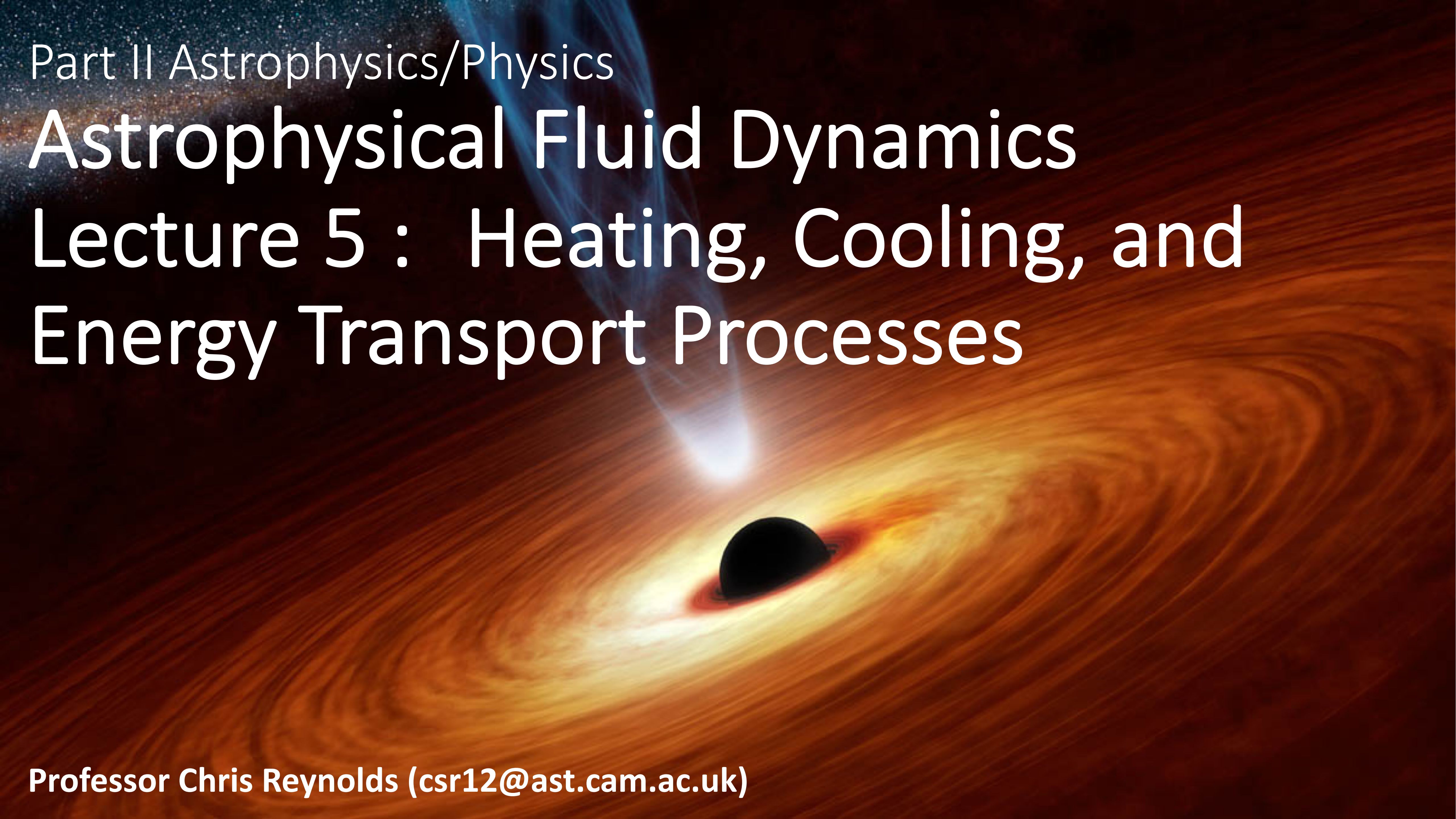


Part II Astrophysics/Physics

Astrophysical Fluid Dynamics

Lecture 5 : Heating, Cooling, and Energy Transport Processes

Professor Chris Reynolds (csr12@ast.cam.ac.uk)

Recap

- Need for an equation of state to close equations of fluid dynamics

$$p = p(\rho, T) = nk_B T = \frac{k_B}{\mu m_p}\rho T$$

- Barotropic fluids
  - Isothermal $p = A\rho$
  - Adiabatic $p = K\rho^\gamma$

- Energy equation

$$\boxed{\frac{\partial E}{\partial t} + \boldsymbol{\nabla}\cdot[(E+p)\mathbf{u}] = \rho\frac{\partial \Psi}{\partial t} - \rho\dot{Q}_{\rm cool}}$$

This lecture

Energy equation (cont.)

- Radiative cooling processes (D.3)
- Cosmic Ray heating (D.3)
- Energy Transport processes (D.4)

D.3 : Heating and Cooling Processes

How do we determine the cooling rate, $\dot{Q}_{\rm cool}$?

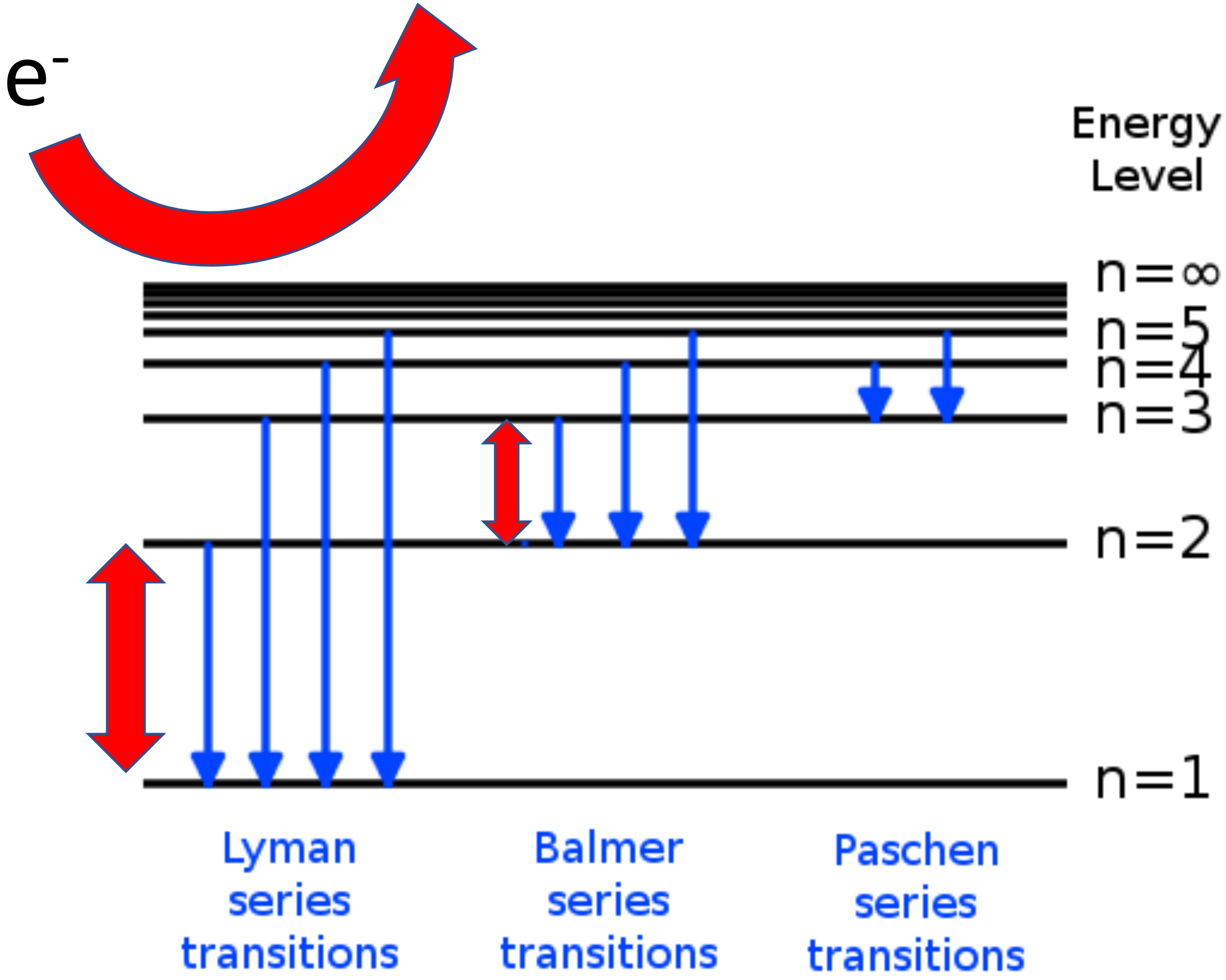
What kind of processes can heat a fluid?

