simulations

- Added to KORAL: Sądowski et al. 2016.

- Electrons and ions are each separate fluids in thermal equilibrium.

- Energy and pressure are related by a **self-consistent adiabatic index**:

$$\Gamma(\theta) \quad , \quad \theta = k_B T / mc^2$$

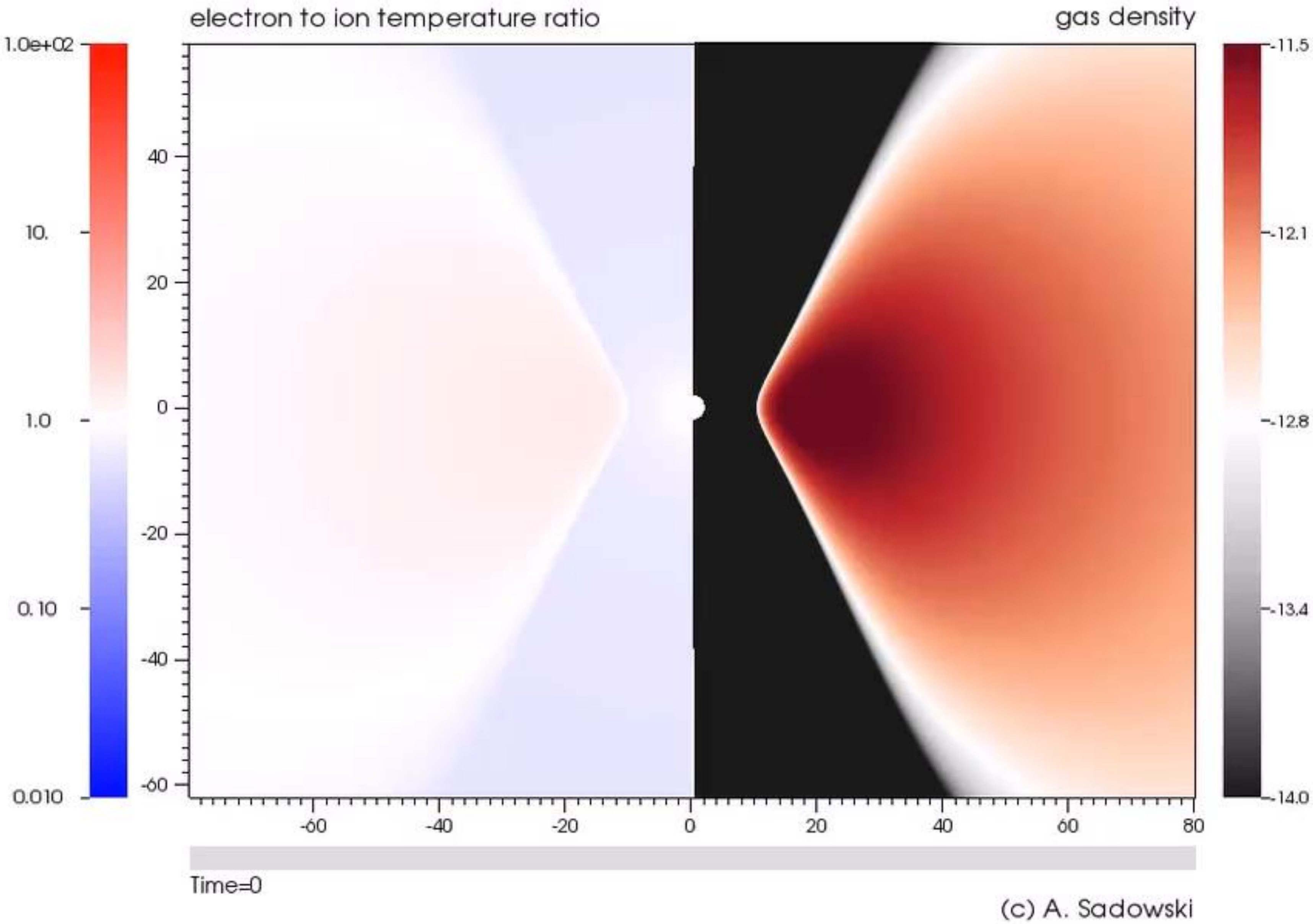
Background: Two-Temperature Simulations

- Entropy per particle is taken as the **“conserved”** quantity.

$$\delta\tau\,(nsu^{\mu})_{;\mu} = (\underbrace{\delta q_{\mathrm{heat}} - \delta q_{\mathrm{cool}}}_{\text{change in energy from dissipative processes}})/T$$

entropy per particle

- Evolve electrons and ions **adiabatically** and compare their energy density with total fluid to identify **viscous heating**.



Video Credit: Aleksander Sądowski

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).

Number, Energy, Pressure

- Nonthermal distribution **fluid quantities come directly from** $n(\gamma)$.

$$n_{e\,\mathrm{ur}} = \int_{\gamma_{min}}^{\gamma_{max}} n(\gamma) d\gamma$$

$$u_{e\,\mathrm{ur}} = m_e \int_{\gamma_{min}}^{\gamma_{max}} n(\gamma)(\gamma - 1)$$

$$p_{e\,\mathrm{ur}} = m_e \int_{\gamma_{min}}^{\gamma_{max}} \frac{1}{3} n(\gamma)(\gamma - \gamma^{-1})$$

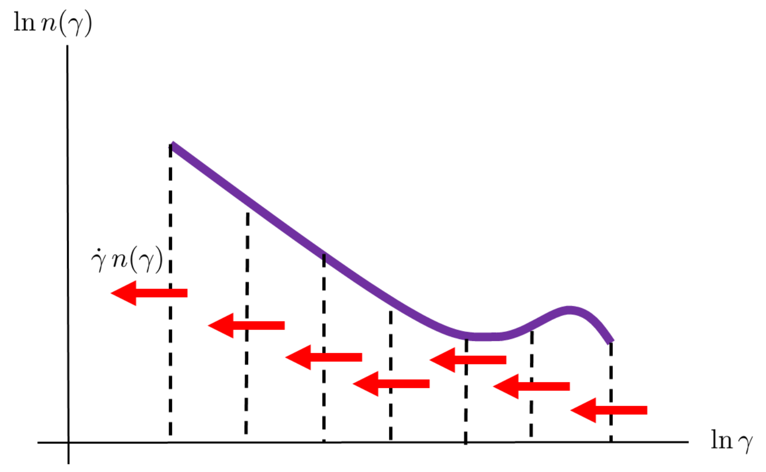
- We have to **subtract off** $n_{\mathrm{e\ ur}}$ from the thermal number density.

Evolution Equation

$$\underbrace{(n(\gamma)u^{\alpha})_{;\alpha}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial\gamma}\left[u^{\alpha}_{;\alpha}\frac{1}{3}(\gamma-\gamma^{-1})n(\gamma)\right]}_{\text{Adiabatic Compression/Expansion}} + S(\gamma)$$

Interaction terms

Evolution Equation



$\dot{\gamma}\, n(\gamma)$ = Flux in Lorentz factor space

$$\underbrace{\left(n(\gamma)u^{\alpha}\right)_{;\alpha}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial\gamma}\left[u^{\alpha}_{;\alpha}\frac{1}{3}(\gamma-\gamma^{-1})n(\gamma)\right]}_{\text{Adiabatic Compression/Expansion}} + S(\gamma)$$

Interaction terms

Interaction Terms

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

Interaction Terms

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

Viscous Heating/Injection:
Total injected energy is a fraction of identified viscous heating

Viscous Heating

- Compare the internal energy of the total fluid to the internal energy of the components **evolved adiabatically**.

$$q^v = \frac{u - u_{i\,\mathrm{th\,adiab}} - u_{e\,\mathrm{th\,adiab}} - u_{e\,\mathrm{ur\,adiab}}}{\Delta\tau}$$

- A fraction δ_e goes directly into both electron populations: δ_{ur} of that goes into non-thermal electrons.

$$\left.\begin{aligned} u_i &\to u_i + (1-\delta_e) q^v \Delta\tau \\ u_{e\,\mathrm{th}} &\to u_{e\,\mathrm{th}} + \delta_e (1-\delta_{\mathrm{ur}}) q^v \Delta\tau \end{aligned}\right\} \text{Thermal heating}$$

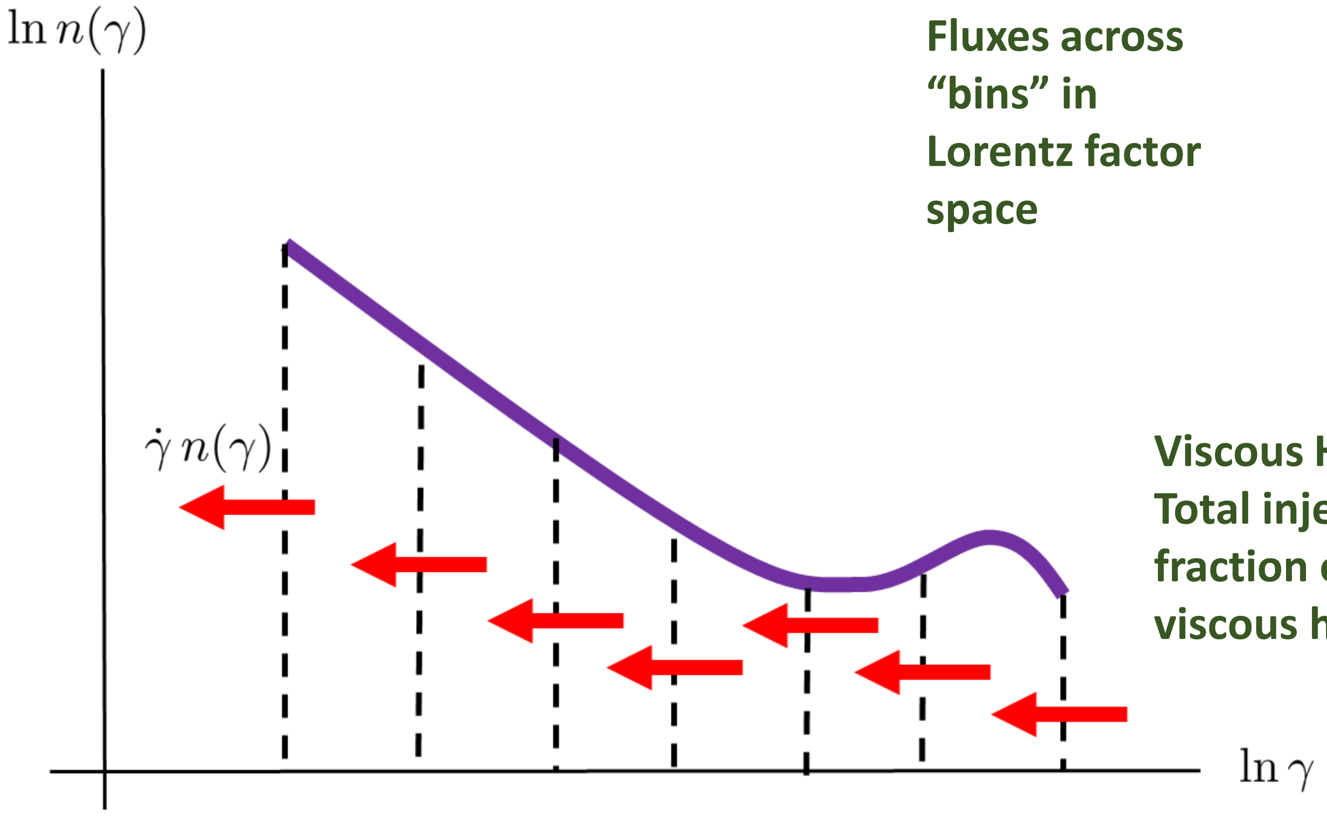
$$n(\gamma) \to n(\gamma) + Q_I(\gamma)\Delta\tau$$

Fixed Power Law normalized to total injected energy $\delta_e \delta_{\mathrm{ur}} q^v$

Interaction Terms

Radiative Cooling

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



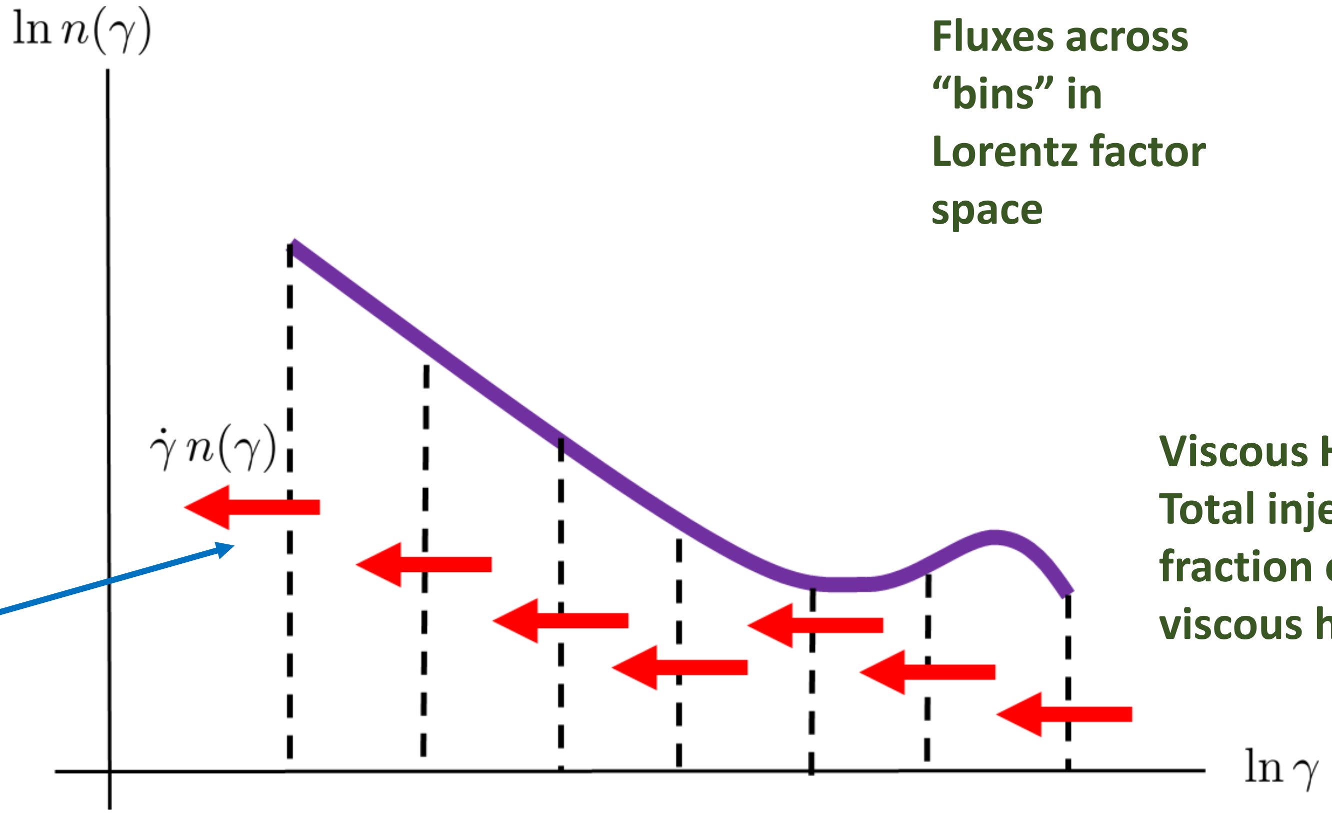
Fluxes across "bins" in Lorentz factor space

Viscous Heating/Injection: Total injected energy is a fraction of identified viscous heating

Interaction Terms

Radiative Cooling

$$(n(\gamma)u^\alpha)_{;\alpha} = \overbrace{\frac{\partial}{\partial\gamma}\left[\frac{1}{3}u^\alpha_{;\alpha}(\gamma-\gamma^{-1})n(\gamma)\right]}^{\text{Adiabatic Part}} - \frac{\partial}{\partial\gamma}\underbrace{\left(\dot\gamma_{\rm tot}n(\gamma)\right)}_{\substack{\text{Fluxes across}\\ \text{“bins” in}\\ \text{Lorentz factor}\\ \text{space}}} + Q^I(\gamma).$$



Account for **boundary loss**.