Cooling (and heating) processes depend upon the detailed microphysics of the system under consideration.

Here, we discuss a few of the most important examples relevant to the energy-budget of a **thermal gas** (i.e. one in which the bulk of the particles are in thermodynamic equilibrium) in an **astrophysical setting** (diffuse and dominant element is hydrogen).

- Collisionally-excited atomic line radiation
    - Electron-ion collision lead to excited electronic states (inelastic collision)
    - Excited state decays via the emission of photons at well-defined energies
    - Number of collisions per ion per unit time ∝ n_e
    - Number of collisions per unit volume per unit time ∝ n_e x n_{ion}

$$L_{\rm c} \propto n_{\rm e} n_{\rm ion} e^{-\chi/kT} \chi/\sqrt{T} \qquad \Rightarrow \qquad \dot{Q} = \rho f(T)$$



Collisional excitation

Image credit : Christopher S. Baird

- Collisionally-excited atomic line radiation
    - Electron-ion collision lead to excited electronic states (inelastic collision)
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$$L_{\rm c} \propto n_{\rm e} n_{\rm ion} e^{-\chi/kT} \chi/\sqrt{T} \qquad \Rightarrow \qquad \dot{Q} = \rho f(T)$$

- Recombination emission
    - Free electron captured by ion… puts ion in excited
    - Electron cascades down energy levels, eventually forming ground state
    - So ion de-excites via line emission
    - Number of recombinations per ion per unit time ∝ n_e
    - Number of recombinations per unit volume per unit time ∝ n_e x n_{ion}