Viscous Heating/Injection: Total injected energy is a fraction of identified viscous heating

Radiative Cooling

- Synchrotron:

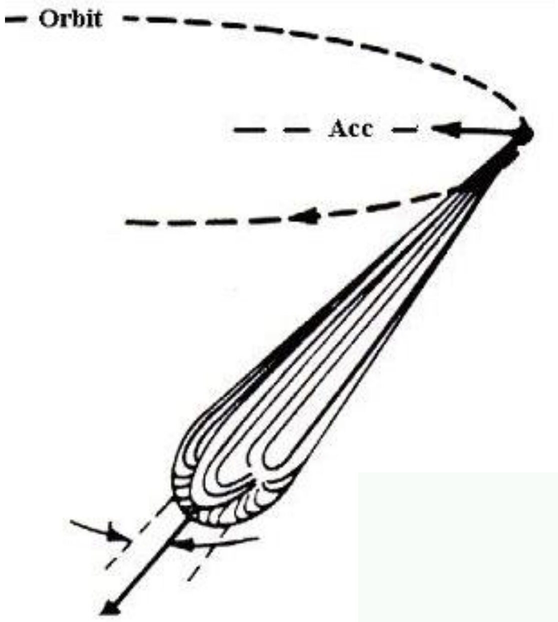
$$\dot{\gamma}_{\rm syn} \sim B^2 \gamma^2$$

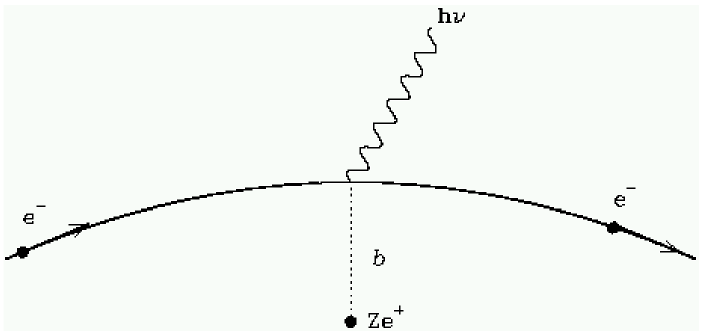
- Free-Free:

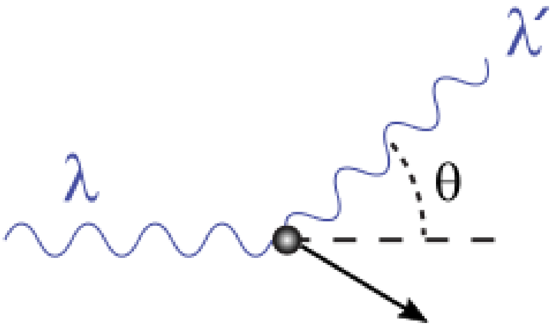
$$\dot{\gamma}_{ff} \sim -n_i\, \gamma\, \log \gamma$$

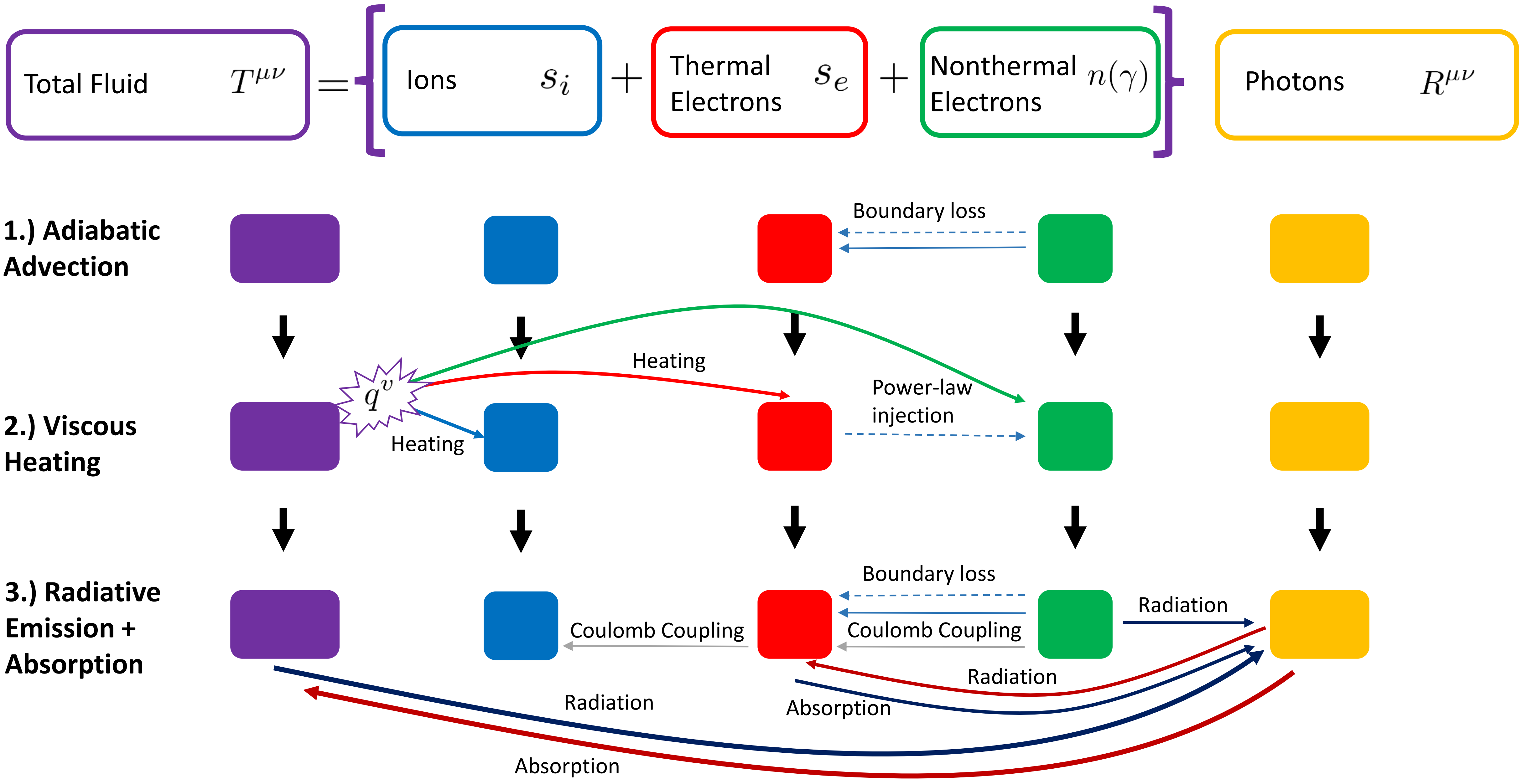
- Inverse Compton:

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







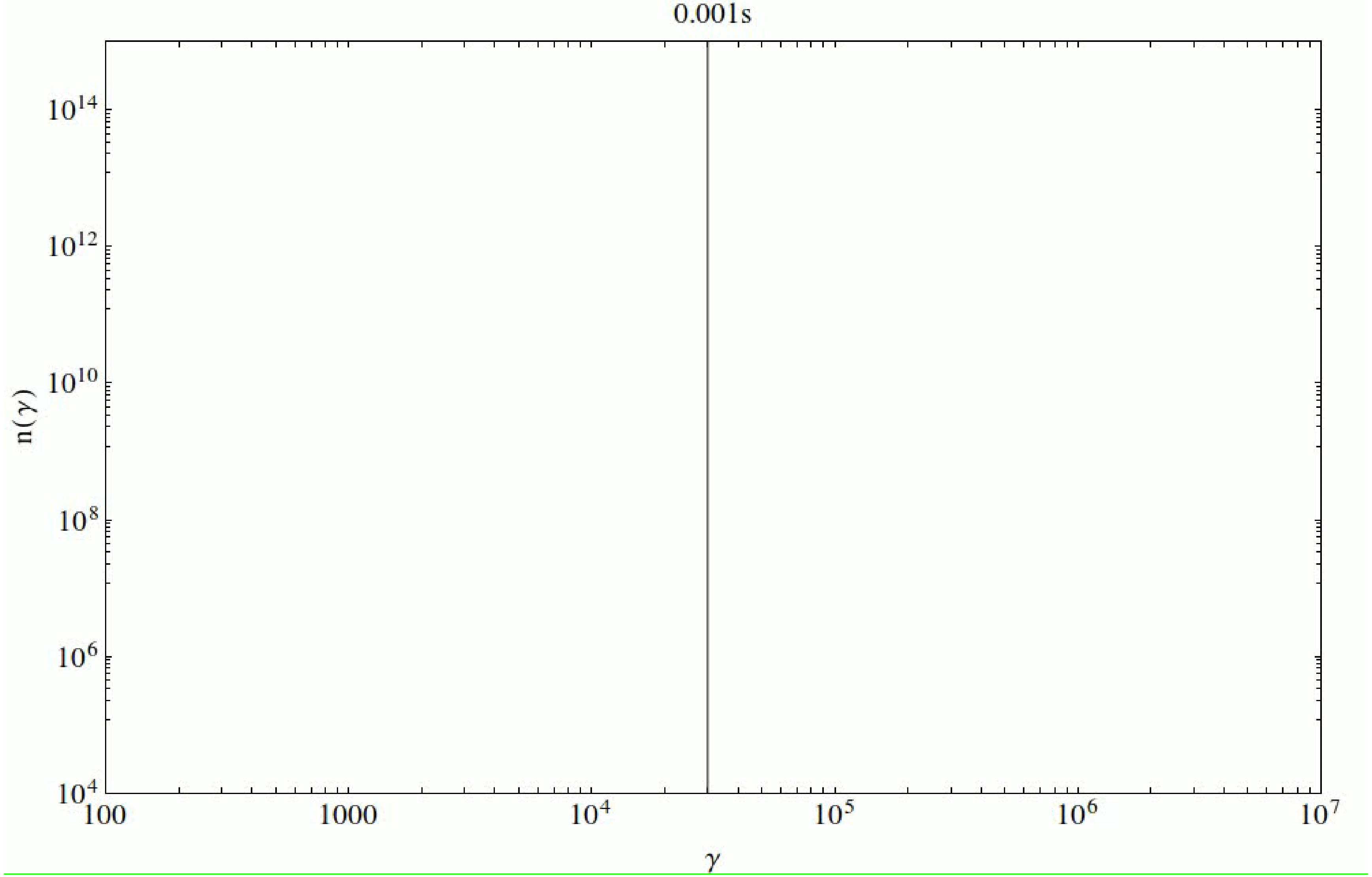


Total Fluid $T^{\mu\nu}$
=
Ions s_i
+
Thermal Electrons s_e
+
Nonthermal Electrons $n(\gamma)$
Photons $R^{\mu\nu}$
1.) Adiabatic Advection
Boundary loss
2.) Viscous Heating
q^v
Heating
Heating
Power-law injection
3.) Radiative Emission + Absorption
Boundary loss
Coulomb Coupling
Coulomb Coupling
Radiation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

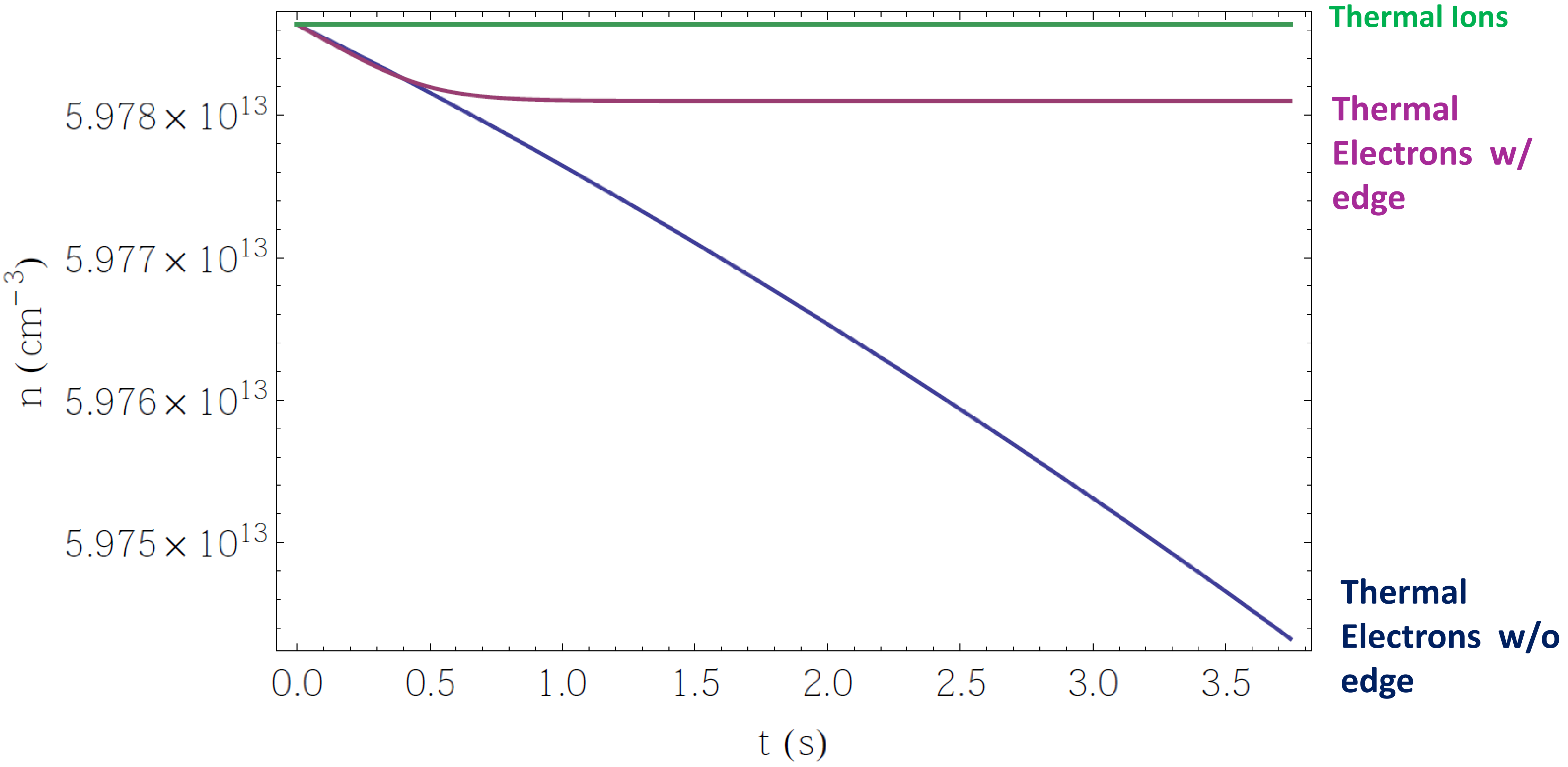
Test #1: Synchrotron Cooling Test

- Power law injection at fixed rate + synchrotron cooling in constant magnetic field.
- Tests both viscous updating step and implicit radiative cooling.

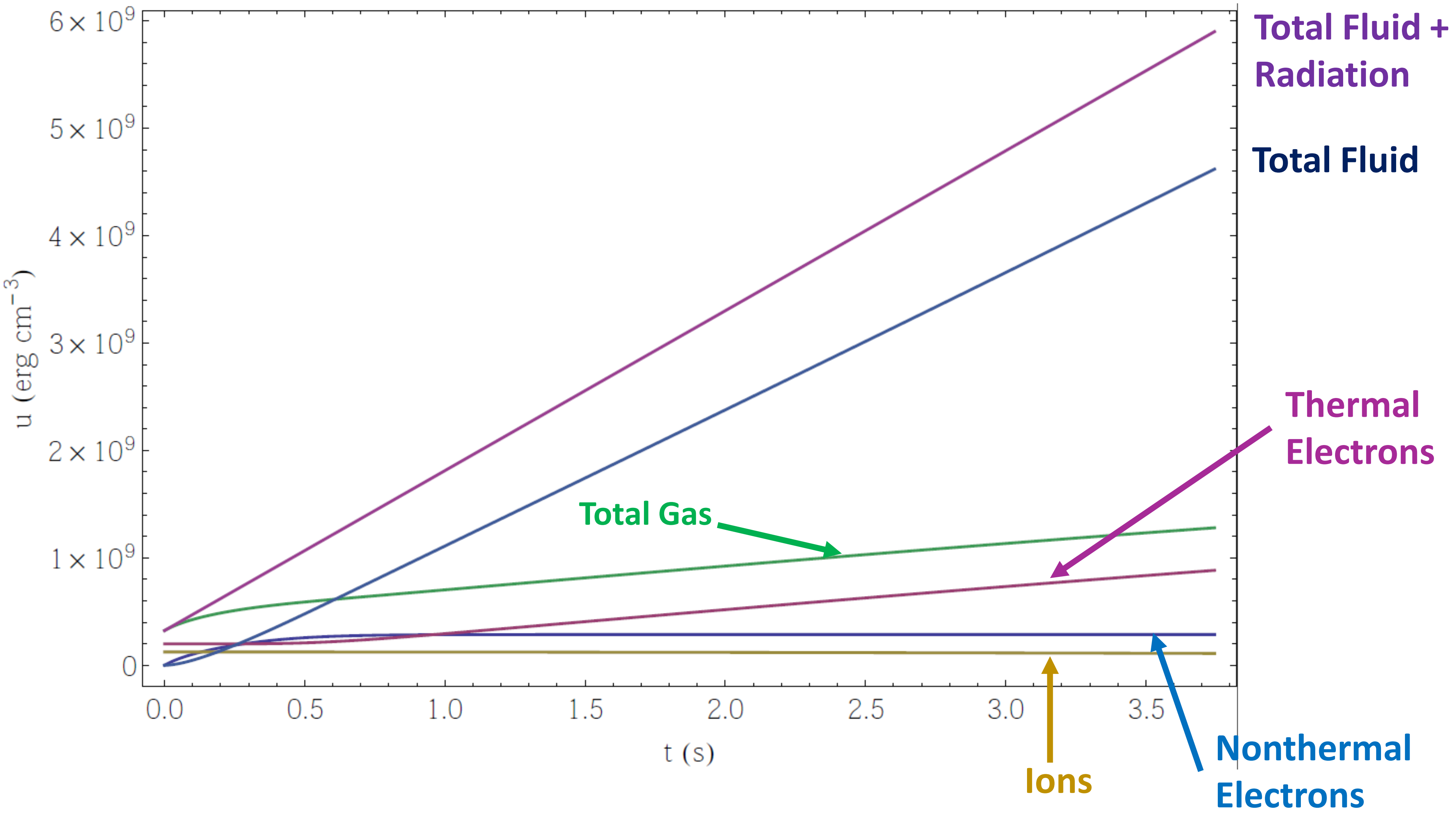
Test #1: Synchrotron Cooling with Boundary