$$\Rightarrow \qquad \dot{Q} = \rho f(T)$$

Recombination

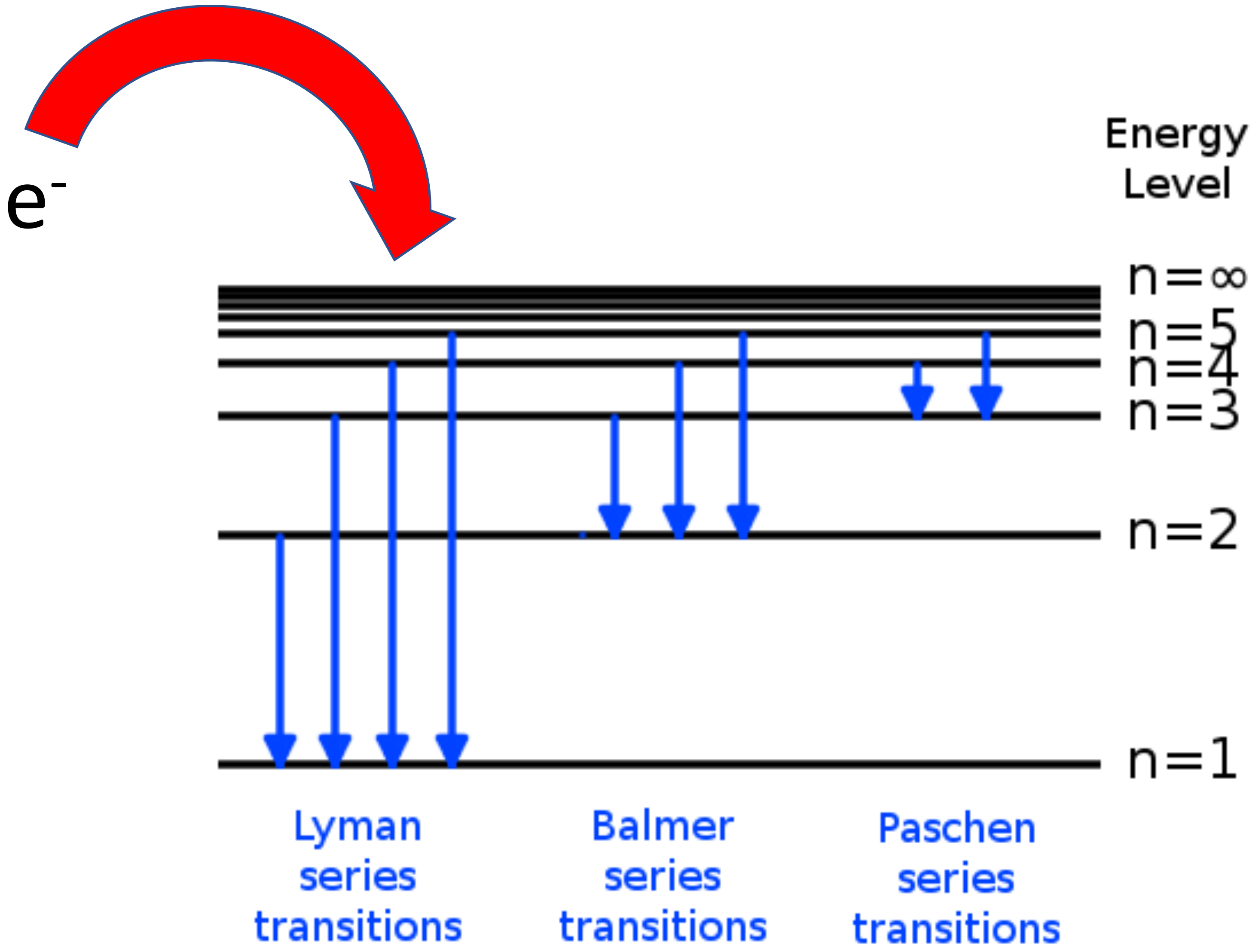
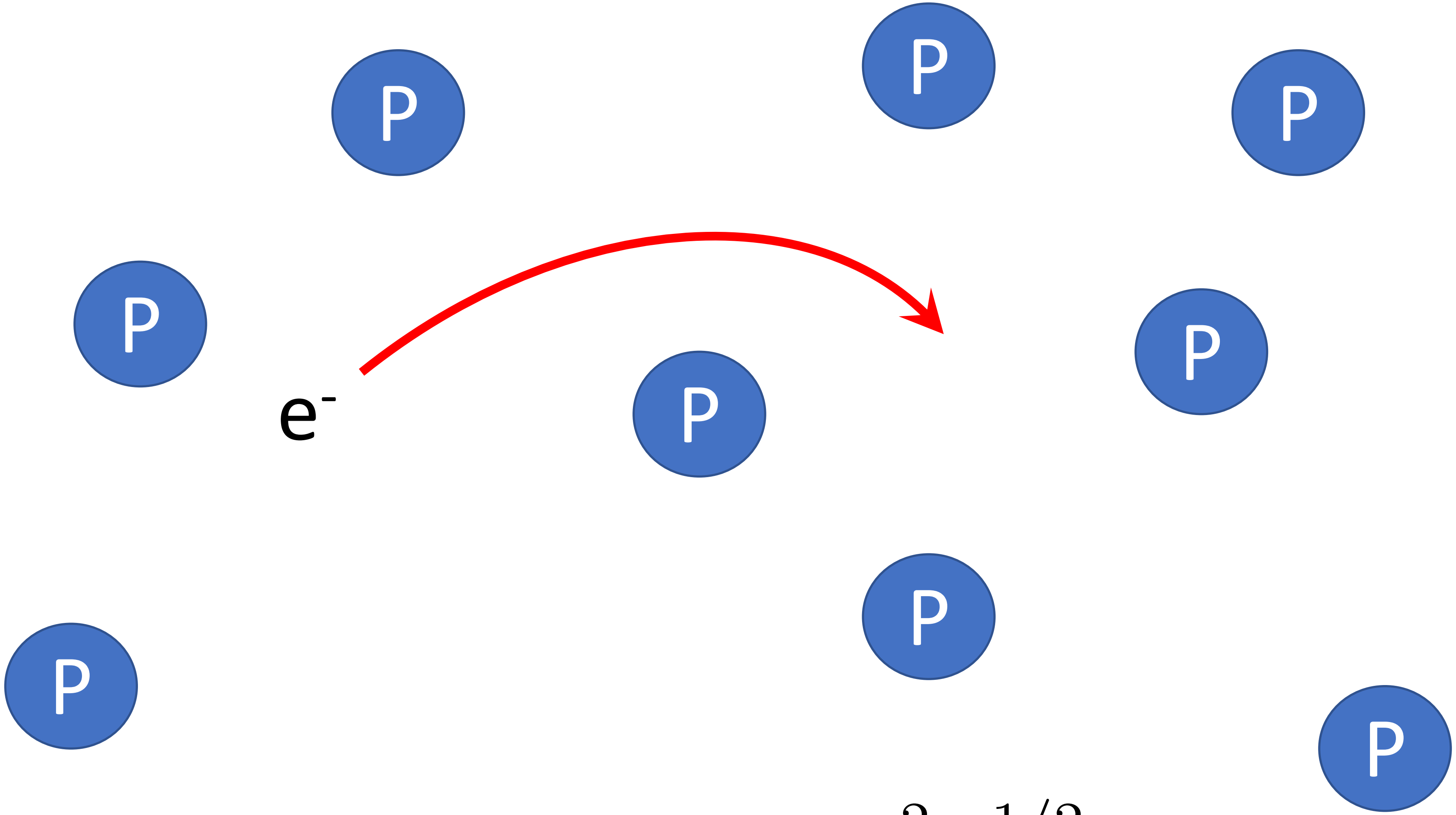