Test #1: Particle number Equilibrium

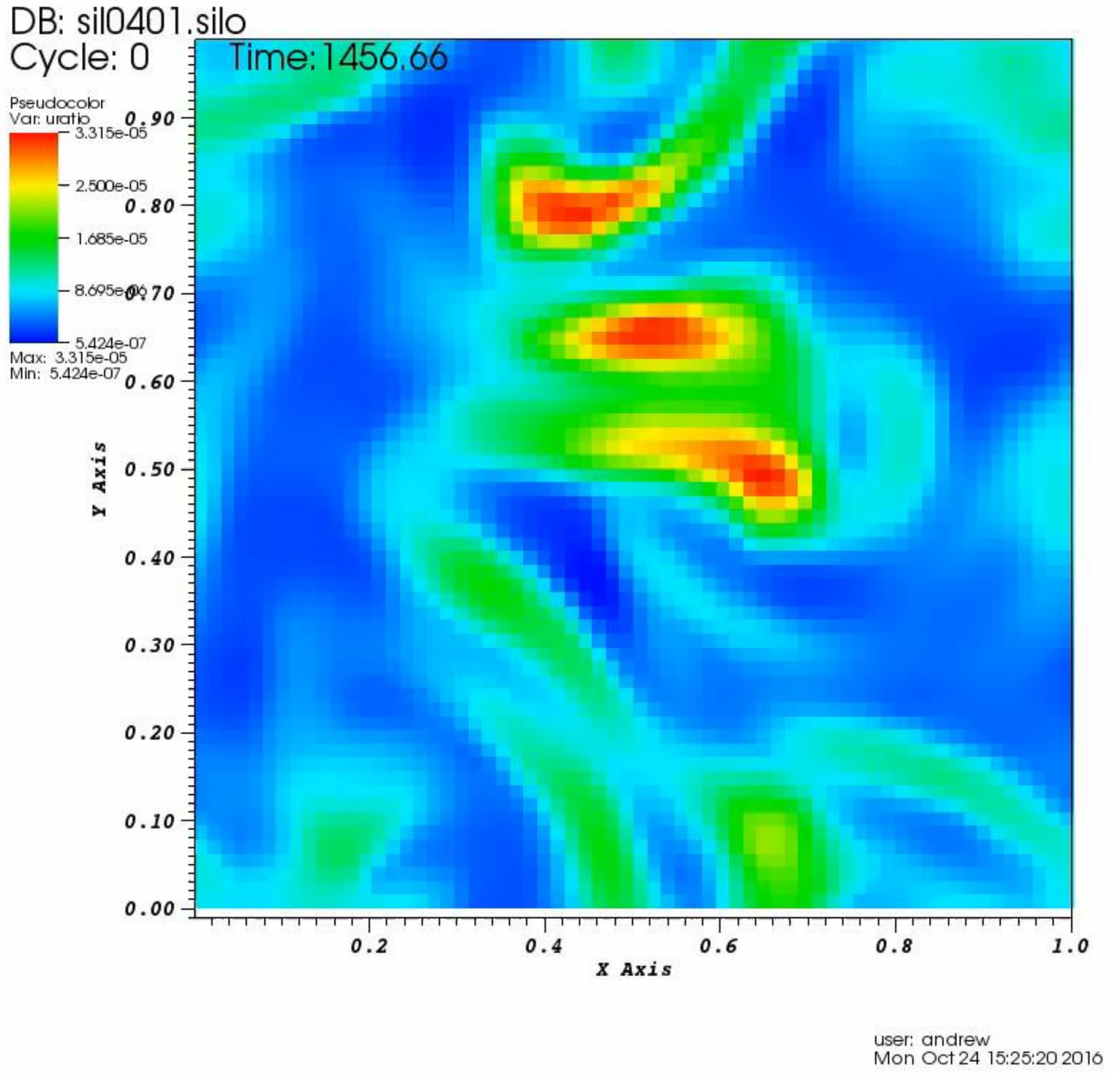


Test #1: Energy Conservation



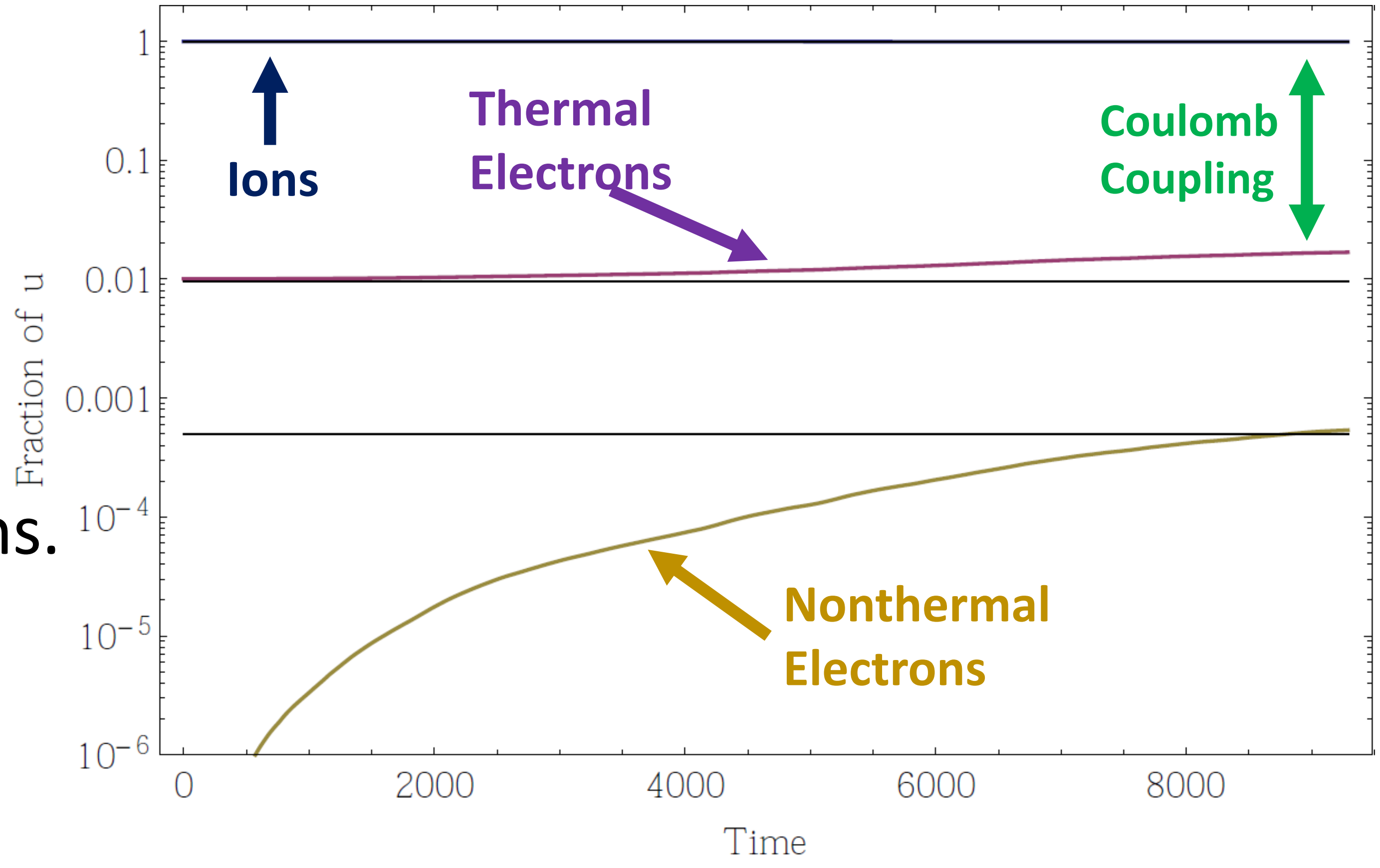
Test #2: Driven Turbulent Box

- No radiation: injection and adiabatic expansion.
- Energy is added by "stirring" with a spectrum of perturbations.
- Parameters: $\delta_e = .1\,,\ \delta_{\mathrm{ur}} = .05$



Test #2: Driven Turbulent Box

- No radiation: injection and adiabatic expansion.
- Energy is added by "stirring" with a spectrum of perturbations.
- Parameters: $\delta_e = .1\,,\ \delta_{\rm ur} = .05$



First Disk Simulation

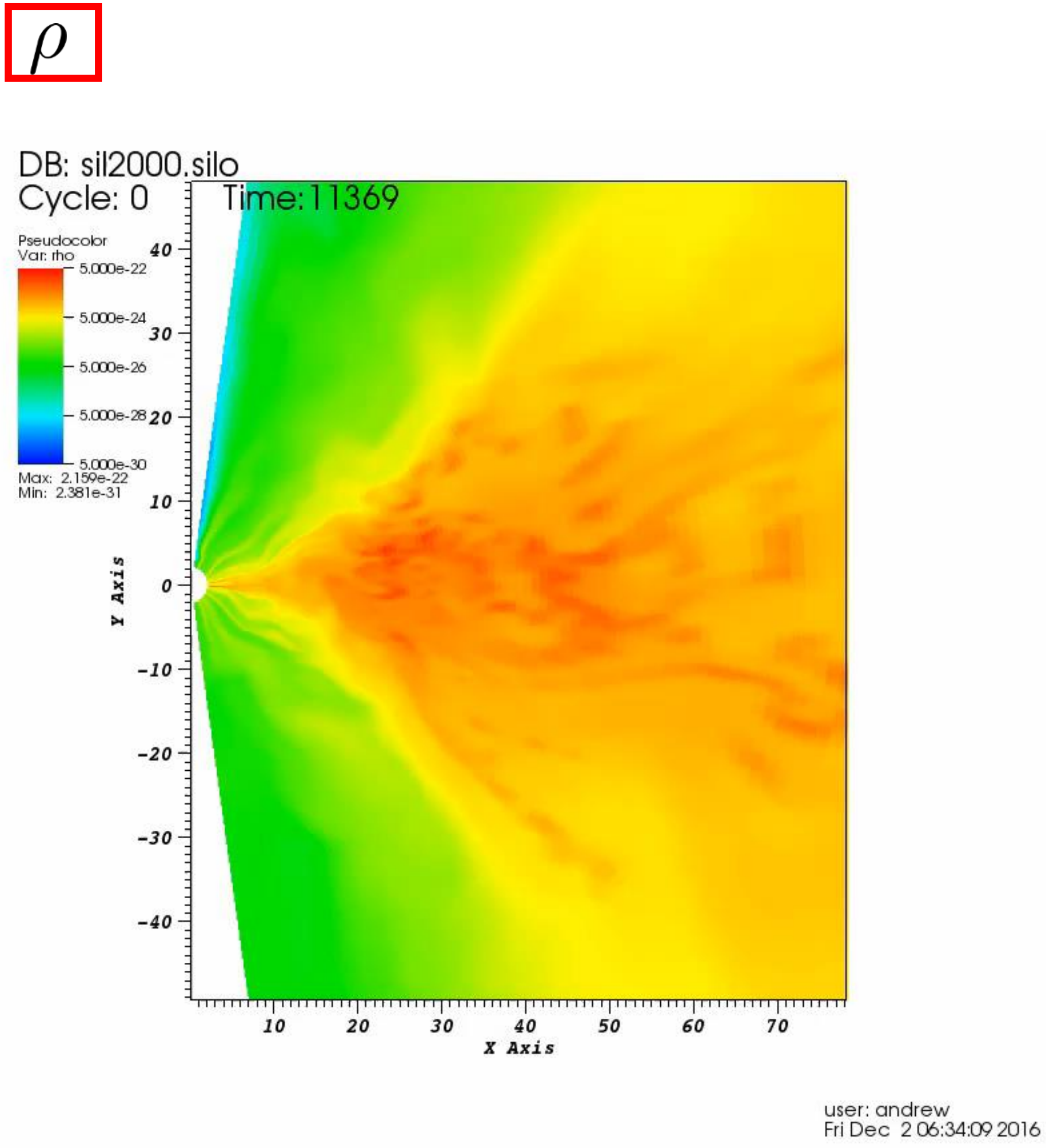
- Synchrotron cooling **only** for rel. electrons.

- Initial conditions: evolved two-temperature GRRMHD disk with **no** rel. electrons.

- Parameters: $\delta_e = .05\,,\ \delta_{\rm ur} = .005$

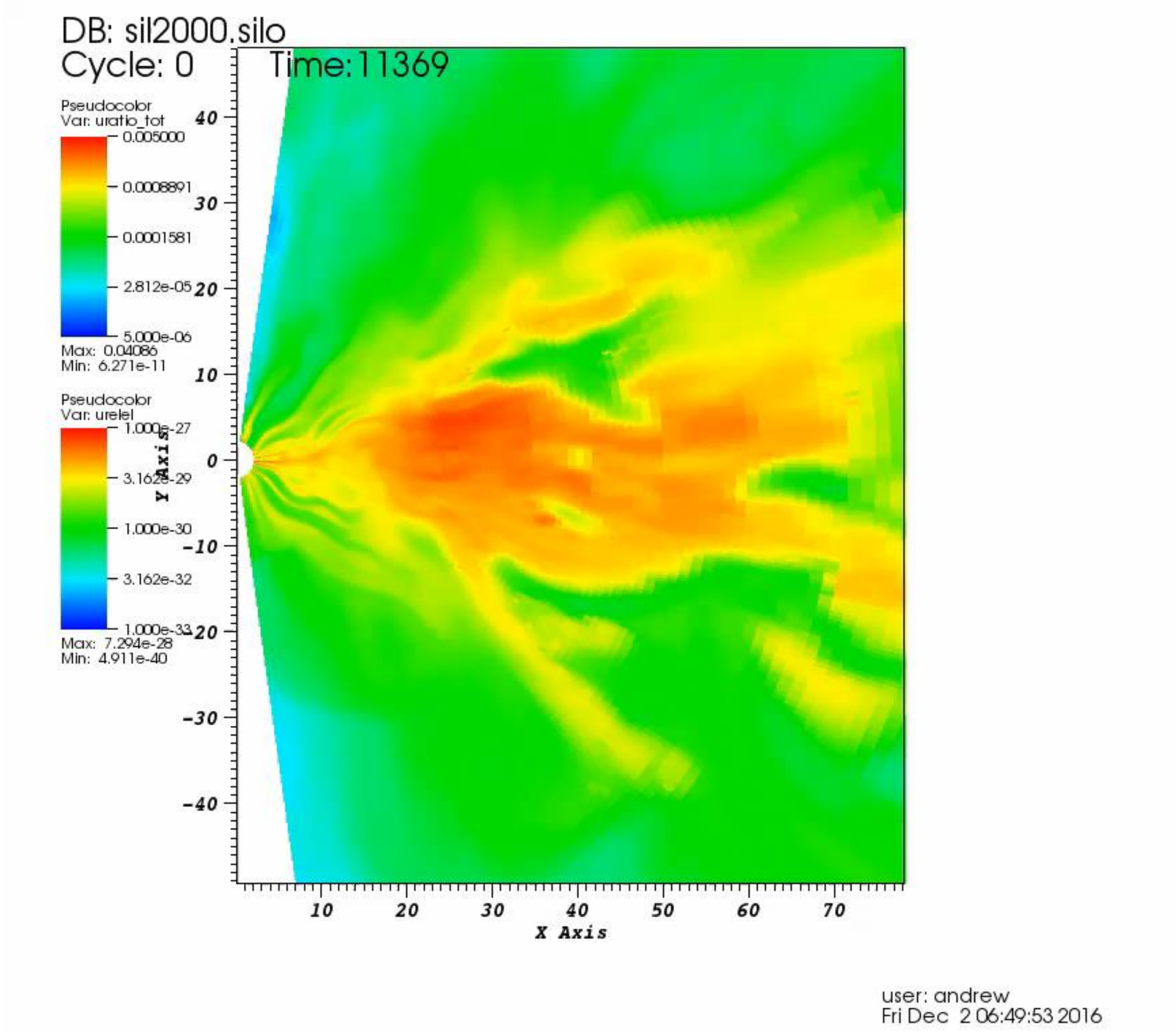
First Disk Simulation

- Synchrotron cooling **only** for rel. electrons.
- Initial conditions: evolved two-temperature GRRMHD disk with **no** rel. electrons.
- Parameters: $\delta_e = .05\,,\ \delta_{\mathrm{ur}} = .005$