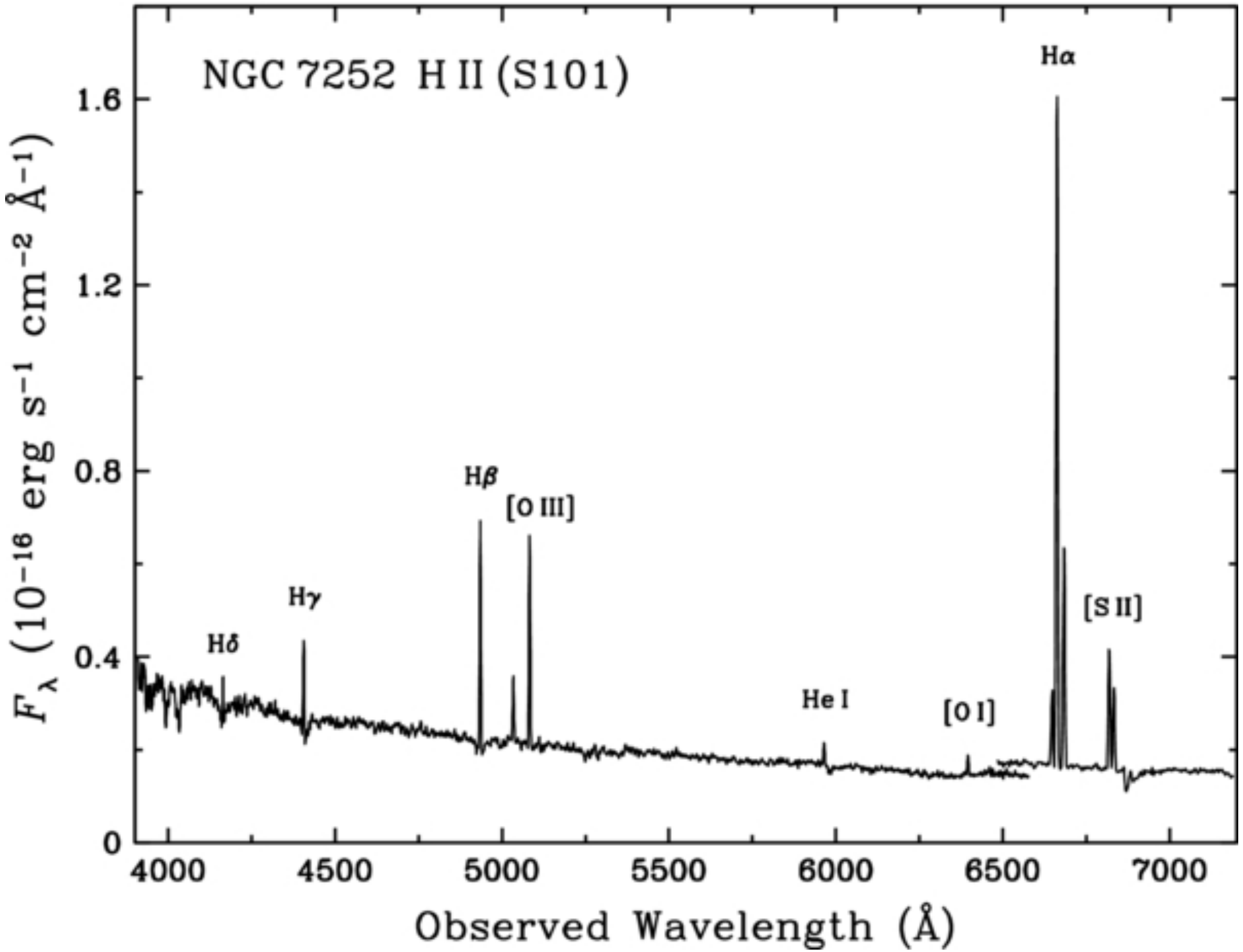
Image credit : Christopher S. Baird



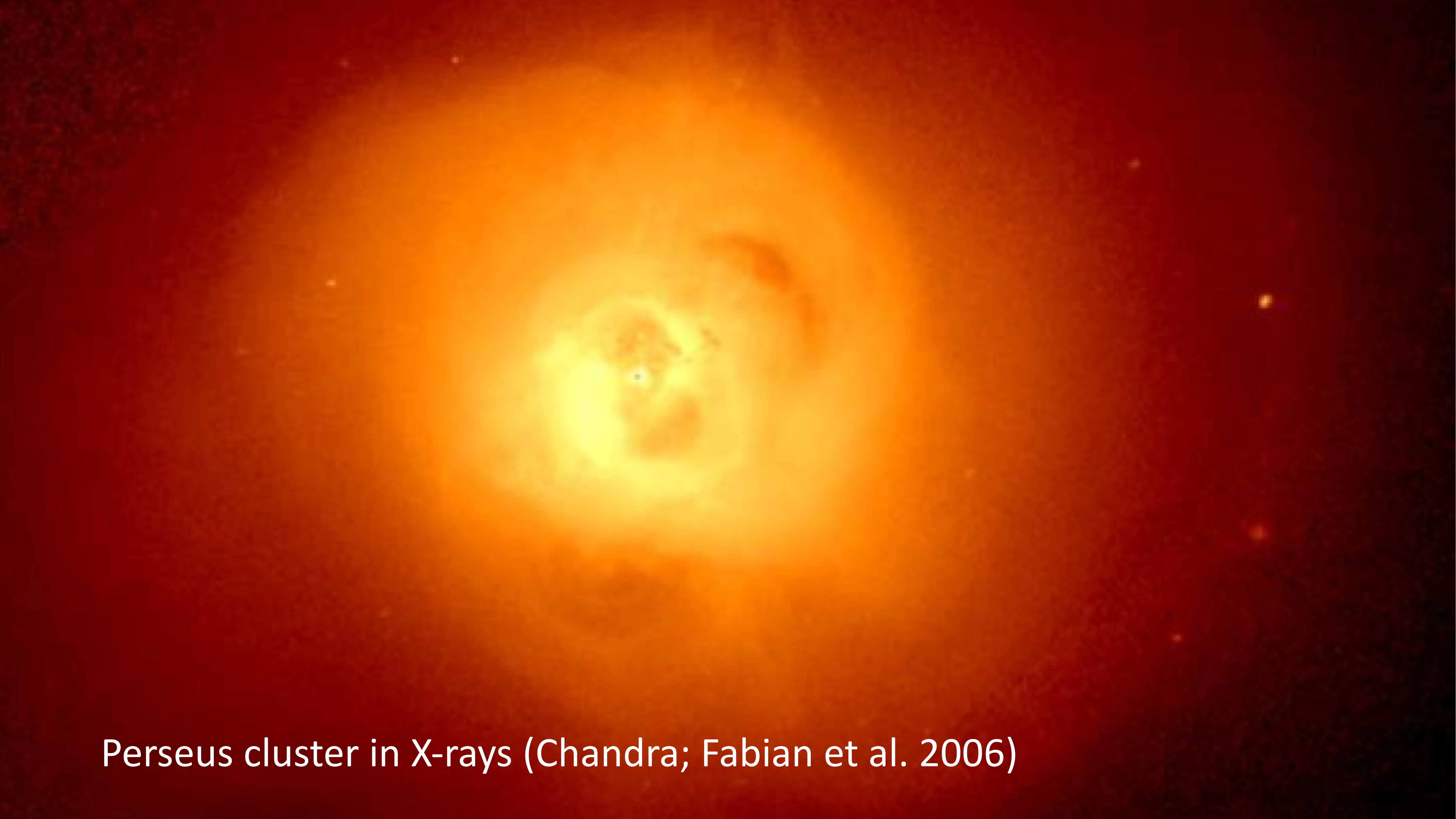
Free-free emission (Bremsstrahlung)