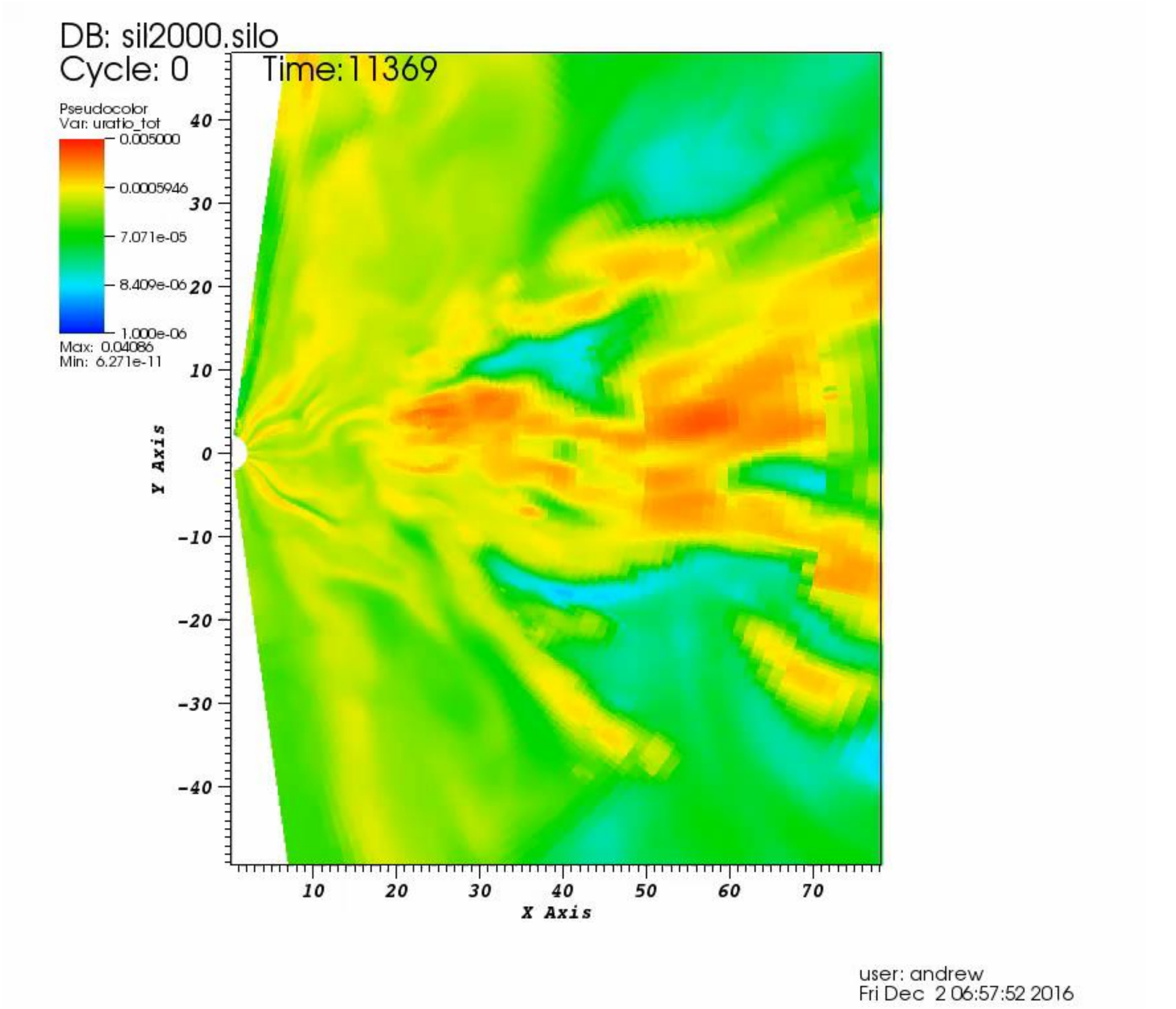


First Disk Simulation

$\boxed{u_{\mathrm{nth.}}}$

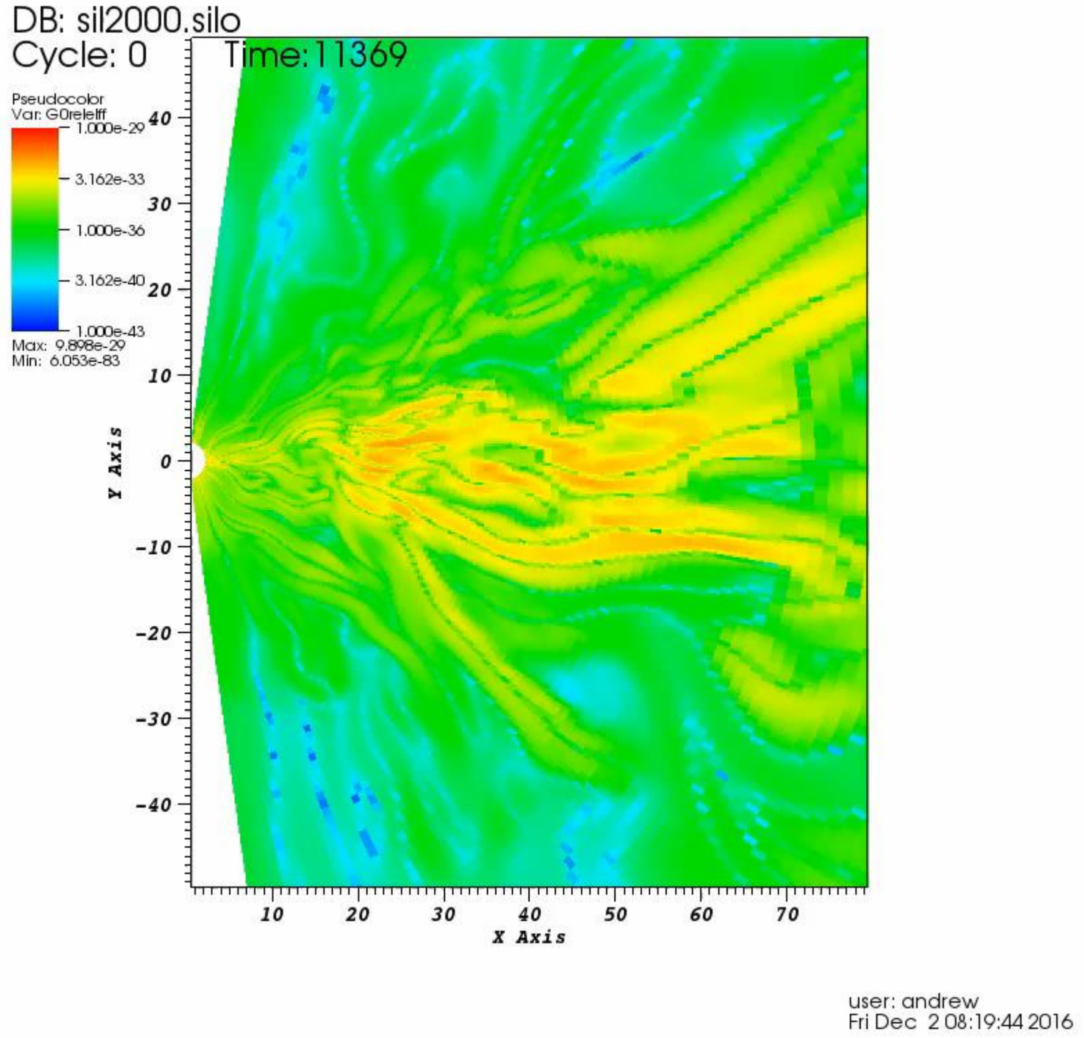


$\boxed{u_{\mathrm{nth.}}/u_{\mathrm{tot.}}}$



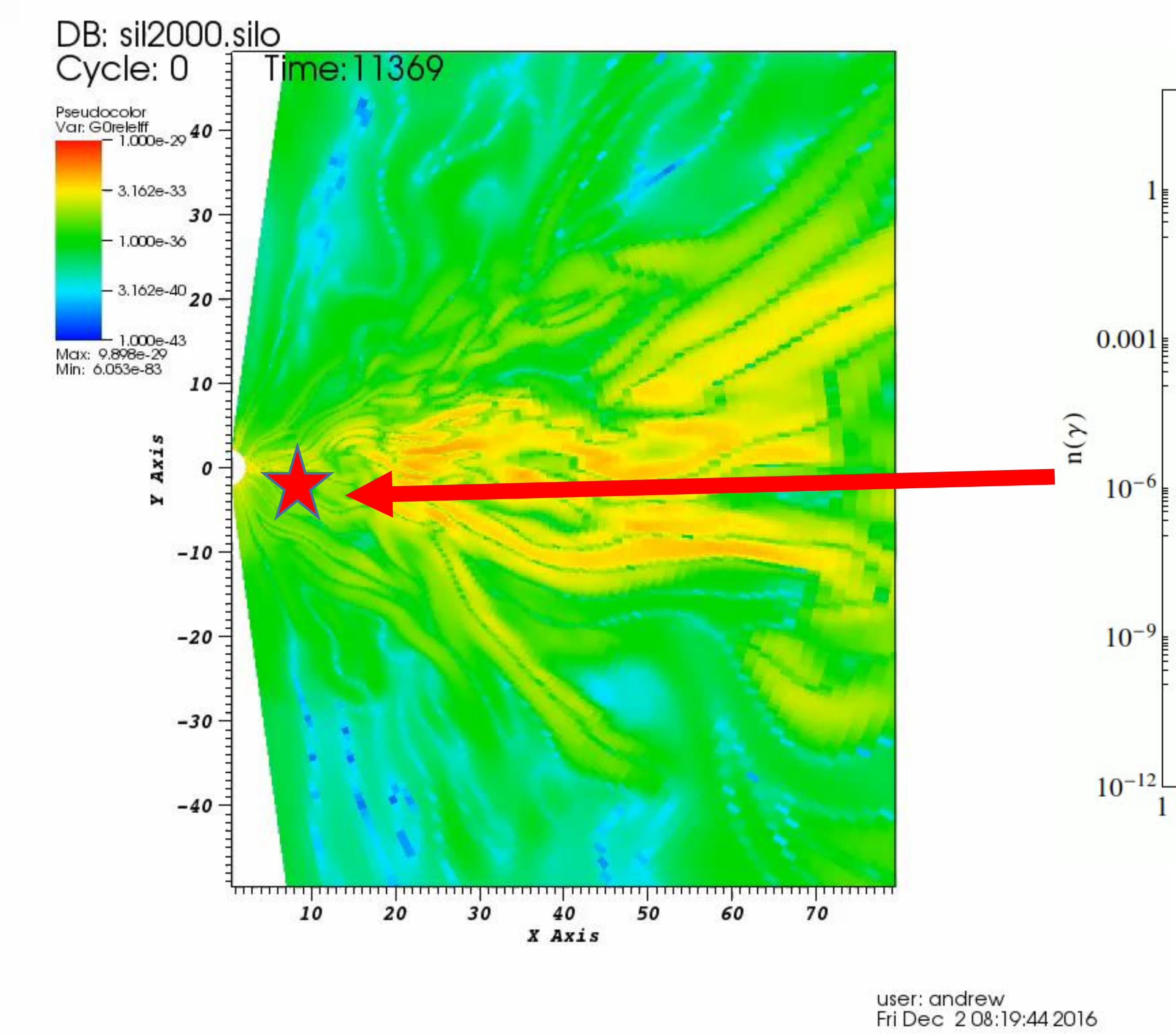
First Disk Simulation

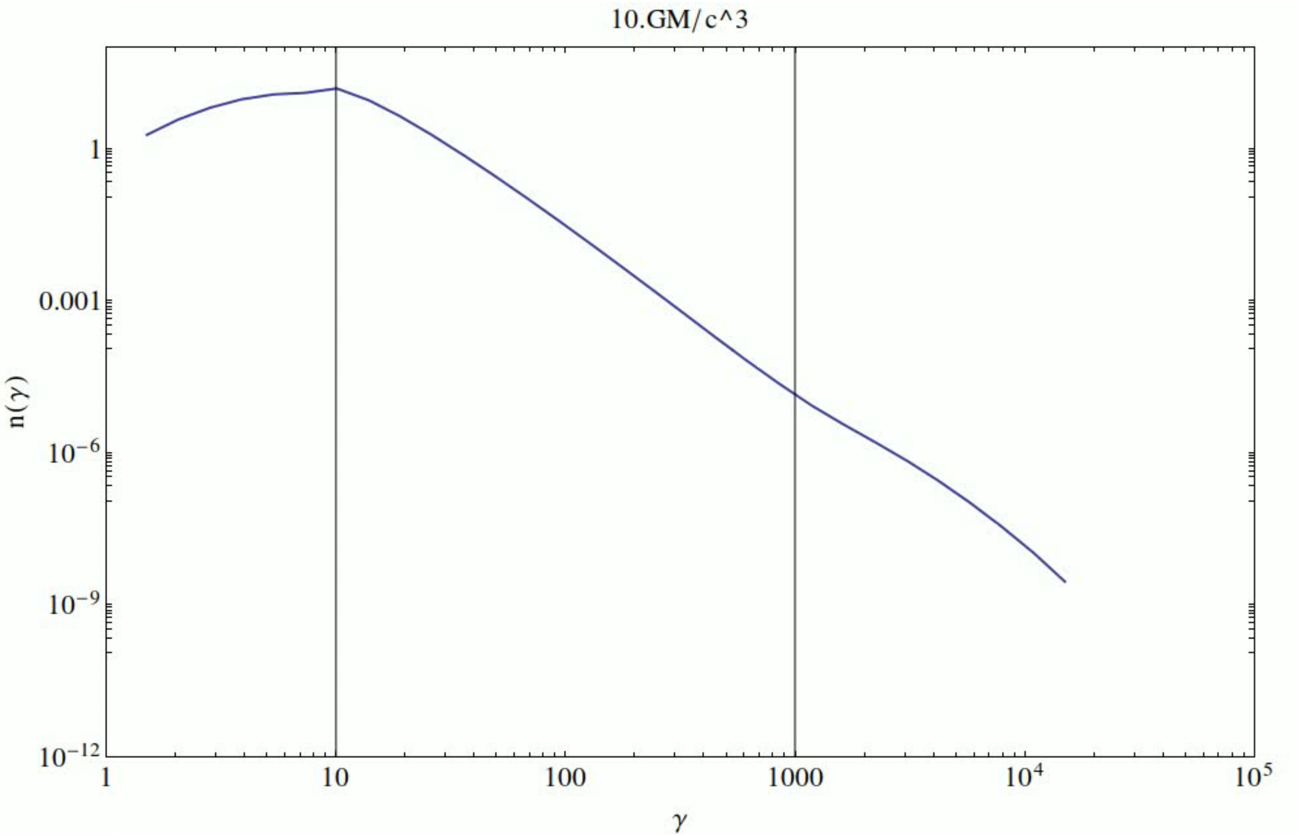
Nonthermal Rad. Power



First Disk Simulation

Nonthermal Rad. Power





Next Steps

- Determine prescriptions for energy injection fraction & power law parameters.

- Use new code in more Sgr A* & M87 simulations.

- Do radiative transfer and look at resulting spectrum and images.

Questions?

What about absorption?

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

$$\left(\frac{\partial n}{\partial t}\right) = \underbrace{-\frac{\partial}{\partial \gamma}\left[\dot{\gamma}\, n(\gamma)\right]}_{\text{Emission: 1st order}} + \frac{\partial}{\partial \gamma}\underbrace{\left[\gamma^2 C(\gamma)\frac{\partial}{\partial \gamma}\left(\frac{n(\gamma)}{\gamma^2}\right)\right]}_{\text{Absorption: 2nd order}}$$

- 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!