$$L_{\mathrm{ff}} = \Lambda_0 \rho^2 T^{1/2}$$

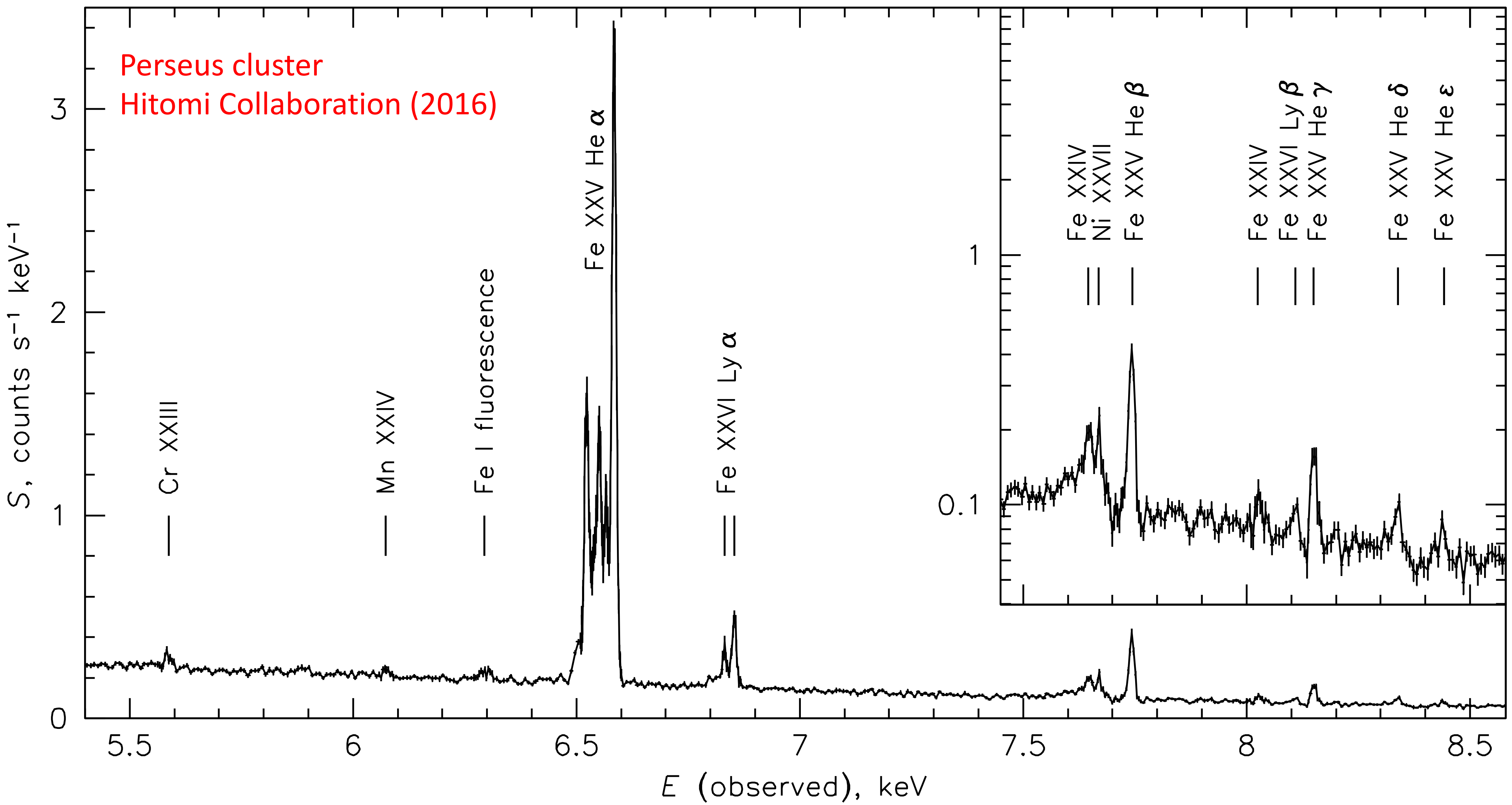
$$\dot{Q} = \Lambda_0 \rho T^{1/2}$$


NGC 7252 H II (S101)
Hα
Hβ
[O III]
Hγ
Hδ
[S II]
He I
[O I]
F_λ (10^{-16} erg s^{-1} cm^{-2} Å^{-1})
1.6
1.2
0.8
0.4
0
4000
4500
5000
5500
6000
6500
7000
Observed Wavelength (Å)

Perseus cluster (Jay GaBany)



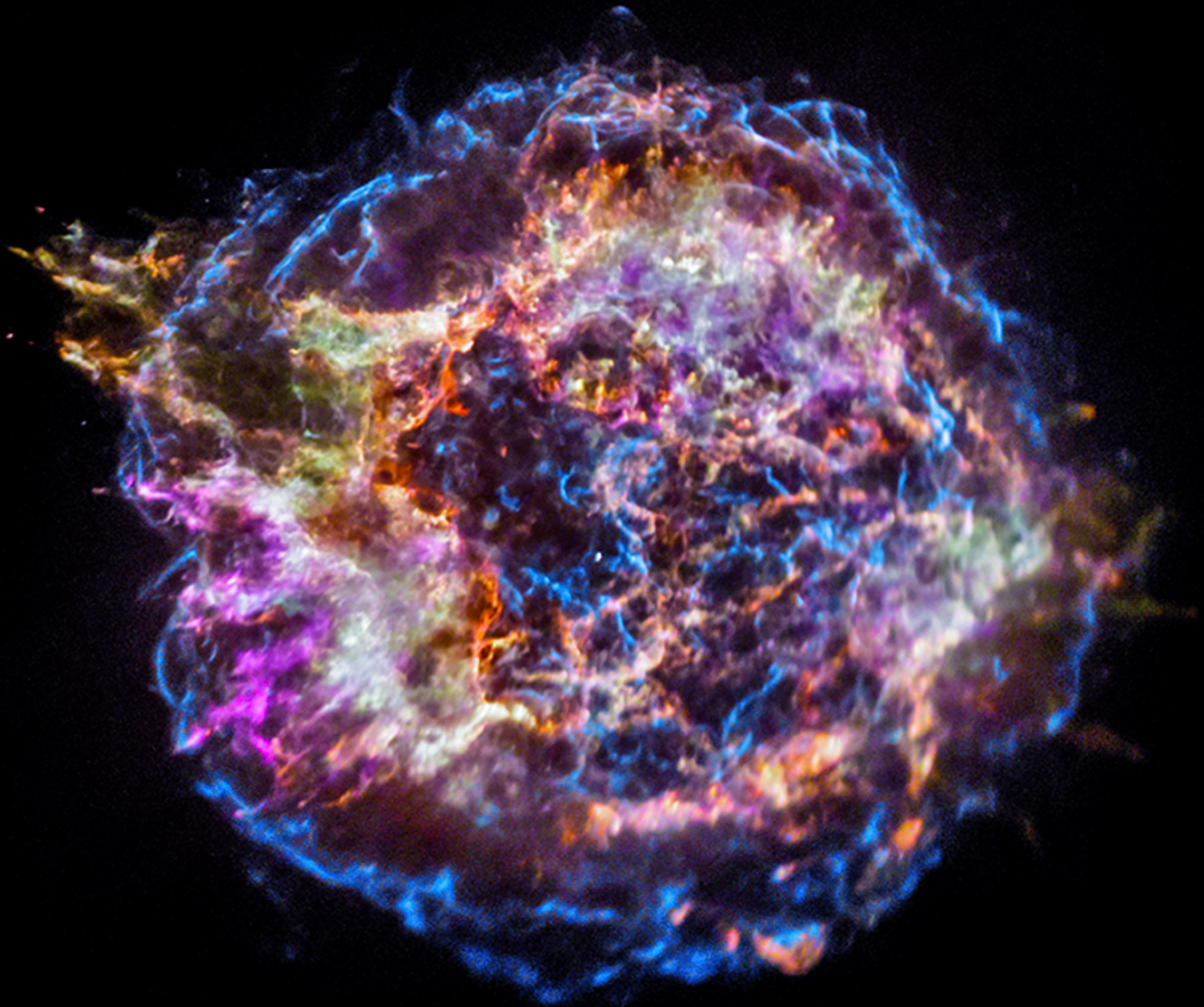
Perseus cluster in X-rays (Chandra; Fabian et al. 2006)



Perseus cluster
Hitomi Collaboration (2016)

Cas-A
Supernova
Remnant

(Chandra X-ray Obs)



Red = Silicon
Yellow = Sulphur
Green = Calcium
Purple = Iron
Blue = high-energy X-rays

What about heating?

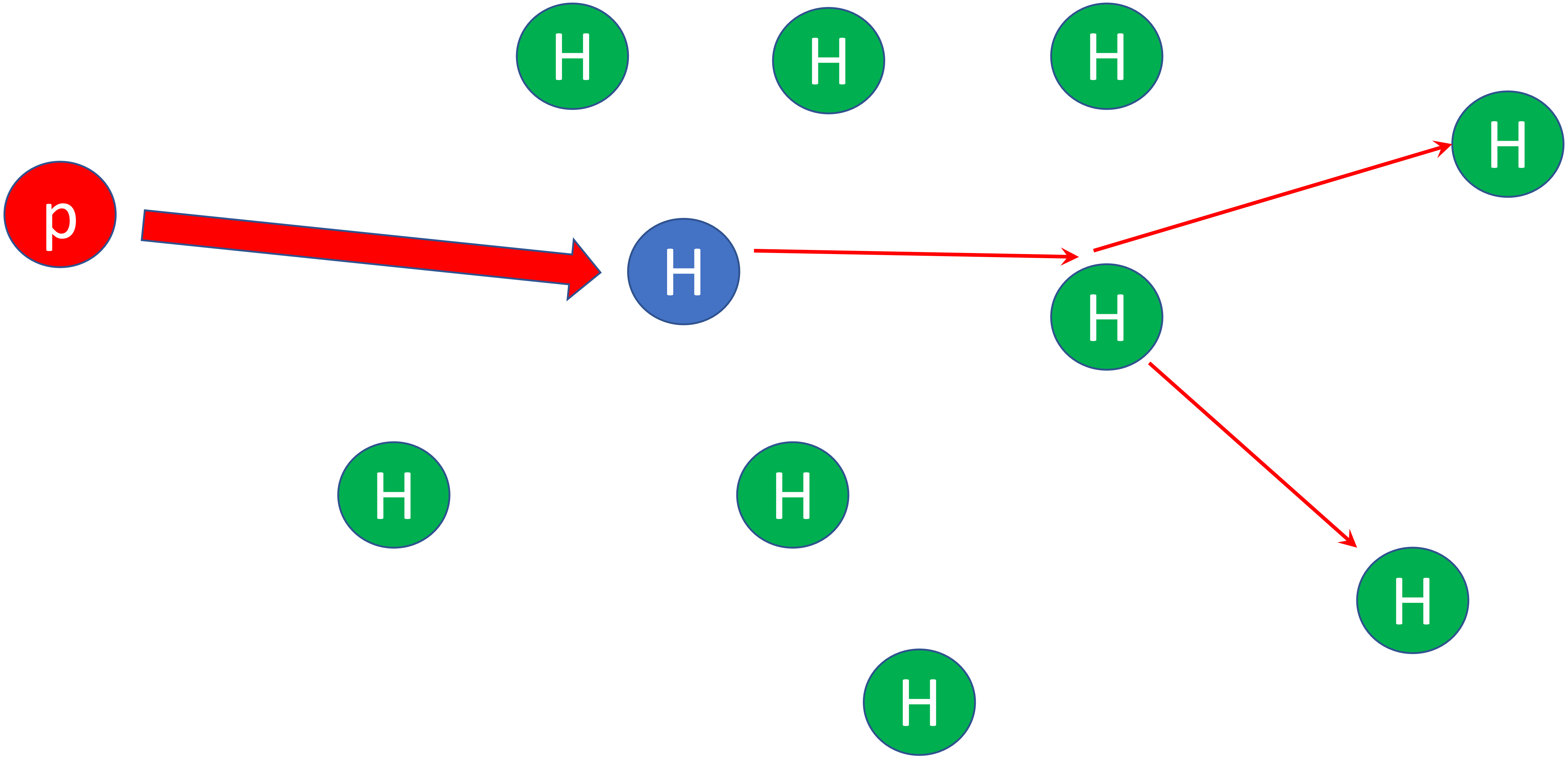
Heating can occur through the dissipation of kinetic energy via internal processes within the fluid… e.g., **shocks** (Chapter F) and **viscosity** (Chapter I).

Heating can also occur from an external agent. Most important example:

- Cosmic Ray Heating : heating by high-energy (often highly relativistic) particles that are diffusing/streaming through the thermal fluid.
  - High-energy particle ionizes atoms in fluid, freeing high-energy electrons
  - High-energy electrons proceed to collide with atoms/ions, thermalizing the energy

$$\text{ionisation rate per unit volume} \;\propto\; \text{CR flux} \times \rho$$

$$\Rightarrow \qquad \dot{Q}_{\rm cool} \propto \text{CR flux.} \;\; (\text{independent of } \rho)$$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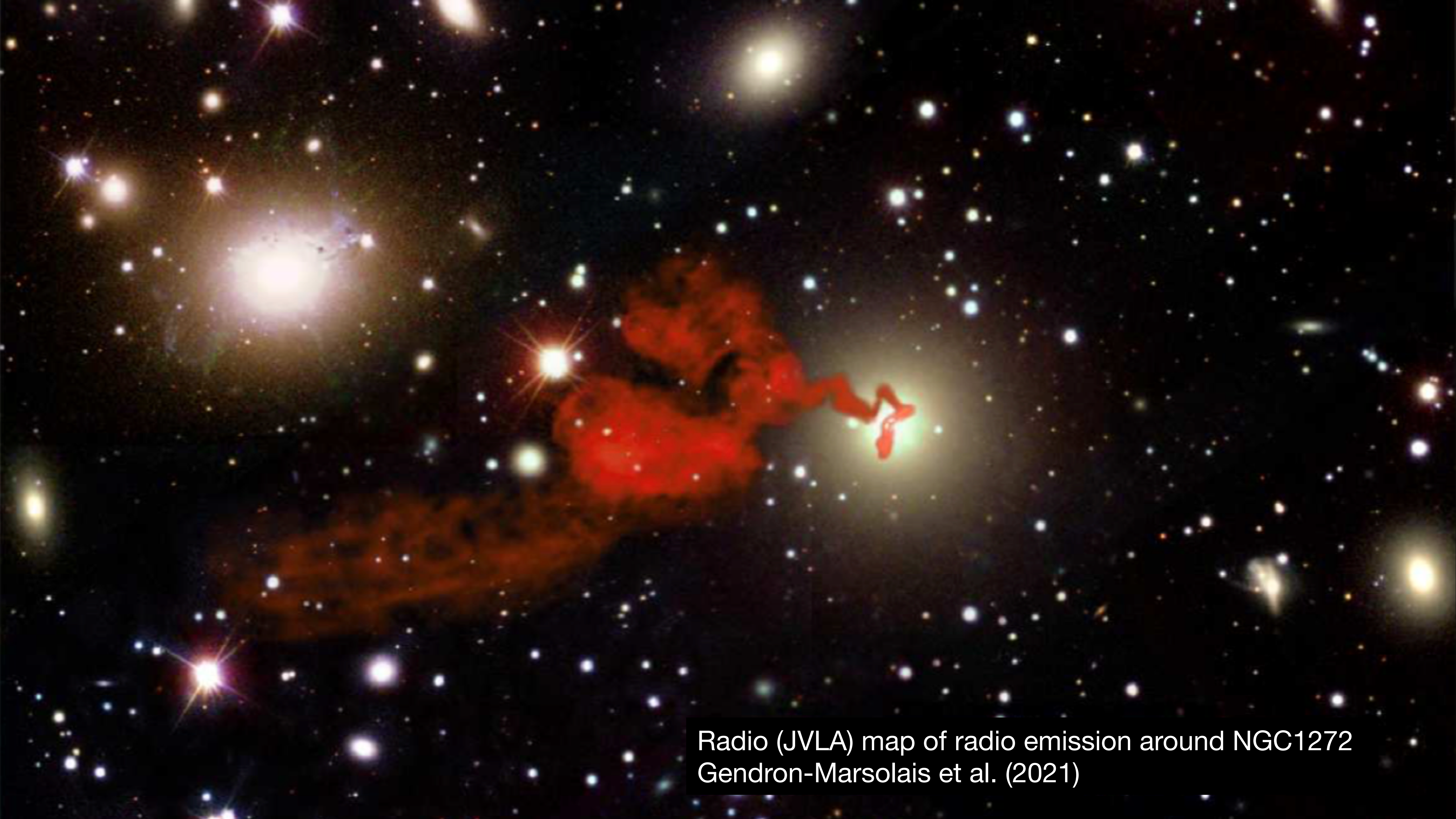


Radio (JVLA) map of radio emission around NGC1272
Gendron-Marsolais et al. (2021)

Putting all of these processes together, we can usually write:

$$\dot{Q}_{\mathrm{cool}} = \underbrace{A\rho T^{\alpha}}_{\substack{\text{radiative}\\ \text{cooling}}} - \underbrace{H}_{\text{CR heating}}$$

D.4 : Energy Transport Processes

Energy transport processes move energy around in the fluid.

Can often write as extra flux term in the energy equation.

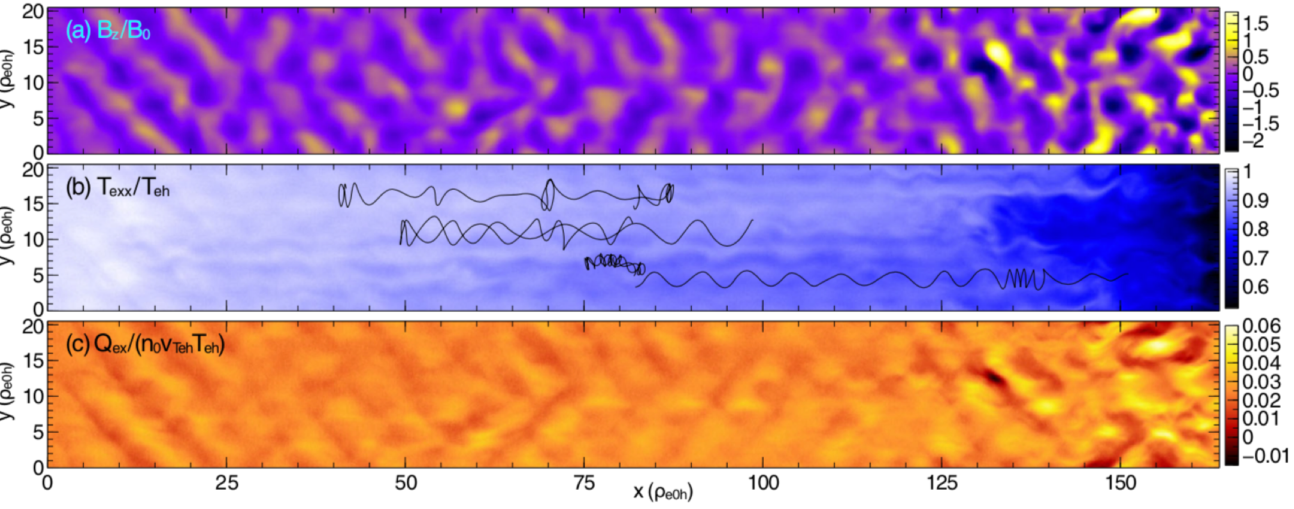
- Thermal conduction (e.g. ionized gas):
  - transport of thermal energy down temperature gradients due to the diffusion of hot e^-.
  - Conductive energy flux:

$$\mathbf{F}_{\rm cond} = -\kappa \boldsymbol{\nabla} T$$

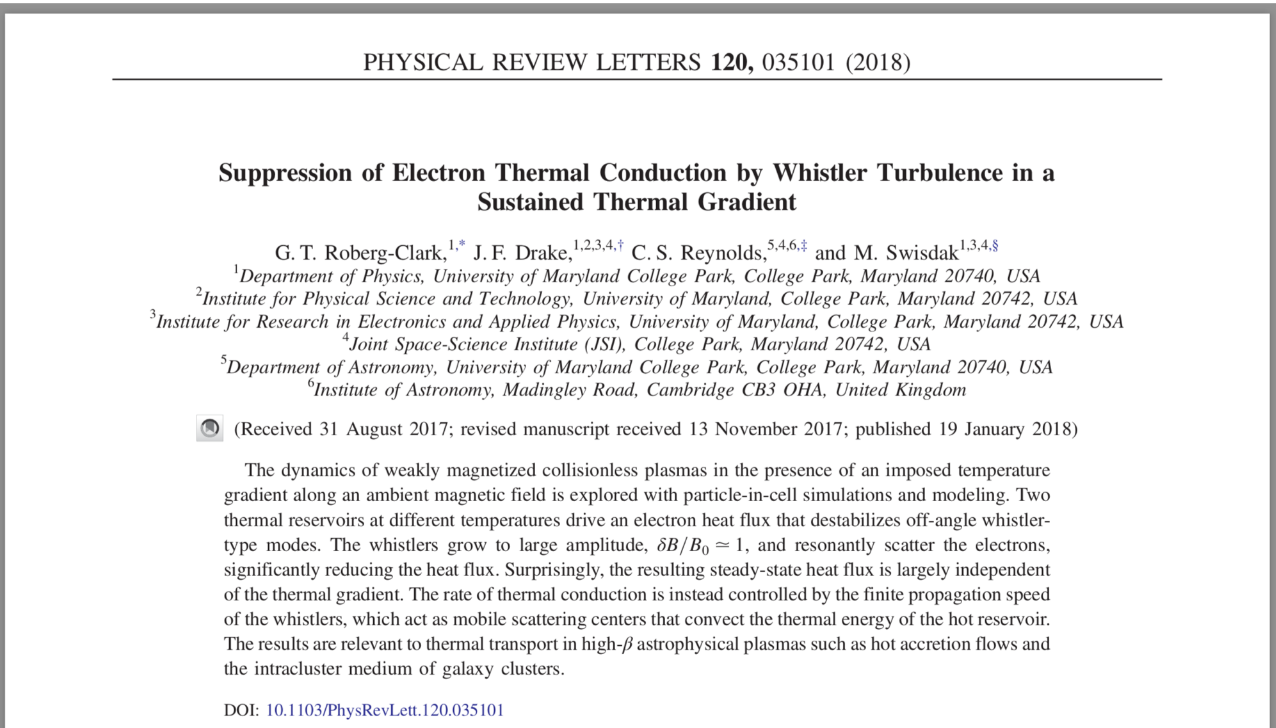
  - Local rate of change of energy density per unit volume due to conduction

$$-\boldsymbol{\nabla} \cdot \mathbf{F}_{\rm cond} = \kappa \nabla^2 T$$

  - Important in ICM cores, white dwarfs, supernova shocks



$$Q = \left(\frac{5}{2} U + \alpha_{10} \frac{\nu_{we}}{\nu_e} V_w \right) nT - \kappa_e \nabla_{\parallel} T.$$



PHYSICAL REVIEW LETTERS **120,** 035101 (2018)

Suppression of Electron Thermal Conduction by Whistler Turbulence in a Sustained Thermal Gradient

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The dynamics of weakly magnetized collisionless plasmas in the presence of an imposed temperature gradient along an ambient magnetic field is explored with particle-in-cell simulations and modeling. Two thermal reservoirs at different temperatures drive an electron heat flux that destabilizes off-angle whistler-type modes. The whistlers grow to large amplitude, $\delta B/B_0 \simeq 1$, and resonantly scatter the electrons, significantly reducing the heat flux. Surprisingly, the resulting steady-state heat flux is largely independent of the thermal gradient. The rate of thermal conduction is instead controlled by the finite propagation speed of the whistlers, which act as mobile scattering centers that convect the thermal energy of the hot reservoir. The results are relevant to thermal transport in high-β astrophysical plasmas such as hot accretion flows and the intracluster medium of galaxy clusters.

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Whistler-regulated MHD: Transport equations for electron thermal conduction in the high β intracluster medium of galaxy clusters

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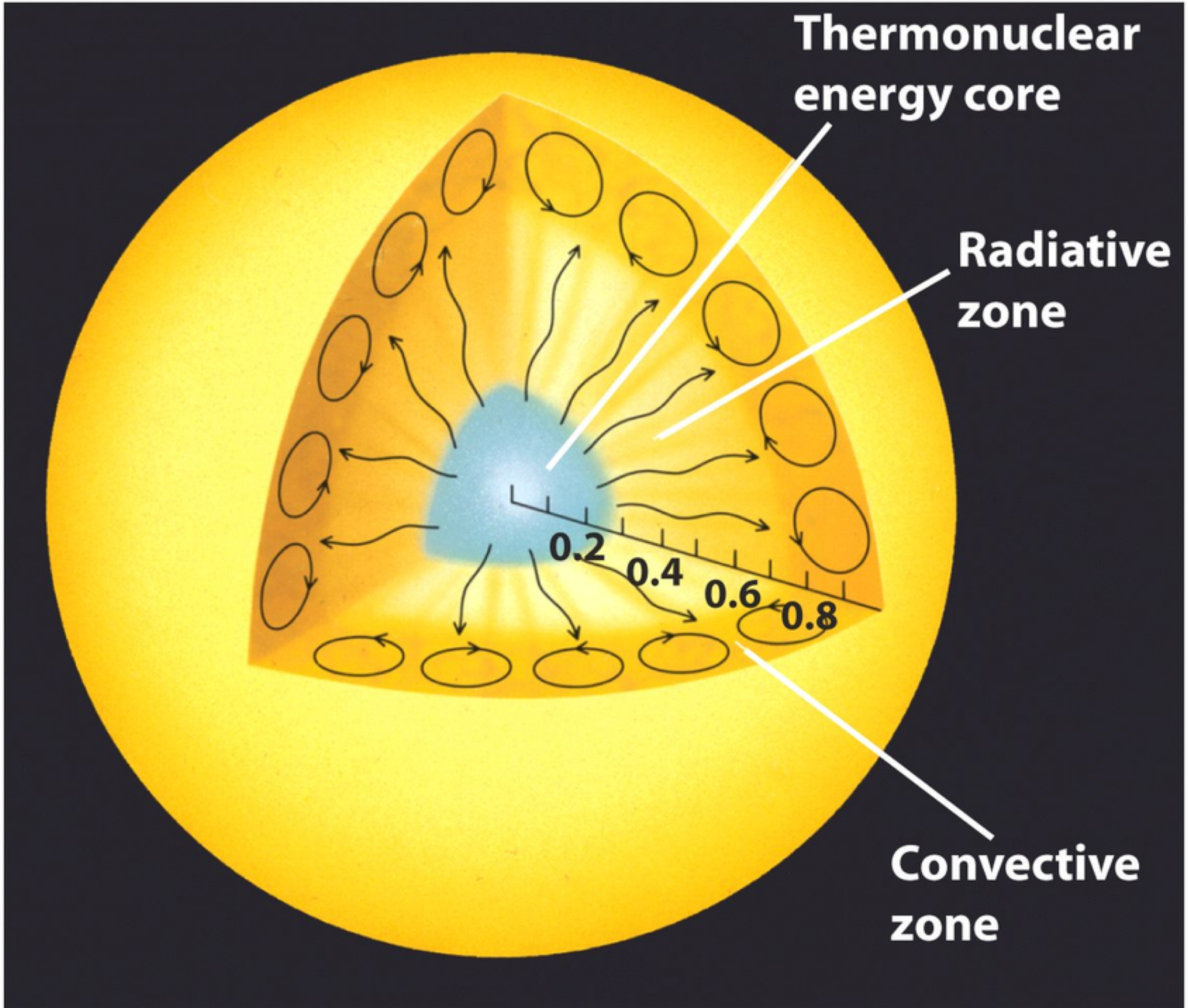
- Radiation transport
  - Transport of energy through system due to radiation – relevant for optically-thick systems
  - If medium is dominated by scattering opacity, this also looks like a diffusion problem:

$$\mathbf{F}_{\mathrm{rad}} \propto -\boldsymbol{\nabla}\epsilon_{\mathrm{rad}}$$

  - The general topic of radiation transport, and the dynamics of fluids that carry along trapped radiation, is very complex and beyond the scope of this course
  - Important in stellar interiors, black hole accretion disks

- Convection
  - Transport of energy by fluctuating or circulating fluid motions
  - Important in core of massive stars, envelopes of low-mass stars, interiors of some planets.


Thermonuclear energy core
Radiative zone
Convective zone
0.2
0.4
0.6
0.8